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Time Course of Quad Strength, Area and Activation after Knee Arthroplasty and Strength Training

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Abstract

Introduction—Changes in strength, activation, and morphology of the quadriceps femoris muscle group were assessed in 61 individuals that underwent unilateral total knee arthroplasty, with progressive postoperative strength training, for primary knee osteoarthritis.

Methods—Assessments of these three parameters were made at 4 time points (preoperatively and 4, 12, and 52 weeks postoperatively). Maximal voluntary knee extension strength was recorded using an electromechanical dynamometer and voluntary muscle activation was measured using a burst superimposition technique. Lean muscle cross sectional area (CSA) was determined using magnetic resonance imaging.

Results—Preoperatively, the surgical limb was significantly weaker and smaller than the nonsurgical limb. Strength, voluntary muscle activation, and CSA of the quadriceps femoris significantly improved over the study period. At 52 weeks, the surgical limb was still significantly smaller in size than the nonsurgical limb, but had greater levels of voluntary muscle activation. In the nonsurgical limb, CSA was the primary determinant of strength across all time points, with voluntary muscle activation progressively contributing more from the preoperative assessment ($R^2=0.11$) to the assessment 52 weeks postoperatively ($R^2=0.26$). In the surgical limb, voluntary muscle activation was the primary determinant of strength preoperatively and 4 weeks postoperatively ($R^2=0.38$ and 0.41 , respectively), whereas CSA was the primary determinant of quadriceps strength 12 and 52 weeks postoperatively ($R^2=0.44$).

Conclusion—Resolving the impairments in voluntary muscle activation after total knee arthroplasty may be necessary before visible gains in strength and muscle hypertrophy are evident.

Keywords

Muscle atrophy; knee replacement; postsurgical rehabilitation; osteoarthritis

INTRODUCTION

Changes in skeletal muscle structure and function are normal consequences of the aging process and chronic musculoskeletal diseases such as osteoarthritis (OA) appear to magnify

age-related changes in muscle. Sarcopenia, from the Greek words *sarx* meaning flesh and *penia* meaning loss, is often used to describe the age-related reduction in muscle mass (18). Previous work has shown that sarcopenia directly contributes to reductions in muscle strength (8,23), often leading to significant functional declines in older adults.

Quadriceps weakness is a hallmark impairment of knee OA (11), the most common musculoskeletal disease among older adults (5). Furthermore, quadriceps weakness is considered a primary risk factor for knee dysfunction (1). In addition to muscle atrophy, neuromuscular impairment, such as the ability to fully activate the quadriceps, appears to substantially contribute to quadriceps weakness in individuals with and without knee OA (1, 6, 12). Voluntary activation deficits range from 4% to 30% in persons with various stages of knee OA (3, 4, 15, 16). Recent evidence supports the notion that quadriceps weakness in individuals with end stage knee OA is more predominantly attributed to failure in voluntary muscle activation than to muscle atrophy (16).

While total knee arthroplasty (TKA) is successful in terms of ameliorating osteoarthritis-related pain (12), restoring knee joint alignment (14) and range of motion (12), as well as improving functional ability (10,12), little is known about the time course of quadriceps strength recovery or the factors contributing to strength changes following surgery. Our recent clinical trial has shown that current standard of care following TKA does not adequately address strength impairments as effectively as progressive postoperative strength training with and without neuromuscular electrical stimulation (17). The purpose of this study was to characterize the changes in quadriceps muscle strength preoperatively through the first postoperative year following TKA in subjects who participated in a progressive postoperative strength training intervention. We hypothesized that, in response to a progressive postoperative strength training intervention for the quadriceps muscle group, strength would improve beyond preoperative levels and would be accompanied by improvements in voluntary muscle activation and muscle hypertrophy. We also hypothesized that voluntary muscle activation would be the primary factor influencing strength preoperatively, with a shift toward lean muscle cross sectional area (CSA) as the primary factor influencing strength within the first postoperative year.

METHODS

Subjects

Sixty-one individuals (34 women; 48–83 yrs) volunteered to participate in the study (**SDC 1 Subject Demographics**). Subjects were scheduled for unilateral TKA by one of three orthopaedic surgeons. Eligibility criteria included BMI <40 (very severe obesity (24)), and no history of cardiovascular disease, diabetes, or uncontrolled high blood pressure. Subjects were excluded if they had a history of symptomatic knee OA in the contralateral knee (symptomatic OA was defined as knee pain greater than 4/10 on a 10 point verbal analog scale) or any other lower extremity pathology that limited function. Subjects were tested preoperatively (~2 weeks before TKA), during the initial post operative evaluation (~4 weeks postoperatively) and again at 12 and 52 weeks after TKA. All subjects were part of a clinical trial assessing rehabilitation programs after TKA (17). The postoperative rehabilitation programs involved either progressive strength training (N=31) or a combination of progressive strength training and neuromuscular electrical stimulation (N=30). Written informed consent was provided by all subjects prior to study participation. The study was approved by the ethics committee of the University of Delaware and is in accordance with the declaration of Helsinki.

Measurement of quadriceps strength and muscle activation

A burst superimposition test was used to measure quadriceps strength and voluntary muscle activation. Subjects were seated in an electromechanical dynamometer (KinCom; Chattecx, Harrison, TN) with the knee stabilized in 75° of flexion. The lateral femoral condyle was aligned with the axis of rotation of the dynamometer lever arm. The force transducer was secured around the lower leg approximately 2 cm above the lateral malleolus. Electrical stimulation electrodes (7.2- × 12.7-cm; CONMED Corp, Utica, NY) were placed over the motor points of the rectus femoris muscle proximally and the vastus medialis muscle distally. Two submaximal and one maximal isometric knee extension contractions were provided for warm-up and familiarization with the testing apparatus. A single maximal contraction was used to minimize fatigue. A series of stimulations were delivered prior to testing to verify placement of electrodes and to familiarize the subjects with the electrical stimulation experienced during testing.

Maximal quadriceps strength was determined from the force data as the peak output prior to administration of the electrical stimulus. To ensure maximal effort, visual feedback on a computer monitor and verbal encouragement were provided. A Grass S8800 stimulator with a Grass model stimulus isolation unit (Grass instruments, West Warwick, RI) was used to deliver a 100-Hz, 12-pulse (pulse duration 600 μ s) stimulus train at 135 Volts. The stimulus train was delivered during the plateau in force of a maximal voluntary contraction using custom written software (LabView 4.01, National Instruments, Austin, TX). Force augmentation at the time of the electrical stimulus indicated incomplete voluntary muscle recruitment. If force augmentation was present, indicating incomplete voluntary activation, the testing procedure was repeated up to 3 times on each leg to ensure the reduced activation was not due to motivation. Subjects were given 5-minute rest period between contractions to minimize the effects of muscle fatigue.

The level of voluntary muscle activation was then quantified using the central activation ration method (CAR) (7) with a curvilinear correction equation (19) applied to the data from the trial with the highest voluntary force produced. CAR was calculated by dividing the maximal force output by the force output at the time of the electrical stimulation. A CAR of 1.0 signifies 100% or complete voluntary muscle activation whereas anything less than 1.0 signifies incomplete muscle activation. Figure 1 illustrates the force traces and superimposed stimuli for an individual subject over the course of the study.

Quantification of quadriceps cross sectional area

Quadriceps CSA was estimated using magnetic resonance imaging. Subjects were positioned in supine with the knees extended in a 1.5 Tesla magnet (Signa, General Electric, Waukesha, WI) with a body coil. Axial images of both thighs were obtained from the greater trochanter to the tibial plateau at 7-mm interslice intervals. A standard GE SPGR sequence imaging protocol was used (2-D spoiled gradient-echo, 500-ms pulse repetition time (TR), 8-ms echo time (TE) with a 256 × 256 encoding matrix and 480- × 480-mm field of view).

Images were processed using IMOD software (The Boulder Laboratory for 3D Electron Microscopy of Cells at the University of Colorado, Boulder, Colorado). The vastus lateralis, vastus medialis, vastus intermedius, and rectus femoris muscles were individually outlined using a digitizing pen/tablet (Intuos 2 tablets, Wacom Corporation, Vancouver, Washington). Custom-developed software was used to scale each outline, calculate the enclosed CSA, and remove the intramuscular fat and connective tissue from CSA measurements using grayscale values for each image slice as previously described (16). The slice with the largest CSA was used for data analysis. Figure 2 illustrates quadriceps CSA from a series of MRI scans for an individual subject over the course of the study.

Rehabilitation protocol

The outpatient rehabilitation protocol was comprised of progressive postoperative strength training exercises alone or progressive postoperative strength training exercises combined with neuromuscular electrical stimulation targeting the quadriceps femoris muscle group (22). All subjects completed a minimum of 12 sessions (2 or 3 sessions for 6 weeks; average=17). In general, the protocol targeted pain, swelling, knee extension and flexion range-of-motion (ROM), patellar mobility, quadriceps strength, and function.

The progressive postoperative strength training program targeted the quadriceps femoris muscle group, hamstrings, triceps surae, hip flexors, and hip extensors of the involved limb. The type and intensity of the training exercises were determined based on each subject's clinical evaluation and follow-up assessments by a licensed physical therapist. Training began with 2 sets of 10 repetitions with the weight adjusted to achieve a 10-repetition maximum. The training progressed to 3 sets of 10 repetitions, with weights adjusted to maintain the targeted intensity (22).

The neuromuscular electrical stimulation treatments consisted of 10 electrically stimulated, isometric contractions delivered to the quadriceps muscle group while subjects were seated on an electromechanical dynamometer (KinCom; Chattecx, Harrison, TN). Two stimulating electrodes (7.62×12.70 cm; ConMed, Utica, NY) were placed proximally over the rectus femoris muscle and distally over the vastus medialis muscle. Each contraction lasted for 10 s and was produced by a 2.5 kHz sinusoidal waveform, with alternating current delivering 50 pulses per second with a pulse duration of 600 μ s. The current amplitude was determined by each subject's maximal tolerance, with minimal target intensities from the electrically generated forces set to 30% of the individual's maximal voluntary contraction (17).

Data analysis

All data were processed using a statistical software package (SPSSv15.0, SPSS Inc, Chicago, IL, USA). Because the findings from the randomized clinical trial demonstrated no significant differences between the strength training groups with and without neuromuscular electrical stimulation (17), data presented here are collapsed across groups. Descriptive statistics were computed for all demographic and experimental data and expressed as means $\pm$ standard deviation. Changes in quadriceps MVIC, CAR, and CSA were analyzed using separate 2×4 repeated-measures ANOVAs (2 limbs and 4 time points). Paired samples t -tests were also performed at each time point to determine differences between the limbs. The Bonferroni correction was used to adjust the alpha level for multiple comparisons ($p < 0.017$). Stepwise linear regression analyses were applied to assess the influence of quadriceps voluntary muscle activation and CSA on quadriceps strength in both the surgical and nonsurgical limbs at each time point.

RESULTS

Quadriceps Strength

Results of the repeated measures ANOVA revealed a significant time by limb interaction ($p < 0.001$) (Figure 3). Quadriceps strength in the surgical limb was significantly weaker than the nonsurgical limb before TKA (20%; $p < 0.001$), 4 weeks after TKA (56%; $p < 0.001$), and 12 weeks after TKA (28%; $p < 0.001$), but was similar at 52 weeks after TKA ($p = 0.56$). Quadriceps strength in the surgical limb decreased by 44% from the preoperative assessment to the 4 week postoperative assessment ($p < 0.001$), improved from week 4 to week 12 ($p < 0.001$), and improved again from week 12 to week 52 ($p < 0.001$) (**SDC 2 Effects sizes and 95% Confidence Intervals**). Quadriceps strength in the nonsurgical limb did not

change between the preoperative and 4 week period ($p>0.05$), but decreased by 8% between the weeks 12 and 52 ($p=0.002$).

Quadriceps Voluntary Muscle Activation

Voluntary muscle activation of the quadriceps exhibited a significant time by limb interaction ($p<0.001$) (Figure 4). The progressive strength training with and without neuromuscular electrical stimulation improved voluntary activation after 52 weeks (14% with and 9% without), but there were no significant differences between the groups (17). Voluntary activation was not significantly different between limbs 12 weeks after TKA ($p=0.249$). However, voluntary activation was significantly lower than in the surgical limb compared with the nonsurgical limb preoperatively ($p<0.016$) and 4 weeks postoperatively ($p<0.001$), and was significantly higher than the nonsurgical limb 52 weeks postoperatively ($p<0.001$) (**SDC 2 Effects sizes and 95% Confidence Intervals**). There were no significant changes in voluntary muscle activation in the nonsurgical preoperatively through 12 weeks postoperatively ($p>0.05$), but voluntary activation was significantly reduced between 12 and 52 weeks ($p=0.33$). Voluntary muscle activation in the surgical limb significantly decreased from the preoperative to the 4 week postoperative assessment ($p=0.04$) and then significantly improved between the 4 and 12 week postoperative assessments ($p<0.001$) and again between the 12 and 52 week postoperative assessments ($p=0.036$). INSERT FIGURE 4

Quadriceps Cross Sectional Area (CSA)

Quadriceps CSA demonstrated a significant time by limb interaction ($p<0.001$) (Figure 5). Quadriceps CSA changed significantly over the study period, with the surgical limb significantly smaller than the nonsurgical limb at all time points (15% preoperatively ($p<0.001$), 22% 4 weeks postoperatively, 15% 12 weeks postoperatively, and 7% 52 weeks postoperatively; $p=0.009$). Interestingly, CSA decreased in both the surgical ($p<0.001$) and nonsurgical ($p<0.001$) limbs from the preoperative assessment to the 4 week postoperative assessment. CSA improved from the 4 week assessment to the 12 week assessment in both the surgical ($p<0.001$) and nonsurgical ($p<0.001$) limbs. There were no significant changes in the quadriceps CSA of the nonsurgical limb between 12 and 52 week postoperative assessments ($p=0.22$), however, CSA significantly improved from the 12 to 52 week assessment in the surgical limb ($p<0.001$) (**SDC 2 Effects sizes and 95% Confidence Intervals**).

Determinants of Quadriceps Strength in the Nonsurgical Limb

In the nonsurgical limb, the variance in quadriceps strength from preoperative measures through the first year after TKA was mostly explained by CSA (Table 1). The level of voluntary muscle activation also contributed significantly to the strength of the nonsurgical limb during these assessments (Table 1). Together, CSA and voluntary muscle activation explained 67 – 72% of the variance in quadriceps strength for the nonsurgical limb ($p<0.001$).

Determinants of Quadriceps Strength in the Surgical Limb

In the surgical limb, the contribution of voluntary muscle activation and CSA changed over the course of the study (Table 1). Preoperatively, voluntary muscle activation explained more than CSA; together explaining 59% of the variance in strength of the surgical limb prior to TKA ($R^2=0.59$, $p<0.001$).

At the initial evaluation, approximately four weeks after TKA, voluntary muscle activation and CSA explained 73% of the variance in quadriceps strength of the surgical limb ($R^2=0.73$,

$p<0.001$), with both voluntary muscle activation and CSA contributing similarly to the variance in quadriceps strength (Table 1). Three months after surgery (~12 weeks), the role of voluntary muscle activation was reduced, explaining 29% of the variance ($R^2=0.29$, $p<0.001$) in quadriceps strength of the surgical limb, whereas the role of CSA increased, explaining 44% of the variance ($R^2=0.44$, $p<0.001$) in quadriceps strength. Together, voluntary muscle activation and CSA explained 68% of the variance ($R^2=0.68$, $p<0.001$) in quadriceps strength 12 weeks after surgery.

Fifty-two weeks after TKA, voluntary muscle activation explained 25% of the variability in quadriceps strength of the surgical limb ($R^2=0.25$, $p<0.001$) and CSA explained 44% of the variability in quadriceps strength ($R^2=0.44$, $p<0.001$) (Table 1). Together, voluntary muscle activation and CSA explained 64% of the variance ($R^2=0.64$, $p<0.001$) in quadriceps strength of the surgical limb 52 weeks after TKA.

DISCUSSION

This study examined the changes in quadriceps muscle strength, voluntary muscle activation and CSA for both the surgical and nonsurgical limbs of individuals who underwent unilateral TKA with progressive post operative strength training. Two groups were tested in the original randomized clinical trial (17), one group received progressive postsurgical strength training and one group received both progressive strength training and neuromuscular electrical stimulation. The findings of the randomized clinical trial showed that both treatment arms resulted in substantial improvements in lower extremity function compared to patients who received standard of care after surgery. However, because there were no significant differences for any measures between the groups, the data presented here were collapsed across groups. All subjects were tested preoperatively through 12 months after TKA. Quadriceps strength in the surgical limb was weaker than the nonsurgical limb preoperatively, with significant improvements over the study period, such that quadriceps strength was similar for the surgical and nonsurgical limbs one year after surgery. Voluntary muscle activation of the quadriceps in the surgical limb from before to after surgery was reduced, but then significantly improved throughout the year after surgery, surpassing the activation levels of the nonsurgical limb at one year after surgery. Similarly, CSA was reduced from before to after surgery, but was also significantly improved throughout the first postoperative year. However, the CSA of the quadriceps group was still smaller in the surgical limb compared with the nonsurgical limb at one year after surgery. CSA was the primary factor influencing strength in the nonsurgical limb at all time points. In the surgical limb, voluntary muscle activation contributed more to quadriceps strength than CSA during the preoperative assessment and 4 weeks after surgery.

Several studies have reported quadriceps recovery after TKA (2, 9, 12, 13, 20), demonstrating significant reductions in quadriceps strength and voluntary muscle activation immediately following TKA. Berth et al. (2) demonstrated that 3 years after TKA quadriceps strength improved to levels similar to that of the nonsurgical limb, however, both limbs remained weaker than healthy matched controls. Similarly, voluntary activation improved, but remained lower than healthy controls. A limitation to the study by Berth et al. was that postoperative measures were only assessed at one time point, shedding little light on the time course of quadriceps recovery or the factors that influence quadriceps strength. To date, no studies have assessed changes in the levels of voluntary activation and morphology longitudinally. Therefore, one novel component of the present study was the longitudinal assessment of CSA and voluntary activation in individuals from before and through the first postoperative year after TKA providing better insight into the recovery of the quadriceps femoris muscle after TKA. Our findings indicate that individuals seeking TKA have significant quadriceps atrophy prior to surgery, which continues to atrophy for at

least 4 weeks after surgery. With strength training, this impairment does improve, but the CSA of the surgical limb remains significantly smaller than the nonsurgical limb, even one year after surgery.

Voluntary muscle activation is instrumental to quadriceps function even prior to OA development. Becker et al (1) demonstrated that persons who underwent partial meniscectomy not only had a reduction in quadriceps strength but also declines in voluntary activation. The authors compared 32 patients approximately 4 years (48 ± 9 months) after partial meniscectomy (posterior region of medial meniscus) to control subjects matched for age and body mass index. The subjects who underwent partial meniscectomy exhibited bilateral deficits in quadriceps strength and voluntary activation. Similarly, although to a lesser extent, Hurley and Newham (6) demonstrated bilateral activation deficits in persons with early, unilateral knee osteoarthritis. The mechanisms responsible for reduced voluntary activation has yet to be fully elucidated, but are likely attributable to pain or effusion related inhibition (25).

Interestingly, strength in the contralateral limb of our subjects declined from the preoperative assessment (727.4 ± 225.3 N) to the 1 year assessment (640.1 ± 233.6 N). There was a non-significant trend toward impaired neuromuscular activation in the nonsurgical limb, such that voluntary activation was initially $90.2 \pm 7.1\%$ and after one year was $87.3 \pm 11.7\%$. These data may reflect disease development and/or progression; of the 61 subjects who participated in this study, 12% underwent TKA for the contralateral knee within 2 years after their initial TKA.

Our findings of weakness, atrophy, and activation deficits in the nonsurgical limb are not novel (2). In conjunction with previous research, these data suggest that deficits in voluntary muscle activation may emerge before muscle atrophy, thereby contributing to the degenerative process. The etiologic nature of quadriceps weakness associated with OA is unclear; however, these data suggest that both muscle activation and muscle atrophy could be contributing factors.

In addition, we demonstrated greater changes in voluntary muscle activation compared to muscle hypertrophy within the first 3 months after TKA. Voluntary muscle activation improved by 6% and lean muscle cross sectional area improved by $<1\%$, however, quadriceps strength was 11% weaker 3 months after surgery. One year after TKA, voluntary activation increased by 13% matching previously reported levels in healthy older adults (21), lean muscle cross sectional area by 6%, and quadriceps strength improved by 8% from preoperative levels. Neural deficits may need to be reversed before gains in muscle hypertrophy can be achieved. Therefore, the immediate changes in quadriceps strength from 1 to 3 months after TKA appear to be more related to neural involvement and motor relearning than muscle hypertrophy.

A limitation of the present study is that we only followed patients for the first postoperative year. It is difficult to determine if patients continued to increase the quadriceps CSA once the volitional activation deficits were resolved. Furthermore, the progressive postoperative strengthening intervention was only implemented for six weeks following the postsurgical rehabilitation period (3–4 weeks after surgery). If in fact neural improvements are responsible for strength gains in the immediate postoperative period, continued strength training may promote greater strength gains in the long term.

The results of this study highlight the contributions of voluntary activation and CSA following TKA from before surgery through the first post operative year. While significant activation deficits in the immediate postoperative period contribute to quadriceps weakness, progressive strength training appears to help reverse these deficits within 3 months. Longer

term strength training programs may help to facilitate the recovery of quadriceps cross sectional area and may help to mitigate the declines noted in the nonsurgical limb.

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Figure 1. Sample force traces from an individual at all time points illustrating quadriceps strength and voluntary muscle activation at all four time points (Preoperative, 4 weeks, 12 weeks, and 52 weeks) for the surgical and nonsurgical limbs.

Figure 2.

ExemplaryMRI scans of the quadriceps muscle group for the surgical and nonsurgical limbs from an individual subject at all four time points (Preoperative assessment, 4 week assessment, 12 week assessment, and 52 week assessment) for the surgical and nonsurgical limbs.

Figure 3.

Changes in quadriceps strength between limbs and within a limb across time. Error bars indicate standard deviations. * indicates significant differences between limbs; † indicates significant difference across time for the surgical limb; p<0.001

Figure 4. Changes in voluntary activation of the quadriceps between limbs and within a limb across time. Error bars indicate standard deviations. * indicates significant differences between limbs; † indicates significant difference across time for a limb; $p < 0.001$

Figure 5.

Changes in lean muscle cross sectional area (CSA) of the quadriceps between limbs and within a limb across time. Error bars indicate standard deviations. * indicates significant differences between limbs; † indicates significant difference across time for a limb; $p < 0.009$

Table 1

Determinants of quadriceps strength in the nonsurgical and surgical limbs. The contributions of voluntary activation, lean muscle cross sectional area (CSA), and the combination of both factors based on linear regression.

Nonsurgical Limb			
	Voluntary Activation	CSA	Voluntary Activation + CSA
Preoperatively	0.11 *	0.60	0.72
4 weeks	0.16	0.56	0.68
12 weeks	0.17	0.52	0.70
52 weeks	0.26	0.43	0.67
Surgical Limb			
	Voluntary Activation	CSA	Voluntary Activation + CSA
Preoperatively	0.38	0.28	0.59
4 weeks	0.41	0.40	0.73
12 weeks	0.29	0.44	0.68
52 weeks	0.25	0.44	0.64

Data are R^2 values. $p < 0.001$, except

*
 $p = 0.008$