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EXAMINING OUTCOMES FROM TOTAL KNEE ARTHROPLASTY AND THE RELATIONSHIP BETWEEN QUADRICEPS STRENGTH AND KNEE FUNCTION OVER TIME

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Abstract

BACKGROUND: Temporal-spatial gait parameters improve following total knee arthroplasty but lower limb kinematics and moments fail to match those of age-matched healthy individuals. The aim of this study was to determine whether quadriceps strength, clinical measures of knee function, lower limb kinematics, and joint moments improve following arthroplasty and normalize over time.

METHODS: Twelve patients underwent total knee arthroplasty were tested at 3 and 12 months following surgery. Twelve matched controls were also tested. All underwent quadriceps strength testing and gait analysis to calculate knee joint kinematics and kinetics. Function was assessed using clinical tests and self-report.

FINDINGS: All clinical measures except for quadriceps strength significantly improved from 3 to 12 months. Gait asymmetry was observed at 3 months (lower stance times, peak knee flexion angle, range of motion and vertical ground reaction force), but ankle, knee and hip moments contributing to the total limb support moment were equivalent between legs. At 12 months, gait speed remained significantly slower than controls. Inter-limb differences in peak knee flexion angle and range of motion persisted. Greater hip and lower knee moments were evident in the operated limb, compared to the non-operated limb and controls. Quadriceps strength was positively correlated with faster times on the Time Up and Go and Stair Climbing Test and greater distances during the 6 Minute Walk test.

INTERPRETATION: Patients who have undergone TKA demonstrate improvements in function as measured by self-report and functional performance measures. Gait becomes more symmetric and quadriceps strength becomes stronger. Some approached the values of healthy control subjects. Important differences still remain however. The larger hip extensor contribution to the total support moment may be to compensate for the diminished knee extensor contribution during level walking. Since instrumented gait analysis and functional performance measures appear to reflect different aspects of recovery following total knee replacement, both should be considered when evaluating gait and function.

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Keywords

Gait analysis; Knee function; Osteoarthritis; Knee Arthroplasty

INTRODUCTION

Total knee arthroplasty (TKA) is one of the most common knee surgeries with over 400,000 performed annually in the United States alone (NIH Consensus Statement on total knee replacement December 8-10, 2003 2004). TKA is very successful with relatively low risks, despite variations in patients' health status and type of prosthesis (NIH Consensus Statement on total knee replacement December 8-10, 2003 2004). TKA reduces arthritic knee pain (Konig et al. 2000) and provide most patients with adequate knee range of motion (Misra et al. 2003). The surgery also typically improves activity limitations (Finch et al. 1998; Heck et al. 1998), but the long-term functional ability of people with TKA lags well behind age-matched healthy cohorts (Finch et al. 1998). Patients can expect excellent implant longevity with modern prosthetic designs with greater than 90% survival rates at 15 years or more after surgery (Gill and Joshi 2001). With an ever increasing survival rate, residual limitations in patients' functional performance have become an important focus of postoperative care.

“When will I walk normally?” remains the surgical candidate's greatest concern before TKA (Macario et al. 2003). Although patients have improved gait speed, cadence and stride length compared to their preoperative status, after TKA they often fail to match the gait characteristics of age-matched healthy individuals even years after surgery (Lee et al. 1999). The reasoning for persistent gait deficits has been mainly speculative as relatively little information is available regarding how impairments relate to gait deviations.

Quadriceps weakness is universally reported in patients with TKA and has a substantial influence on the movement patterns of the knee during gait (Mizner et al. 2005a; Mizner et al. 2005b; Mizner and Snyder-Mackler 2005). Several studies cite improvements in quadriceps strength and coincident normalization of gait patterns during postoperative recovery, but only one reported a direct relationship between quadriceps strength and gait patterns (Berman et al. 1991; Steiner et al. 1989). The work of Mizner found that at 3 months after surgery, asymmetry between limbs in quadriceps strength was related to knee flexion excursion asymmetry during weight acceptance (Mizner and Snyder-Mackler 2005). It remains to be seen how the passage of time with subsequent continued recovery may influence the relationship between quadriceps strength and gait pattern.

Most investigations have focused on the involved lower extremities' gait characteristics and relatively little information is known about of the non-operated leg. Since asymmetrical gait patterns between limbs have been reported in patients with TKA, a simple comparison of the involved side's performance over time might not be an appropriate measure of gait outcome. The non-operated leg's strength has been shown to play an important role in patients' ability to complete performance based functional assessments and deserves due consideration (Mizner et al. 2005a; Mizner and Snyder-Mackler 2005). Gait characteristics of the non-operated side compared to that of age-matched healthy individuals is important information in order to better understand whether TKA patients gait patterns are normalized over time. Studies investigating the time course of recovery for gait patterns with impairments and the characteristics of the uninvolved limb will be essential to understand a clearer picture of performance in patients after TKA. The aim of this study was to ascertain whether gait asymmetry persisted over time for patients who underwent TKA and whether knee function was restored as measured by quadriceps strength, knee motion and moments during walking. We postulated that quadriceps strength, joint moments, movement patterns would improve significantly from early post-

operative levels and be similar to those of healthy age matched control subjects. Moreover, knee function would be normalized, as measured by self report questionnaires and clinical measures.

METHODS

Subjects

Twelve individuals with knee OA who underwent unilateral tricompartmental, cemented TKA using a medial parapatellar surgical approach were recruited and then assessed at 3 and 12 months after TKA (Table 1). These twelve subjects were part of an original cohort of fourteen whose 3 month data have been previously published (Mizner and Snyder-Mackler 2005). Of the original cohort, one subject refused to return for 12 month follow-up and the second underwent contralateral TKA within the first post-operative year. Potential subjects were excluded if they had musculoskeletal involvement other than unilateral TKA that limited their physical function, had a history of uncontrolled blood pressure, diabetes mellitus, neurological impairment, a body mass index (BMI) $\leq 40 \text{ kg/m}^2$ (morbidly obese), walked with an assistive device, a significant knee flexion contracture ($\leq 5^\circ$). All participants signed an informed consent form approved by the Human Subjects Review Board at the University of Delaware. Standard post-operative rehabilitation involved 3 days of inpatient physical therapy followed by 2-3 weeks of home physical therapy visits. Outpatient physical therapy spanned six weeks (2-3 times/week). Therapy was designed to control pain and swelling, and improve knee range of motion, muscle strength and functional ability (Mizner et al. 2005a).

Twelve healthy individuals were recruited by telephone interviews, and matched within 10% of the age and body mass for each individual in the TKA group. The same exclusion criteria were used for the healthy individuals as for those who underwent TKA, except the possible musculoskeletal involvements to limit function were applied to both limbs. Testing was performed over two days: the first day was for clinical assessment including interviews using self-report questionnaires, performance based functional outcome measurements and quadriceps strength assessment; the second day, which was held within a week from the first day, was for gait analysis using motion analysis equipment.

Measurements of Physical Function

Self report of functional ability was assessed using the Knee Outcome Survey – Activities of Daily Living Scale (KOS-ADLS) (Irrgang et al. 1998). The KOS is a fourteen item questionnaire to assess how knee symptoms and knee condition affect the ability to perform daily physical functions. The KOS-ADLS is a knee specific self-reported measure of knee function and is used to assess knee function over time. The physical component score of the Medical Outcome Study Short-Form 36 (SF-36 pcs) was used to assess the subjects' perceived general physical health (Ware and Sherbourne 1992). Physical scores are scaled to 50 and correspond to the population norm. Ten points above or below equates to 1 standard deviation about the norm.

All subjects completed three performance based functional tests after completing the questionnaires: the Timed Up and Go (TUG) test, the Stair Climbing Test (SCT), and the 6 minutes walk (6MW) test. The timed up and go test measures the time it takes a subject to rise from a standard chair, walk 3 meters, and then return to sitting in the same chair (Podsiadlo and Richardson 1991). The stair climbing test measures the time it takes a subject to go up and down a flight of stairs as quickly as they feel safe and comfortably (Mizner et al. 2005a; Mizner et al. 2005b). In the six minute walk test, subjects were asked to cover as much distance as possible while walking laps on a 157 m course in a 3.05 m wide hall (Enright 2003; Enright et al. 2003).

Knee Range of Motion (ROM) Measurement

Knee ROM was measured using a standard, plastic long arm goniometer with the subjects positioned in supine. The axis of the goniometer was aligned with the center of the lateral epicondyle of the femur. The distal arm of the goniometer was aligned with the lateral malleolus and the proximal arm was aligned with the greater trochanter. To determine knee flexion ROM, patients were asked to actively slide the heel towards the buttocks and the angle of maximal active knee flexion was measured. For knee extension ROM, the patient's heel was propped off the treatment table and subjects were asked to actively extend their knee. The angle of maximal extension was recorded. Positive values were used to indicate a position of flexion at maximal knee straightening and negative numbers were used to represent positions in knee hyperextension. Examination of knee ROM in patients with knee OA has acceptable reliability with a coefficient of 0.96 for flexion and 0.81 for extension (Cibere et al. 2004).

Quadriceps Strength Measurement

Isometric quadriceps strength was tested using a burst superimposition technique, as described for patients with TKA (Mizner and Snyder-Mackler 2005). Subjects were seated on an isokinetic dynamometer (Kin-Com 500H, Chattecx Corporation, Harrison, TN, USA) with the hip flexed to approximately 90° and the trunk supported against the back of the test chair. The knee was stabilized at 75° flexion for all subjects. Two pregelled, 3 × 5", self-adhesive electrodes (ConMed Corporation, Utica, NY) were placed over the proximal vastus lateralis and distal vastus medialis to deliver a supramaximal the electrical stimulation. Subjects performed two sub-maximal and one near maximal voluntary isometric contraction (MVIC) lasting 2 to 3 seconds for familiarization and to potentiate the muscle. Intense verbal encouragement and visual feedback of force output were provided to motivate the subjects to produce an MVIC. Approximately 2-3 seconds into the contraction, the stimulator (Grass S8800 stimulator with a Grass model SIU8T stimulus isolation unit, Grass Instruments, Braintree, MA, USA), delivered a supramaximal electrical stimulus to the quadriceps muscle. Knee extension force (peak torque (N)) was measured and evaluated at 200-Hz using custom-written software (Labview 5.1, National Instruments, Austin, TX), as previously described (Stevens et al. 2003). If maximal voluntary force output was achieved, (no increase in torque during the stimulation) the quadriceps was considered fully activated (i.e. optimal recruitment) and testing was concluded for that limb. If the subject failed to generate a volitional force within ninety-five per cent of the electrically elicited force, the test was repeated, up to three times with five minutes rest intervals between tests to minimize fatigue. The volitional force (N) that immediately preceded the electrical stimulus was normalized to the subject's BMI (kg/height in m²) to allow for comparison between subjects and groups. The highest volitional force (N) achieved during the 3 attempts was used for analysis. Testing was first performed on the uninvolved limb followed by the operated limb for the TKA group, and randomly assigned for the comparison group. A quadriceps index (QI) is used as a measure of symmetry in quadriceps force production between limbs, and was calculated as follows:

$$\text{Quadriceps index (QI)} = \frac{\text{Operated volitional torque}}{\text{Non-operated volitional torque}} \times 100 \% \quad (1)$$

A QI of 100% was considered symmetric.

Motion Analysis

The subjects underwent 3-dimensional lower extremity gait analysis using a passive 6-camera motion analysis system (VICON 512, Oxford Metrics, Oxford, UK) integrated with two Bertec force platforms (Bertec Corp, Worthington, OH, USA). Kinematic and kinetic recordings were synchronized for simultaneous collection at 120Hz and 1080Hz respectively. Twenty five millimeter retro-reflective markers were placed bilaterally over the iliac crest, greater

trochanters, lateral femoral condyles, and lateral malleolus, and the heads of the 5th metatarsals to determine center of joints and to identify the end of body segments. Rigid thermoplastic shells affixed with four markers oriented orthogonally were secured with elastic wraps (SuperWrap™, FabriFoam, Inc. Exton, PA, USA) bilaterally to the shank and thigh respectively to minimize movement artifact during walking trials. To track pelvis movement, a triad of markers on a shell was placed at the midline over the sacrum. Two markers on the subject's heel counter along with the marker placed over the 5th metatarsal head were used to track the foot's coordinate system. After completing a standing calibration to identify joint centers and to define a coordination system for each segment, the subjects practiced walking trials until they obtained a consistent self-selected pace. Walking speed was determined by measuring the time it took to cross between two photoelectric cells placed 286.5 cm apart. A total of 10 successful walking trials were averaged and used for analysis. A successful trial was defined by a walking velocity within 5% of the practice trials and if the involved and uninvolved foot made clear contact with the successive steps onto the force platforms without targeting.

Data Management

Sagittal plane hip, knee and ankle kinematics were derived using rigid body analysis employing Euler angles using a custom written software program (Labview 8i, National Instruments, Austin TX, USA) and Visual 3D (Visual 3D, Version 3.77, C-Motion, inc., Rockville, MD, USA). Joint kinetics were also analyzed using the custom written software and normalized to body mass and height. Marker trajectories and force plate signals were low pass filtered using a recursive 4th order Butterworth filter at 6 Hz and 40 Hz respectively. As knee kinematics, the excursion of knee flexion angle between heel strike and peak knee flexion during stance was analyzed. Asymmetry in knee excursion was calculated defined as (Mizner and Snyder-Mackler 2005);

$$\text{Asymmetry in knee excursion} = \frac{\text{Operated knee flexion excursion}}{\text{Non-operated knee flexion excursion}} \times 100 \% \quad (2)$$

Asymmetry in knee excursion of 100% was considered symmetric.

The total lower extremity support moment was calculated as the sum each joints internal extensor moment. Individual joint contributions to the support moment were the ratios of hip, knee and ankle internal extensor moments to the total support moment and are expressed as a percentage (Winter and Eng 1995). For each trial, weight acceptance was defined from heel strike to the first peak knee flexion during stance and was normalized to 100%. Trials within a testing session were averaged within a testing session and the resultant mean was used for analysis.

Statistical Methods

All statistical analyses were performed using SPSS 14 (SPSS inc., Chicago, IL). Nonparametric tests were used for analysis to reduce the threat of outliers in this sample from inaccurately skewing the findings of the investigation. For within TKA group comparisons, Wilcoxon Signed-Ranks tests were used to assess differences between limbs and for comparing means at 3 and 12 months post-op. Variables examined were quadriceps strength, peak joint moments, peak flexion angles, peak vertical ground reaction force during weight acceptance, and clinical measures (self-report questionnaires), functional outcomes (TUG, SCT and 6MW), and active knee range of motion. Mann-Whitney U-tests were performed to compare data of individuals 12 months after TKA to the healthy limbs. Since gait parameters for healthy individuals (time of stance phase, knee flexion angle at heel strike, peak knee flexion during weight acceptance, peak vertical ground reaction force and peak knee moment) were not statistically different between limbs ($p > 0.05$), the limb was matched to the one that underwent surgery for the TKA group. Spearman Correlation Coefficients were used to analyze the relationship of between

peak quadriceps torque during strength testing and functional performance during the TUG, SCT, and 6MW. Spearman's rank correlation coefficient was used for analyzing relationships between symmetry of knee flexion excursion during weight acceptance and symmetry of quadriceps strength between sides. An alpha level was set at 0.05 for significance.

RESULTS

Questionnaires and Functional Tasks

All clinical measures for the involved limb (questionnaires, performance tests, knee ROM, and quadriceps strength) significantly improved ($p < 0.05$) between 3 and 12 months except quadriceps strength on the non-operated leg ($p = 0.308$) (Table 2). At 12 months, involved quadriceps strength showed significant improvement ($p = 0.020$) and was equivalent to the non-operated ($p = 0.06$). But the operated limb remained significantly weaker than healthy controls ($p = 0.01$). Active knee extension range of motion, uninvolved quadriceps strength, TUG and SCT times, SF-36 pcs scores, and 6MW distance were equivalent to healthy controls ($p > 0.05$). Knee flexion range of motion, operated quadriceps strength and the KOS-ADLS scores remained significantly below that of the matched healthy cohorts ($p < 0.05$) (Table 2).

Relationship between Quadriceps Strength and Functional Outcomes

Correlation coefficient revealed significant associations between quadriceps strength and performance measures (TUG, SCT, and 6MW). Greater quadriceps strength resulted in significantly faster times in performing the TUG and SCT tests and greater distances traveled during the 6MW test ($p < 0.05$) (Table 3). At 3 months, the association between quadriceps strength and performance measures were weaker for the operated limb, resulting from the operated limb being significantly weaker than the non-operated limb ($p < 0.05$). After 12 months post-operation, the relationship strengthened (Table 3).

Gait Characteristics between 3 and 12 Months

Gait asymmetry was observed at 3 months after the surgery. Subjects walked with diminished knee flexion excursions ($p = 0.006$) and less peak flexion ($p = 0.033$) on their operated limb, spent significantly less time in stance ($p = 0.002$) with statistically lower vertical ground reaction force (v-GRF) ($p = 0.021$) compared to their non-operated limbs (Table 4). The relative ankle, knee and hip moments contributing to the total limb support moment were equivalent between legs ($p > 0.05$, Figure 1). At 12 months, no differences in walking speed were evident ($p > 0.05$). Only the v-GRF of the involved leg significantly increased between testing periods ($p = 0.041$). Although stance time equalized between legs ($p > 0.05$), knee flexion excursions remained asymmetric over time ($p = 0.013$). Statistically significant correlations between asymmetric knee flexion excursion and asymmetric quadriceps strength were observed at 3 months ($\rho = 0.664$, $p = 0.026$), but they were not correlated ($\rho = 0.173$, $p = 0.611$) at 12 months (Figure 2). The relative hip, knee and ankle moments contributing to the total support moment were asymmetrical between limbs, with greater hip ($p = 0.021$) and lower knee moments ($p = 0.050$) evident in the involved limb at one year after the surgery (Figure 1).

Gait patterns between the TKA and age matched healthy group

At 12 months, gait speed was significantly slower than matched controls ($p < 0.01$) although double support times and stance times were not different between limbs or across groups ($p > 0.05$). The vertical force profile was significantly lower in the TKA group compared to the healthy individuals ($p = 0.05$). Between groups, operated hip and knee external moments were significantly different, with greater hip ($p = 0.002$) and lower knee extensor moments ($p < 0.01$) being observed in the operated limb although knee flexion angle at heel strike, peak flexion and knee flexion excursion were not statistically different during weight acceptance ($p > 0.05$).

No differences were observed between the non-operated limb and the healthy group ($p>0.05$), demonstrated by similar kinematic and kinetic gait variables.

DISCUSSION

Individuals with TKA did undergo an expected recovery 3 to 12 months with improvements in the involved knee's ROM and quadriceps strength, functional performance capacity, and perceived function questionnaire scores. While their functional scores are similar to the age- and body mass -matched healthy individuals, their operated quadriceps strength and self-selected gait patterns continued to differ substantially from the comparison group. Persistent quadriceps weakness is of particular concern as quadriceps strength had a strong relationship to functional performance test results at both test points. When the surgical leg is still quite weak at the 3 month test, symmetry in quadriceps strength had a relationship with knee kinematics during gait, but when strength was improved at 12 months the relationship substantially weakened. The TKA group's self-selected gait was slow paced with limited knee flexion excursions during weight acceptance that persisted over time. The TKA group's gait kinetics during weight acceptance is characterized by a large contribution from the hip joint and a small contribution from the knee. The atypical distribution of joint torques actually worsened over time despite often perceived and measured improvements.

While patients should experience functional improvement after surgery, achieving functional outcomes that can match healthy subjects is a challenging goal. Some investigators question whether it is possible to expect patients with TKA to improve to the point that they match their healthy peers (Finch et al. 1998; Heck et al. 1998). The subjects in the current study performed exceptionally well and actually did achieve comparable functional performance to the matched healthy cohort. Their good functional results may be, in part, explained by the inclusion criteria of the study and is a potential limitation in the application of our findings. But even with similar functional outcome scores between groups, there were substantial differences in gait between groups with the TKA group walking more slowly with less knee flexion excursion during weight acceptance, and a hip dominated lower extremity support moment distribution. These differences are consistent with findings of past studies of TKA gait patterns (Bolanos et al. 1998; Chen et al. 1991). Thus, the performance outcomes and gait analysis provide conflicting messages when trying to determine if the functional ability of our TKA group can be defined as normal.

The apparent conflict in measures of walking ability could be a result of the differences in methodology between the measures. While the subjects were asked to walk at a self-selected speed in the gait analysis, the clinical functional outcomes asked them to perform the tasks "as quickly" as they felt safe and comfortable (Kennedy et al. 2006; Podsiadlo and Richardson 1991). Those encouragements can influence performance (Ikai and Steinhaus 1961) and they may have helped raise the performance of the TKA group to nearing the capability of the healthy state on those tests. When the TKA group is pressed to perform they can achieved near healthy equivalency, but when allowed to perform at their typical pace they perform below the healthy standard. We expected to observe the opposite finding based on the work of Noble et al. with a greater likeness between groups with less demanding tasks and greater differences between groups when the functional measure was more demanding (Noble et al. 2005). Perhaps, the physical performance outcome measures are more reflective of potential functional capacity and the gait analysis results may be a better reflection of the actual patient performance during typical daily activity.

By the three month test, patients with TKA typically have recovered from the acute pain and swelling experienced after surgery and yet they continue to exhibit pronounced quadriceps weakness (66% of the non-operated strength). In their weakened state, there was a greater

reliance on the strength of the non-operated limb to perform functional tasks with higher correlations between non-operated quadriceps strength and performance measures of TUG, SCT, and 6MW as compared to the operated. Subjects in the TKA group maintained a limp during their self-selected gait pattern with the operated limb exhibiting less v-GRF, stance time, and knee flexion excursion during weight acceptance when compared to the non-operated leg. Quadriceps strength did play a moderate role in gait patterns at this time point as asymmetry in quadriceps strength related to asymmetry in knee flexion excursion.

When strength improved at the 12 month point (87% of non-operated), there was a reduced reliance on the non-operated limb for functional performance. The relationship between the non-operated quadriceps strength and the performance tests remained strong, but the relationship had a general weakening between tests. Concurrently, the relationship between functional performance and operated quadriceps strength increased from the 3 month test. With increased strength during recovery, the TKA group achieved better functional performance with an increased utilization of the operated limb's strength. It appears that during the physically challenging tasks of physical performance tests, patients in the TKA group needed and used their involved limb's strength gains over time and had subsequent better scores on functional tasks.

The phenomenon of increased dependence on the non-operated leg for performance in the subacute phase evolving into more of a shared utilization between limbs at the end of recovery is also supported from the gait kinematic results, but the findings are more subtle. As mentioned previously, the TKA group has significant differences between legs in multiple variables of interest during 3 month analysis which can be general grouped into a finding of limping on the operated limb. Most of the differences in kinematics present at 3 months are not significantly different by the 12 month test. While it is expected that individuals would strive towards coordinating their limbs to enhance gait symmetry (Reisman et al. 2005), the expectation was for greater utilization of the operated limb with increased gait speed. The data suggest that the lack of difference in peak knee flexion between limbs at a year stem from a non-significant yet potentially clinically meaningful increase in knee motion in the operated and a tendency towards reduced motion in the non-operated knee. We hypothesize that when the operated limb has a very weak quadriceps, like many patients at the 3 months after TKA, then patients depend on the non-operated side to compensate by placing greater forces on the non-operated limb and using more knee excursion during weight acceptance. As strength recovers, then the limbs moved closer to balance in kinematics and GRF rather than a simple improvement in the involved.

While the TKA group takes advantage of their operated quadriceps strength with better performance scores over time, they don't seem to maximize the potential of their greater strength during the gait analysis measures. Some of the differences in relationship between quadriceps strength and the performance tests versus self selected walking could be attributed to diminished physical demand during self-pace walking. Unlike the findings in the performance tests, the correlation between symmetry in quadriceps strength and symmetry in knee flexion excursion actually weakened over time. The original hypothesis was that as there was expected improvement in quadriceps strength over time then there would be a coincidental improvement in knee flexion excursion during weight acceptance. While involved quadriceps strength made gains, there was no statistically significant improvement in corresponding knee flexion excursion. A reduced knee excursion during limb loading in gait is often associated with low knee internal extension moments which minimally challenge the knee extensor musculature. Thus, as the TKA group maintained a stiff legged gait pattern between test sessions, it is reasonable to accept that there would be a reduction in the correlation between quadriceps strength symmetry and knee flexion symmetry. Perhaps there is a threshold when quadriceps strength can impact knee kinematics during self-selected gait that is surpassed once

symmetry reached 87% at the year test. Combined, these findings suggest that improving quadriceps strength outcomes may not be enough to reach the full potential gains in function possible from TKA surgery. The addition of a gait retraining program that encourages patients with TKA to utilize improvements in quadriceps strength with greater knee excursions during stance may be efficacious.

The comparison to normal helps keep perspective beyond just symmetry between limbs. This is especially evident when interpreting the kinetic results. Self-selected gait speed failed to make a customary improvement from 3 to 12 months after surgery. Patients with TKA coupled their slow gait speed with a stiff knee movement with a greater dependence on the torque at the hip to contribute to the support moment of the limb during the end of weight acceptance. The hip extension dominated support moment present at 3 months actually is accentuated at 12 months with even less contribution of the total support moment coming from the knee extension moment and an even greater contribution from the hip. This compensatory mechanism between hip and knee extension moment is often present in patients with knee OA and perhaps the TKA group's distribution of torque is a remnant of preoperative gait habits (McGibbon and Krebs 2002). Since individuals after TKA place greater reliance on the hip extension moment during weight acceptance there is diminished stimulation to the quadriceps muscle during limb loading. An insufficient mechanical stimulus could negatively effect muscle strength gains over time (Mueller and Maluf 2002) and may help to explain why the operated quadriceps strength is less than the normal cohort.

The current study does have limitations that deserved to be considered when interpreting our data. The TKA group did have exceptional functional outcomes and may represent more of a "best case" scenario in terms of what can currently be expected after surgery. While this may be a factor that could limit our external validity, it may also strengthen the weight of the message in that even patients with some of the best outcomes do not adopt normal gait patterns. Comparisons with the non-operated leg must also be considered since many with unilateral TKA eventually go on to have the other knee replaced due to degenerative changes and pain. It is not difficult to argue that the non-operated knee may be at least in the early stages of OA or may require surgery. The gamut is wide and can cause considerable variability in the findings, especially with a relatively limited sample size. While we have a well matched healthy comparison group, our sample may predispose the project towards type II error in reporting no significance differences which may have actually achieved statistical significance with a larger sample.

CONCLUSIONS

Patients who have undergone TKA demonstrate improvements in function as measured by self-report and functional performance measures. Gait becomes more symmetric and quadriceps strength becomes stronger. Some approached the values of healthy control subjects. Important differences still remain however. The larger hip extensor contribution to the total support moment may be to compensate for the diminished knee extensor contribution during level walking. Since instrumented gait analysis and functional performance measures appear to reflect different aspects of recovery following total knee replacement, both should be considered when evaluating gait and function.

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Figure 1.
 Distribution of Lower Extremity Joint Moments.
 (Individual hip, knee, and ankle internal extensor moments expressed as a percentage of the support moment.)

Figure 2.
Relationships between Quadriceps Strength and Knee Flexion Excursion after Total Knee Arthroplasty (TKA).

Table 1

Subject Information [mean (standard deviation)]

	TKA group (N=12)	Healthy group (N=12)
	male=7 female=5	male=8 female=4
Age (year)	61.33(6.88)	61.58(6.23)
Height (m)	1.73(0.10)	1.76(0.11)
Weight (kg)	86.02(11.23)	84.34(9.94)
BMI (kg/m ²)	28.94(3.60)	27.35(3.97)

BMI= body mass index

Table 2

Clinical Assessments [mean (Standard deviation)]

	TKA		Healthy	
			p-value (3-12mo)	p-value (vs 12 mo)
	3 months	12 months		
KOS-ADLS	0.79(0.01)	0.89(0.10)	0.005	0.99(0.02)
SF-36 (pcs)	45.8(7.4)	51.5(7.2)	0.005	53.0(6.1)
ext-ROM (°)	0.8(2.3)	hyper1.2(2.2)	0.014	hyper0.8(2.3)
Flex-ROM (°)	116.4(10.4)	124.1(7.8)	0.005	136.3(6.9)
TUG (sec)	7.33(1.34)	6.83(1.46)	0.015	6.40(0.93)
SCT (sec)	11.40(3.26)	10.13(2.76)	0.003	8.65(1.59)
6MW (m)	558(121)	630(136)	0.012	732(116)
NMVIC (N/BMI)				
(operated side)	19.6(7.4) *	24.6(10.4)	0.028	34.2(10.5)
(non-operated side)	29.7(9.6)	28.4(10.4)	0.308	0.101

mo: months

KOS-ADLS The Knee Outcome Survey – Activities of Daily Living Scale

SF-36 (pcs) The Medical Outcome Study Short-Form 36

ext-ROM Extension active range of motion of the operated knee

flex-ROM Flexion active range of motion of the operated knee

TUG (sec) Timed Up and Go (second)

SCT (sec) Stair Climbing Test (second)

6MW (m) 6 Minutes Walk (meter)

NMVIC Normalized maximum voluntary isometric contraction (by body mass index) BMI (body mass index) = kg/m²

* p<0.05 comparison between the operated side and the non-operated side

Table 3

Pearson Product Moment Correlations (p-values) between Functional Outcomes Measurements and Quadriceps Strength

		Correlation of Function and NMVIC		
		TUG	SCT	6MW
3 Months	Operated	−0.594 (0.042)	−0.797 (0.002)	0.762 (0.004)
	Non-operated	−0.713 (0.009)	−0.846 (0.001)	0.825 (0.001)
12Months	Operated	−0.790 (0.002)	−0.790 (0.002)	0.902 (<0.01)
	Non-operated	−0.608 (0.036)	−0.783 (0.003)	0.853 (<0.01)

Table 4

Gait Parameters [mean (Standard deviation)]

		TKA		Healthy
		3 months	12 months	p-value (3mo)
Speed (m/sec)		1.40(0.10)	1.41(0.11)	1.69(0.11)
DST (% of gait cycle)		0.25(0.08)	0.24(0.08)	0.24(0.03)
Stance phase	operated	0.62(0.01)*	0.62(0.02)	0.63(0.01)
	non-operated	0.64(0.01)	0.63(0.02)	0.63(0.02)
v-GRF		1.03(0.06)*	1.09(0.10)	1.17(0.11)
	(% of BW)	1.11(0.09)	1.12(0.11)	0.041
Knee flexion angle		8.99(4.71)	8.00(3.75)	0.445
	at heel strike (°)	7.43(4.75)	6.53(4.70)	0.878
Peak knee flexion angle		18.99(8.63)*	20.53(6.97)	0.241
	during WA (°)	24.96(7.65)	22.17(7.59)	0.333
Knee flexion excursion		9.17(7.14)**	11.48(7.82)*	0.158
	during WA (°)	16.07(8.17)	14.33(6.92)	0.433
Hip extension moment		55.2(9.5)	61.7(17.5)*	0.721
at PKF (% of support moment)	operated	53.8(12.9)	48.8(19.4)	0.859
	non-operated			
Knee extension moment		28.4(10.4)	19.9(15.5)*	0.203
at PKF (% of support moment)	operated	28.2(14.8)	35.6(18.4)	0.678
	non-operated			
Ankle PF moment		16.3(8.7)	18.4(21.6)	0.878
at PKF (% of support moment)	operated	18.0(11.2)	15.6(9.5)	0.173
	non-operated			

TKA: Total Knee Arthroplasty

DST: double support time

BW: body weight

v-GRF: vertical ground reaction force

WA: weight acceptance

PKF: peak knee flexion

PF: plantar flexion

* p<0.05 comparison between the operated side and the non-operated side

** p<0.01 comparison between the operated side and the non-operated side