The Long-Term Contribution of Muscle Activation and Muscle Size to Quadriceps Weakness Following Total Knee Arthroplasty

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ABSTRACT

Purpose: Many older individuals have persistent quadriceps strength impairments after a total knee arthroplasty (TKA). A combination of muscle atrophy and neuromuscular activation deficits apparently contributes to residual strength impairments. The purpose of this short report is to describe the contribution of quadriceps muscle activation and muscle volume to impaired muscle strength in older individuals an average of 21 months following a TKA. **Methods:** Seventeen individuals (males: 3, females: 14; mean age: 68 yrs ± 8.7; BMI: 33 ± 4.8 kg/m^2; number of TKA: 24; average postoperative months: 21 ± 11.3) recruited from an orthopaedic surgeon's practice provided their written consent and participated in this study. Quadriceps strength (MVIC) and voluntary quadriceps muscle activation (QA) were measured with use of a burst-superimposition technique in which a supramaximal burst of electrical stimulation is superimposed on an MVIC. Quadriceps volume (QV) was assessed from magnetic resonance images of the quadriceps. **Results:** The mean quadriceps strength was 107.3 Nm ± 36.4 (range: 43.22 – 205.2). The mean QA (as described with a central activation ratio) was 0.97 ± 0.04 (range: 0.83 – 1.00). The mean QV was 1093 cm^3 ± 311.80 (range: 653.66 – 1706.56). QA and QV explain 85% of the variance in quadriceps strength (R^2 = .85, $p < 0.001$), with QV having the greatest contribution to strength (R^2 = .77, $p < 0.001$). **Conclusions:** QV is a much stronger predictor of quadriceps strength than QA in individuals more than 1 year following TKA. Activation levels contributed little to strength one year following TKA, compared to its profound contribution in the first few postoperative months. Physical therapy interventions focused on improving muscle size in this population should be considered more relevant than countermeasures addressing neuromuscular activation.

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Key Words: total knee arthroplasty, quadriceps strength, voluntary muscle activation, quadriceps muscle volume

INTRODUCTION

After a total knee arthroplasty (TKA), the predominant impairment is a characteristic reduction in quadriceps strength that has been associated with a limitation in postoperative functional activity.[1-4] Recent studies have highlighted an inability to fully activate the quadriceps muscle during a voluntary effort as an important factor in postoperative weakness.[1,5-7] This activation deficit is ubiquitous and pronounced (> 20% activation failure) one month following surgery.[5,7,8] While the ability to volitionally activate the quadriceps muscle improves over time, activation deficits persist as muscle dysfunction can last for years after TKA.[1]

A loss in quadriceps muscle strength prior to surgery can also be related to decreased muscle mass. The maximal quadriceps' cross-sectional area (CSA) of older patients who are awaiting surgery for their painful osteoarthritic knees is approximately two-thirds that of age-matched individuals.[9-12] This atrophy worsens in the first month after TKA surgery with a loss of 5% to 20% of quadriceps mass reported.[6,8,13] One month following surgery, however, it is the loss of voluntary activation that contributes more to quadriceps weakness: activation deficits having 2-fold the impact on quadriceps strength when compared to muscle atrophy.[5,8]

While the relative contributions of activation deficits and muscle atrophy are relatively well understood as it relates to the loss of quadriceps strength early after TKA surgery, their influence on residual long-term weakness is not yet known. Therefore, the purpose of this short report is to describe the contribution of quadriceps muscle activation and muscle size to impaired muscle strength in older individuals more than 10 months following a TKA.

MATERIALS AND METHODS

Subjects

Seventeen older individuals (mean age = 68 years ± 8.7), who had received either a unilateral or bilateral TKA more than 10 months prior to enrolling in this study (mean time following TKA surgery = 21 months ± 11.3), were recruited from an orthopaedic surgeon's (CP) list of follow-up patients in the Department and Orthopedics at the University of Utah. A total of 24 TKA knees were included from this cohort of 13 women and 4 men. Though more symptomatic than a similar cohort of older TKA recipients, the participant's pain, activity, recreation levels, and health-related quality of life are similar to that previously reported[14,15] (Table 1).

Study procedures were approved by the University of Utah Health Sciences Center Institutional Review Board. All participants provided written consent prior to beginning the study. The TKA surgical procedures were performed via a "mini" medial parapatellar arthrotomy

Table 1. Participant Characteristics. Mean (standard deviation) age, BMI, KOOS and SF-36 of the individuals, males and females, who had a TKA.

	Participants (n=17)
Age in years	68 (8.7)
Women/Men	13/4
Total TKA procedures	24
BMI (kg/m²)	33 (4.9)
KOOS	
Symptoms	58.2 (12.6)
Pain	80.2 (22.7)
Activities of Daily Living	83.3 (22.4)
Sports and Recreation	60.7 (31.8)
Quality of Life	61.6 (28.5)
SF-36	
Physical Component Summary	43.7 (11.6)
Physical Function	63.2 (25.7)
Bodily Pain	67.9 (25.7)

BMI = body mass index, KOOS = knee injury and osteoarthritis outcome score, SF-36 = Short Form-36 Health Questionnaire, TKA = total knee arthroplasty

with minimal patella eversion.[16,17] A conventional tri-compartmental knee replacement was performed in all cases with the Biomet Vanguard knee system (Biomet, Warsaw, IN). Following TKA, patients received in-patient care and home health physical therapy visits for the first 2 weeks following surgery. Thereafter guidelines for outpatient physical therapy and independent exercises were provided to the patient.[18] The 8-week comprehensive postoperative rehabilitation guidelines are provided in Table 2.

Table 2. Total Knee Arthroplasty Postoperative Rehabilitation Guidelines

Days Postoperative	Recommended Rehabilitation
1 to 5	Inpatient: 2 times per day • Bedside exercises: 1-3 sets of 10 repetitions for all strengthening exercises; ankle pumps, quadriceps sets, gluteal sets, hip abduction(supine), short arc quads, straight leg raise • Exercises for active range of motion, active assisted range of motion, and terminal knee extension • Bed mobility and transfers • Gait training with assistive device on level surfaces and stair training (if applicable)
6 to 14	Home health: 2-3 times per week, 2-3 weeks • Exercises: 1-3 sets of 10-15 repetitions, 1 to 2 times per day independently; ankle pumps, quadriceps sets, straight-leg raise, hamstring sets, standing leg curls, seated knee extension, supported single standing for balance • Exercises for range of motion; seated or supine knee active range of motion • Bed mobility and transfers; sit to stand transfers • Gait training with appropriate assistive device
15 to 42	Outpatient physical therapy: 2-3 times per week, 4-6 weeks • Exercises: 1-3 sets of 10-15 repetitions, exercises as above, exercise bike (10-15 min), step ups, wall slides • Exercises for range of motion; seated or supine knee action range of motion • Neuromuscular electrical stimulation to augment quadriceps muscle activation if indicated • Gait training: walking backward, side step, march, or crossover steps, walking in obstacle course
43 to 56	Independent exercise program: 2-3 time per week, 4-6 weeks • Exercises: continue all exercises- 1to 3 sets at 10 to 20 repetitions, as home exercise program or a gym membership

Quadriceps Strength

Maximal voluntary isometric contraction (MVIC) of the quadriceps muscle was measured on a Kin Com dynamometer (KinCom, Chattanooga, Hixon, TN).[5,7,19] Participants were seated with their hips flexed to 85° and their knees flexed to 75°. Prior to testing, participants practiced using submaximal contractions at 50% and 75% of their maximal effort to familiarize themselves with the testing procedure. Participants then performed a MVIC of knee extension lasting 5 seconds. The subjects received visual feedback on a computer monitor and were verbally encouraged to exert maximal effort. The MVIC value was entered into a custom-written software program using Labview V 6.0 (Labview, National Instruments) so that the MVIC values could be used for the burst superimposition technique to assess quadriceps activation.

Quadriceps Activation

The burst superimposition technique was used to determine quadriceps activation (QA). This technique involves superimposing a train of high voltage pulses with rapid frequency during a MVIC effort[5,14,20,21] with 2 (7.8x12.7cm) self-adhesive neuromuscular stimulation electrodes (CONMED Corporation, Utica, NY) secured to the thigh on the limb with TKA. The cathode was placed over the motor point of the vastus medialis and the anode was placed over the motor point of the rectus femoris.[7] During a maximal knee extension effort, and when torque values reached >94% of peak MVIC, the participants held their MVIC effort for 0.5s at which time a burst of electrical stimulation (Grass S88000 with a Grass model SIU8T stimulus isolation unit, (Grass Instruments, West Warwick, RI) consisting of an electrical current (10 pulses, 100pps train, 600 µsec pulse duration, 135 Volts) was delivered to the quadriceps. Torque data was digitized at 200 samples*s-1 and analyzed with custom written software. Voluntary activation of the quadriceps was reported as an index known as the central activation ratio (CAR).[8,22,23] The CAR index is derived from the volitional MVIC divided by the total torque; with the total torque being calculated as a combination of the MVIC and a superimposed burst of electrical stimulation (E) (Figure 1). A CAR of 1.0 denotes complete activation of muscle.[23,24]

$$CAR = MVIC/ MVIC + E$$

Quadriceps Volume

Quadriceps volume (QV), a measure of muscle size, was determined by magnetic resonance imaging (MRI). Participants were positioned in a standardized fashion; using in-house MRI protocol procedures. All participants were asked to lie supine in the MRI magnet with their lower extremities in a pillow-supported, resting knee extension posture with their feet comfortably strapped to avoid movement. A 1.5T GE Signa LX MRI instrument and body coil was used to obtain a coronal scout and axial T1-weighted images of the quadriceps muscle between the inguinal crease and the proximal pole of the patella. The axial MRI images were digitized through DICOM Works and MATLAB (Mathworks, Natick, MA) software packages, and analyzed to determine the CSA of the quadriceps muscle (independent of bone and fat). The MRI produced 18-22 axial slices to evaluate (slice thickness of 8 mm and an inter-slice distance of 15 mm). Volume measurements were estimated

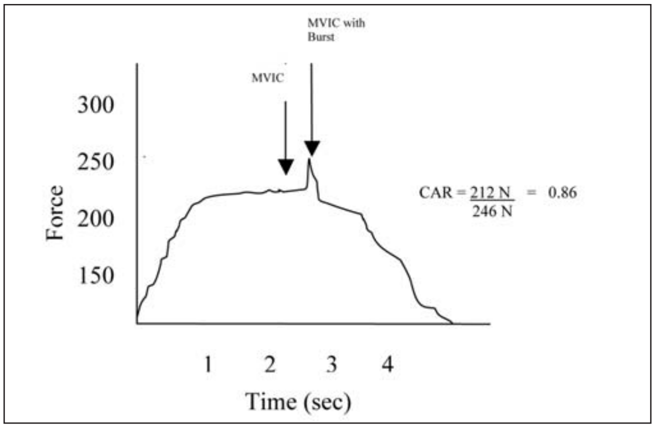

Figure 1. A schematic representation of a quadriceps force tracing from a maximal voluntary isometric contraction with an electrically-elicited force during a burst superimposition.

by summing the volumes from each slice to give total volume as described previously.[25,26]

Statistics

Data were analyzed with SPSS 12.0 (SPSS, Chicago, IL). Descriptive statistics were calculated for demographic variables and dependent measures. For each dependent measure, the assumptions for parametric statistical analysis were met. Pearson correlation coefficients were calculated to determine the relationship between quadriceps strength, QV, and QA. Stepwise multiple regression analysis was performed to determine the relative contributions of QV and QA to quadriceps strength. The alpha level was set at 0.05.

RESULTS

The mean quadriceps strength produced by participants during their TKA knee extension effort was 107.3 Nm ± 36.4 (range: 43.22 – 205.2). The mean QA was 0.97 ± 0.04 (range: 0.83 – 1.00). The average QA was 0.97; only 13% of the knees with a TKA exhibited activation levels less than healthy older adults with no known knee pathology.[20] The mean QV was 1093 cm^3 ± 311.80 (range: 653.66 – 1706.56).

A significant correlation existed between quadriceps strength and QV ($r = 0.88$; $p < .001$) and a nonsignificant correlation between quadriceps strength and QA ($r = .04$, $p = 0.85$) was observed (Figure 2).

The results of the linear regression analysis indicated that muscle volume and muscle activation explain 85% of the variance in quadriceps strength ($R^2 = .85$, $p < 0.001$). Quadriceps volume was the greatest contributor to quadriceps strength, explaining 77% of the variance ($R^2 = .77$, $p < 0.001$).

DISCUSSION

The novel finding of this short report is that QV is a much stronger predictor of quadriceps strength than QA in individuals approximately 1 to 3 years following TKA. The low contribution of volitional activation failure in explaining the variance in quadriceps strength is the reverse of what is found early after TKA, when activation deficits are the primary contributors to quadriceps strength.[5] When combined with existing evidence it is clear quadriceps strength remains impaired over time,[1-3,27] yet quadriceps activation deficits present early after TKA seem to resolve in most individuals. This is encouraging as previous findings report older individuals with knee osteoarthritis who have not received a knee replacement have deficits

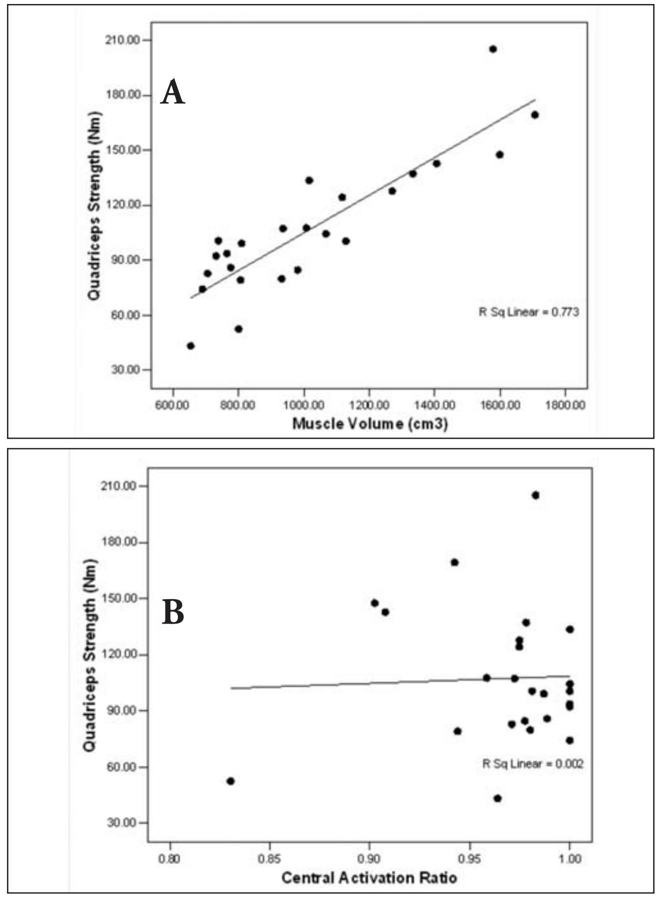

Figure 2. The relationship between quadriceps strength and: (a) quadriceps muscle volume and (b) quadriceps activation as determined by the central activation ratio. The relationships are described by linear regression equations: (a) MVIC = 2.292 + .103(QV), r =.88, p < 0.001, (b) MVIC = 70.043 + 38.548(QA), r = 0.042, p = 0.846.

in QA.[28] When coupled with our findings, it seems that if these older individuals were to choose to replace their osteoarthritic knee with a TKA their QA deficits would likely resolve over time. Therefore, the relative impact of volitional activation on quadriceps strength approximately 1 to 3 years following TKA is overshadowed by the impact of residual quadriceps atrophy.

It should be noted that several limitations of this study warrant caution when interpreting the results. Considering the variability in the amount of time since TKA surgery, our participants should be considered a heterogeneous cohort with very few deficits in activation. Moreover, despite a programmatic approach to rehabilitation during the first 3 to 4 months (see Table 2) following TKA, it is not clear what fraction of participants were compliant with this program. This TKA cohort's overall functional status does, however, resemble that of TKA recipients typically depicted in the literature one year following surgery.[29-31] As well, considering that impairments in muscle and mobility peak 6 to 9 months following surgery[14] and the remaining deficits continue to be present over subsequent years,[1-3,27,32,33] we made an apriori decision to include only those older individuals > 9 months following TKA surgery.

The results of our study do suggest that rehabilitation efforts should include countermeasures that will improve quadriceps muscle size, thereby addressing the long-term quadriceps weakness present after TKA. Prospective longitudinal research of this evolving relationship between quadriceps weakness and impairments in volitional activation and atrophy is warranted to determine the optimal rehabilitation approach that can predictably mitigate the long-term quadriceps strength deficits in individuals following TKA.

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