

# Quadriceps and Hamstrings Muscle Dysfunction after Total Knee Arthroplasty

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## Abstract

**Background/rationale** Although TKA reliably reduces pain from knee osteoarthritis, full recovery of muscle strength and physical function to normal levels is rare. We presumed that a better understanding of acute changes in hamstrings and quadriceps muscle performance would allow us to enhance early rehabilitation after TKA and improve long-term function.

**Questions/purposes** The purposes of this study were to (1) evaluate postoperative quadriceps and hamstrings muscle strength loss after TKA and subsequent recovery using the nonoperative legs and healthy control legs for comparison, and (2) measure hamstrings coactivation before and after TKA during a maximal isometric

quadriceps muscle contraction and compare with nonoperative and healthy control legs.

**Methods** We prospectively followed 30 patients undergoing TKA at 2 weeks preoperatively and 1, 3, and 6 months postoperatively and compared patient outcomes with a cross-sectional cohort of 15 healthy older adults. Bilateral, isometric strength of the quadriceps and hamstrings was assessed along with EMG measures of hamstrings coactivation during a maximal isometric quadriceps contraction.

**Results** There were no differences in strength loss or recovery between the quadriceps and hamstrings muscles of the operative leg throughout the followup, although differences existed when compared with nonoperative and healthy control legs. Hamstrings muscle coactivation in the operative leg during a maximal quadriceps effort was elevated at 1 month (144.5%) compared to the nonoperative leg.

**Conclusions** Although quadriceps dysfunction after TKA typically is recognized and addressed in postoperative therapy protocols, hamstrings dysfunction also is present and should be addressed.

**Clinical Relevance** Quadriceps and hamstrings muscle strengthening should be the focus of future rehabilitation programs to optimize muscle function and long-term outcomes.

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Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.

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## Introduction

More than 500,000 TKAs are performed each year in the United States [2] and future projections indicate by 2030, 3.48 million will be performed each year to alleviate pain and disability associated with knee osteoarthritis (OA) [18]. Although TKA reliably reduces pain and improves

function in older adults with knee OA, the recovery of muscle strength and function to normal levels is rare, which predisposes patients to future disability with increasing age [32, 39, 44].

The loss of quadriceps strength after TKA has been studied extensively and is a result of a combination of insults, including preexisting quadriceps weakness characteristic of knee OA [11, 20, 33, 40], surgical trauma during TKA [8, 37], and age-related limitations in the recovery of muscle function [12, 23, 45]. One month after surgery, quadriceps strength decreases to 60% of preoperative levels despite initiating postoperative rehabilitation within 24 hours after surgery [26, 41]. Even 6 to 13 years after surgery, quadriceps weakness persists [13], walking performance remains approximately 20% to 30% less than that of healthy age-matched older adults [29, 44], and more physically demanding tasks such as stair climbing are almost 50% less than those of healthy age-matched adults [44].

Although quadriceps strength has been investigated extensively [5–7, 24–28, 41, 42], less investigation has focused on the strength of other lower extremity muscles before and after TKA [1]. In particular, few studies have evaluated hamstrings muscle strength [5, 21, 39, 44], and those that measured hamstrings strength did so months to years after surgery [39, 44]. Some of these studies suggest hamstrings strength recovers faster than quadriceps strength [5, 39], but others suggest the hamstrings remain comparably dysfunctional to the quadriceps years after surgery [39, 44]. Thus, we presume better understanding of acute changes in muscle strength would help guide the focus of rehabilitation early after surgery.

Both the quadriceps and hamstrings provide functional stability and shock absorption to the tibiofemoral joint [38]. In a healthy joint, coactivation of the quadriceps and hamstrings occurs to functionally reduce shear forces and strain across the tibiofemoral joint [38], but excessive coactivation also may increase compressive forces and joint loading causing extra wear and tear of articular cartilage or knee prostheses [4, 15, 19, 38]. Furthermore, although some coactivation during normal lower limb movement may improve movement efficiency by increasing joint stabilization and protection, excessive coactivation may result in impaired movement and weakness [4, 9]. Weakness with severe OA has been associated with greater coactivation of muscles surrounding the knee [14]. Therefore, profound weakness in the quadriceps and hamstrings muscles early after TKA could further increase muscle coactivation and compromise normal lower extremity function acutely, yet no investigations have explored this possibility to date. It is unclear if the hamstrings are as compromised as the quadriceps in the acute postoperative phase, but if so, both muscle

groups should be targeted in aggressive postoperative rehabilitation.

Therefore, the purposes of this investigation were (1) to evaluate postoperative quadriceps and hamstrings muscle strength loss after TKA and subsequent recovery using the nonoperative legs and healthy control legs for comparison, and (2) to measure hamstrings coactivation before and after TKA during a maximal isometric quadriceps muscle contraction and compare with nonoperative and healthy control legs. We hypothesized that (1) compared with the quadriceps, the hamstrings would show less strength loss and faster recovery after TKA, but both muscle groups would be weaker than muscles of nonoperative and healthy control legs preoperatively and 6 months after TKA; and (2) hamstrings coactivation during maximal isometric quadriceps muscle contraction would be elevated compared with that of nonoperative and healthy control legs acutely (ie, 1 month after TKA) and 6 months after TKA.

## Patients and Methods

We prospectively followed patients scheduled for a unilateral, primary TKA between June 2006 and August 2008. We evaluated bilateral quadriceps and hamstrings strength and hamstrings EMG coactivation at 2 weeks preoperatively and 1 month, 3 months, and 6 months postoperatively for comparisons with a cross-sectional cohort of healthy adults. We chose to examine the recovery of muscle strength and function after TKA through 6 months postoperatively because previous studies suggest strength and functional recovery typically plateau approximately 6 months after surgery [5, 16].

Sample size calculations were centered on our primary hypothesis that the hamstrings would show less strength loss after TKA compared with the quadriceps. We considered a difference of 15 percentage points to be clinically relevant because a 10% side-to-side strength difference is common yet functionally unnoticeable in healthy individuals [17, 34]. With a standard deviation of 19 (unpublished data) and assuming a two-sided Type I error protection of 0.05 and a power of 0.80, we anticipated that 27 patients were required; therefore, we enrolled 30 patients.

Thirty patients (13 women and 17 men; Table 1) were included between the ages of 50 and 85 years. The patients were control (untreated) subjects from an ongoing clinical trial examining the early effects of neuromuscular electrical stimulation after TKA. Exclusion criteria for the clinical trial included the following: (1) uncontrolled hypertension; (2) uncontrolled diabetes (HbA1C greater than > 7.0); (3) body mass index (BMI) greater than 35 kg/m<sup>2</sup>; (4) symptomatic OA in the contralateral knee (defined as patients reporting at least half of the pain on

**Table 1.** Demographic information for patients undergoing TKA and healthy age-matched control subjects

Patients	Number of patients	Gender (male:female)	Age (years)*	Body mass index (kg/m <sup>2</sup> )*
Patients undergoing TKA	30	17:13	64.3 ± 9.2	29.8 ± 4.3
Healthy age-matched control subjects	15	9:6	66.5 ± 6.5	27.1 ± 3.5
p Value			0.34	0.03

\* Values are expressed as mean ± SD.

their nonoperative knee compared with their operative knee on an 11-point verbal analog scale); (5) lower extremity, unstable orthopaedic problems beyond knee OA that limited the patient's physical function; and (6) any neurologic impairment. During the time of recruitment (June 2006 to August 2008), 504 patients underwent primary, unilateral TKA, of which 259 were screened for eligibility in the clinical trial.

We also recruited a convenience sample of 15 healthy control subjects from the community between December 2008 and March 2009 for comparison (Table 1). These healthy individuals had no history of knee pain and no lower extremity orthopaedic problems that limited function. All participated in at least 30 minutes of aerobic activity three times a week. There were no differences in the ages of healthy control subjects and patients undergoing TKA (Table 1). There were differences in BMI between groups, but previous investigation has shown, for BMIs less than 40 kg/m<sup>2</sup>, BMI does not influence strength or functional performance after TKA [43]. The study was approved by the Colorado Multiple Institutional Review Board. All participants provided written informed consent before participation.

TKA was performed by one of three surgeons using a medial parapatellar approach and PCL-sparing, cemented, modular fixed-bearing components. Surgery began with a medial parapatellar incision from the level of the distal tibial tubercle to approximately 6 cm proximal to the superior border of the patella. Resurfacing began with patellar resection, then proceeded with a proximal tibial osteotomy followed by resurfacing of the femur with distal, anterior, posterior, and chamfer cuts. Closure was performed using absorbable sutures for the capsule, subcutaneous tissue, and skin.

All postoperative rehabilitation was standardized using progressive exercises focused on quadriceps and hamstrings muscle strength. Inpatient rehabilitation at the University of Colorado Hospital (3–4 days) was followed by 2 weeks of home physical therapy (six to seven visits), after which patients proceeded to outpatient physical therapy for an average of 10 additional visits. All home therapists and outpatient clinics used a standardized rehabilitation protocol that was centered on an impairment-based model previously described [36, 42]. Although all

impairments were treated, interventions targeted knee ROM, patellar mobility, pain control, gait deviations, and strength of the quadriceps, hamstrings, hip abductors, and plantar flexors. Open and closed-chain exercises were initiated with two sets of 10 repetitions and then progressed to three sets of 10 repetitions. Weights were increased to maintain a 10-repetition maximum targeted intensity level.

Bilateral, isometric strength of the quadriceps and hamstrings was measured before (preoperatively) and after (1, 3, 6 months) unilateral TKA. In brief, subjects were positioned in an electromechanical dynamometer (Humac Norm; CSMI, Stoughton, MA) with their knee flexed and stabilized at 60° flexion. The anatomic axis of the knee was aligned with the axis of the dynamometer. A force transducer was secured around the lower leg 2 cm above the proximal pole of the lateral malleolus. A seat belt harness was placed around the patient's chest and waist for stabilization. Patients were asked to perform a maximal voluntary isometric contraction (MVIC) of the hamstrings followed by an MVIC of the quadriceps muscles using visual and verbal feedback. Testing for each muscle group was repeated up to three times, with 1 minute of rest between trials, until two attempts were within 5% of each other. The trial with the largest maximal volitional isometric force output was used for data analysis.

EMG was used to quantify hamstrings coactivation during a quadriceps MVIC similar to previously described methods [30]. A pair of surface EMG electrodes (20-mm diameter) was placed over the muscle belly of the biceps femoris at approximately one-third of the muscle length from the popliteal fossa. Electrodes were placed 2 cm apart over the biceps femoris and a ground electrode was placed over the medial malleolus. The surface electrodes were attached to a Biopac MP150WSW system (Biopac Systems, Inc, Goleta, CA) for data acquisition at 2 kHz. All EMG signals were digitally high-pass filtered at 10 Hz, low-pass filtered at 500 Hz, notch filtered at 60 Hz, and subsequently smoothed by a moving root mean square average with a time constant of 50 ms. After signal processing, the hamstrings (biceps femoris) peak EMG signal during a maximal quadriceps MVIC was normalized to the peak hamstrings EMG signal during a maximal hamstrings MVIC to calculate coactivation (peak hamstrings EMG during quadriceps MVIC/peak hamstrings EMG during

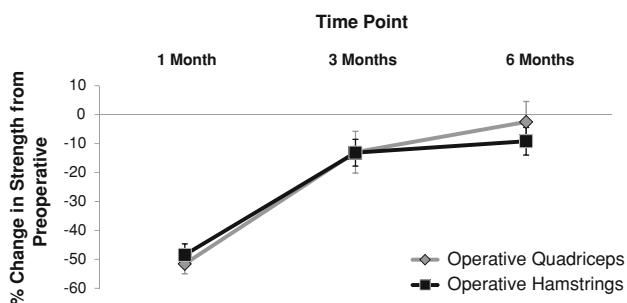
hamstrings MVIC). The healthy control subjects were tested at one time using identical methods for comparison of muscle strength and hamstrings coactivation outcomes.

To address the first hypothesis comparing hamstrings and quadriceps muscle weakness after TKA, a two-way analysis of variance (ANOVA) (muscle group × time) was used to test for differences between the quadriceps and hamstrings in the operative leg over time (ie, recovery of strength after TKA) using preoperative strength as a covariate. Furthermore, a one-way ANOVA was used to assess differences in muscle strength between the operative legs, nonoperative legs, and legs of control subjects preoperatively and 6 months after surgery. Comparisons to healthy control subjects used the right leg of control subjects because there were no statistical differences in muscle strength or coactivation between the right and left legs of healthy control subjects.

To address the second hypothesis that hamstrings coactivation during a maximal isometric quadriceps muscle contraction would be elevated after TKA compared with nonoperative and healthy control legs, a multivariate ANOVA (leg × time) was used to test for differences in hamstrings coactivation between legs across all four times with Tukey’s post hoc testing as appropriate. All statistical analyses were performed with SPSS® for Windows®, Version 17.0 (SPSS Inc, Chicago, IL).

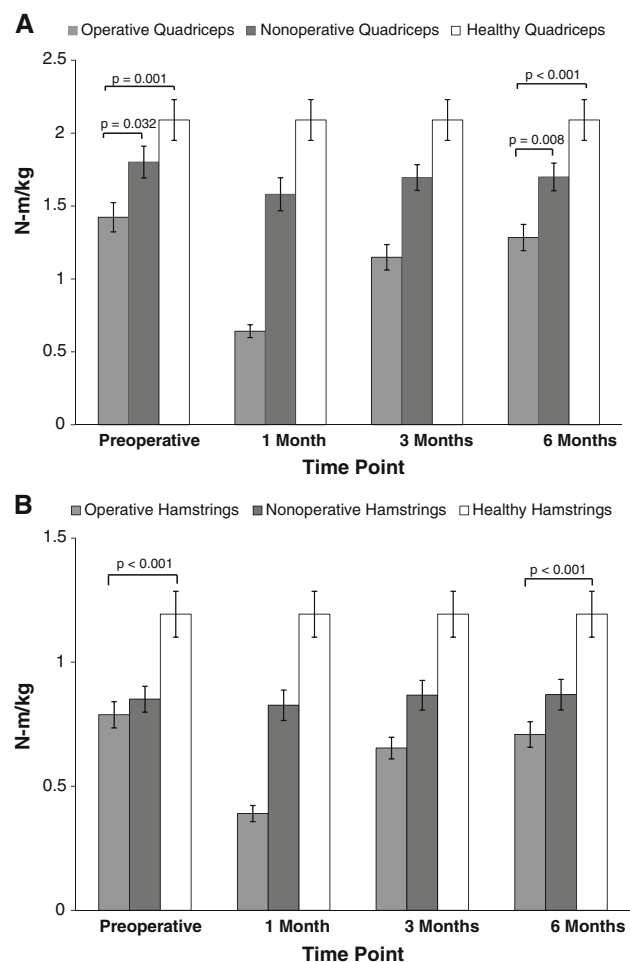
**Results**

There were no differences ( $p = 0.17$ ) in strength loss or recovery between quadriceps and hamstrings strength throughout the followup (Fig. 1). Preoperatively, the quadriceps strength of the operative leg was weaker than that of the nonoperative leg (21.0%;  $p = 0.032$ ) and

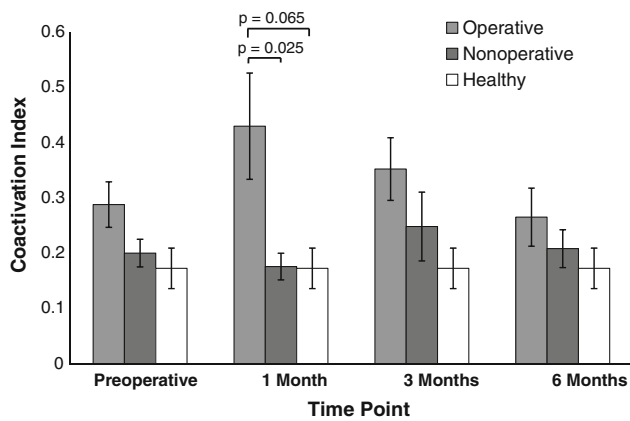


**Fig. 1** The percentage change in quadriceps and hamstrings strength in the operative leg after TKA is shown. There were no differences in strength loss or recovery between the quadriceps (dark gray) and hamstrings (light gray) muscles during the first 6 months after TKA (mean ± SE of the mean [SEM]). Statistical analyses were performed on raw strength (N-m)/body weight (kg) values, not percentage change from preoperative levels.

healthy control legs (32%;  $p = 0.001$ ; Fig. 2A), whereas the strength of the hamstrings of the operative leg was not weaker than that of the nonoperative leg ( $p = 0.702$ ; Fig. 2B), but was weaker than that of healthy control legs (34%;  $p < 0.001$ ). One month after TKA, quadriceps and hamstrings muscle strength decreased 51.56% and 48.43%, respectively. Following the same pattern seen preoperatively, at 6 months after surgery, the quadriceps strength of the operative leg remained weaker than the nonoperative (24.4%;  $p = 0.008$ ) and healthy control legs (38.5%;  $p < 0.001$ ; Fig. 2A), whereas the hamstrings strength of the operative leg was not weaker than that of the nonoperative leg ( $p = 0.142$ ), but was weaker than that of healthy control legs (40.6%;  $p < 0.001$ ; Fig. 2B).



**Fig. 2A–B** Strength with time for the operative, nonoperative, and healthy control (A) quadriceps and (B) hamstrings are shown. Quadriceps strength in the operative leg (A) was significantly less than for the nonoperative and healthy legs preoperatively and 6 months after TKA. Hamstrings strength in the operative leg (B) was significantly less than for healthy legs, preoperatively and 6 months after TKA, yet was not significantly different from nonoperative legs at either time. Strength (N-m) is normalized to body weight (kg) (mean ± SEM).



**Fig. 3** Hamstrings EMG coactivation across time is shown. The coactivation index was defined as (peak hamstrings EMG during quadriceps maximal voluntary isometric contraction [MVIC]/peak hamstrings EMG during hamstrings MVIC). One month after TKA, hamstrings coactivation in the operative leg was significantly elevated compared with that of the nonoperative leg with a similar trend for comparisons with healthy control subjects.

We observed differences in hamstrings coactivation during an MVIC of the quadriceps (operative, nonoperative, and healthy control legs) 1 month after TKA: there was greater coactivation in operative legs compared with nonoperative legs (144.5% elevation;  $p = 0.025$ ; Fig. 3). A trend for differences between operative legs and healthy control legs also was observed at 1 month (149% elevation;  $p = 0.065$ ). By comparison, before TKA, hamstrings coactivation in the operative leg was elevated 43.8% relative to the nonoperative leg and 66.8% relative to healthy control legs. Similar patterns of hamstrings coactivation persisted three and six months after TKA, but again, differences were not statistically significant.

## Discussion

An understanding of the acute and subacute changes in hamstrings and quadriceps muscle function is important to optimize rehabilitation after TKA. Studies have shown the quadriceps lose more than 50% of preoperative strength 1 month after TKA [26, 41], which explains why rehabilitation programs currently target quadriceps strengthening and surgeons debate the optimal quadriceps-sparing surgical approach. Less information has been available regarding hamstrings muscle strength, especially within the first months after surgery. We therefore compared: (1) postoperative quadriceps and hamstrings muscle strength loss after TKA and subsequent recovery using the nonoperative legs and healthy control legs for comparison, and (2) hamstrings coactivation during a quadriceps MVIC before and after TKA compared with that of nonoperative and healthy control legs.

We acknowledge several limitations: (1) exclusion criteria; (2) potential for OA in the nonoperative leg; and (3) open-chain testing rather than closed-chain, functional testing. First, exclusion criteria such as a BMI of 35 kg/m<sup>2</sup> or less were conservative because these patients were also control subjects for an ongoing randomized clinical trial. Yet, it is unlikely that including patients with greater BMIs (35–40 kg/m<sup>2</sup>) would change these results because BMI does not seem to impact strength or functional performance after TKA when less than 40 kg/m<sup>2</sup> [43]. A second limitation is the potential for OA in the nonoperative leg in a subset of patients; therefore, we also included healthy adults (no knee pain) for additional comparison. During quadriceps strength testing, our patients reported average Visual Analog Scale pain levels in the operative leg of  $1.9 \pm 2.5$  (range, 0–7) preoperatively and  $2.5 \pm 2.5$  (range, 0–8) 1 month after TKA. Pain in the nonoperative leg was  $0.2 \pm 0.7$  (range, 0–4) across all times, suggesting that the nonoperative leg was minimally involved in most patients. Finally, our hamstrings coactivation was assessed using an open-chain task, which may make it difficult to relate these findings to more dynamic, closed-chain tasks such as walking. We chose this approach so that we could specifically evaluate hamstrings coactivation during strength testing without introducing additional confounding variables such as movement strategies or the use of assistive devices during more dynamic tasks. However, our results suggest additional investigation is warranted to evaluate early hamstrings coactivation during more functional, closed-chain activities.

In contrast to our initial hypothesis, we found no differences in strength loss or recovery between the quadriceps and hamstrings muscles during the first 6 months after TKA. Importantly, hamstrings muscle strength in operative legs, compared with nonoperative legs, was not as compromised as quadriceps strength before and 6 months after surgery, yet the quadriceps and hamstrings muscles in these patients remain significantly weaker than healthy controls before and 6 months after TKA. Previous investigations evaluating quadriceps and hamstrings muscle strength many months to years after surgery (relative to preoperative levels, nonoperative leg, and healthy controls) generally support our findings (Tables 2, 3). Across patient groups, Perhonen et al. [35] reported a 39.4% deficit in hamstrings strength and 42.9% deficit in quadriceps strength 3 weeks after TKA, which improved to only a 15.2% hamstrings deficit and a 7.1% quadriceps deficit at 3 months. When comparing the operative with nonoperative leg, Walsh et al. [44] found larger side-to-side deficits in hamstrings muscle isokinetic strength (20.7%) than quadriceps muscle strength (11.3%) 1 year after TKA. When compared with healthy control subjects, Berman et al. [5] reported slightly larger deficits in isokinetic quadriceps strength (41.6%) than

hamstrings strength (28.7%) 3 to 6 months after TKA compared with those of healthy control subjects and still a 28.9% (quadriceps) and 14.6% (hamstrings) deficit 7 to 12 months after TKA. More than 2 years after TKA, Silva et al. [39] observed a 47.1% deficit in quadriceps strength and a 55.2% deficit in hamstrings strength compared with those of healthy control subjects. Although the relative degree of hamstrings versus quadriceps muscle strength deficit varies across studies, findings consistently indicate the hamstrings and quadriceps muscles experience a compromise in strength that persists years after surgery [13, 21, 24, 35, 39, 44].

Our study findings support our second hypothesis that the level of hamstrings coactivation in operative legs during a maximal quadriceps contraction would increase after TKA compared with nonoperative and healthy control legs. In a healthy joint, some coactivation during normal lower limb movement may improve movement efficiency by increasing joint stabilization and protection, but excessive coactivation may result in impaired movement and weakness [4, 9] and detrimentally augment stresses to articular cartilage or a knee prosthesis [4, 15, 19, 38]. Coactivation measures similar to ours have been used in previous studies with other populations. Newham and Hsiao [30] examined

**Table 2.** Comparison of published studies of absolute strength in patients undergoing TKA

Study	Test mode	Time point	Absolute strength (N-m)					
			Quadriceps			Hamstrings		
			TKA operative	TKA nonoperative	Healthy	TKA operative	TKA nonoperative	Healthy
Walsh et al. [44] <sup>†</sup>	Isokinetic 90°/s	1.7 years	57.2	64.5	88.3	33.2	41.8	48.7
Silva et al. [39] <sup>‡</sup>	Isometric 60°	2.8 years	93.0 (44.6)*		175.9 (60.4)	45.9 (16.3)		102.4 (42)
Berth et al. [7] <sup>§</sup>	Isometric 90°	Preoperative	66.3 (33.4)	81.9 (38.1)	105 (28.4)			
		2.8 years	84.8 (35.5)	79.4 (30.5)				
Lorentzen et al. [21] <sup>  </sup>	Isometric 75°	Preoperative	66	87		24	32	
		3 months	55	92		21	32	
		6 months	65	92		20	33	
Berman et al. [5] <sup>¶</sup>	Isokinetic 60°/s	Preoperative	35.5 (9.5)	59.8 (10.7)		21.5 (8.4)	32.8 (9.1)	
		3–6 months	39.1 (9.2)	66.9 (11.0)		26.1 (8.0)	36.6 (9.9)	
		7–12 months	50.4 (9.5)	70.9 (10.7)		30.4 (7.7)	35.6 (9.3)	
		13–23 months	55.8 (9.6)	69.1 (10.6)		28.7 (7.7)	33.4 (9.1)	
		> 23 months	56.9 (9.9)	68.1 (9.6)		32.4 (9.9)	32.6 (8.4)	
Mizner et al. [28] <sup>#</sup>	Isometric 75°	Preoperative	183.7	225.6				
		1 month	70.7	222.8				
		2 months	95.7	228.1				
		3 months	148.8	231.7				
		6 months	179.9	228.9				
Perhonen et al. [35]**	Isometric 60°	Preoperative	~70.0			~33.0		
		3 weeks	~40.0			~20.0		
		6 weeks	~55.0			~23.0		
		12 weeks	~65.0			~28.0		
		24 weeks	~75.0			~32.0		
		52 weeks	~85.0			~35.0		
Current study	Isometric 60°	Preoperative	121.7 (45.7)	154.2 (52.8)	165.3 (57.9)	68.1 (27.9)	72.9 (24.6)	95.2 (32.5)
		1 month	56.1 (23.2)	136.8 (51.0)		33.7 (15.7)	71.9 (28.9)	
		3 months	100.4 (46.8)	146.8 (45.8)		57.0 (25.5)	74.9 (29.5)	
		6 months	113.3 (45.9)	145.9 (47.6)		61.4 (26.6)	74.2 (28.5)	

\* Values are expressed as mean with SD in parentheses; <sup>†</sup>TKA, n = 29 (mean age, 63.9 years); healthy age-matched, n = 40 (mean age, 62.8 years); <sup>‡</sup>TKA, n = 32 knees (mean age, 67.3 years); healthy, n = 53 knees (mean age, 40.0 years), values were converted from foot-pounds; <sup>§</sup>TKA, n = 50 (mean age, 65.8 years); healthy age-matched, n = 50 (mean age, 63.2 years); <sup>||</sup>TKA, n = 30 (mean age, 74.0 years); <sup>¶</sup>TKA, n = 68 (mean age, 63.0 years), values were converted from foot-pounds; <sup>#</sup>TKA, n = 40 (mean age, 64.0 years); <sup>\*\*</sup>TKA, n = 30 (mean age, 67.5 years); three training groups (TG1, TG2, Control) were averaged across all three groups, and values were delineated from graphs since no values were provided.

**Table 3.** Comparison of published studies of percent differences in strength in patients undergoing TKA

Study	Test mode	Time point	Percent differences (%)					
			(A) Postop operative leg strength deficits: compared to preop		(B) Operative leg strength deficits: compared to nonoperative leg		(C) Operative leg strength deficits: compared to healthy individuals	
			Quadriceps	Hamstrings	Quadriceps	Hamstrings	Quadriceps	Hamstrings
Walsh et al. [44] <sup>†</sup>	Isokinetic 90°/s	1.7 years			-11.3	-20.7	-35.3	-31.9
Silva et al. [39] <sup>‡</sup>	Isometric 60°	2.8 years					-47.1	-55.2
Berth et al. [7] <sup>§</sup>	Isometric 90°	Preop			-19.0		-36.9	
		2.8 years	27.9		6.8		-19.2	
Lorentzen et al. [21] <sup>  </sup>	Isometric 75°	Preop			-24	-25	-24.0	-25.0
		3 months	-16.7	-12.5	-40	-34	-40.0	-34.0
		6 months	-1.5	-16.7	-29	-39	-29.0	-39.0
Berman et al. [5] <sup>¶</sup>	Isokinetic 60°/s	Preop			-40.6	-34.5		
		3–6 months	10.1	21.4	-41.6	-28.7		
		7–12 months	42.0	41.4	-28.9	-14.6		
		13–23 months	57.2	33.5	-19.2	-14.1		
		> 23 months	60.3	50.7	-16.4	-0.6		
Mizner et al. [28] <sup>#</sup>	Isometric 75°	Preop			-19.0			
		1 month	-61.5		-68.0			
		2 months	-47.9		-58.0			
		3 months	-19.0		-36.0			
		6 months	-2.1		-21.0			
Perhonen et al. [35]**	Isometric 60°	Preop						
		3 weeks	-42.9	-39.4				
		6 weeks	-21.4	-30.3				
		12 weeks	-7.1	-15.2				
		24 weeks	7.1	-3.0				
		52 weeks	21.4	6.1				
Current study	Isometric 60°	Preop			-21.1	-6.6	-26.4	-28.5
		1 month	-51.6 (18.9)*	-48.4 (20.8)	-59.0	-53.1	-66.1	-64.6
		3 months	-12.0 (38.7)	-13.1 (25.3)	-31.6	-23.9	-39.3	-40.1
		6 months	-2.5 (37.5)	-9.2 (25.2)	-22.3	-17.3	-31.5	-35.5

\* Values are expressed as mean, with SD in parentheses; equations: (A) [(postoperative – preoperative)/preoperative] × 100; (B) [(operative – nonoperative)/nonoperative] × 100; (C) [(operative – healthy)/healthy] × 100; negative numbers indicate a deficit while positive numbers indicate an increase; <sup>†</sup>TKA, n = 29 (mean age, 63.9 years); healthy age-matched, n = 40 (mean age, 62.8 years); <sup>‡</sup>TKA, n = 32 knees (mean age, 67.3 years); healthy, n = 53 knees (mean age, 40.0 years), values were converted from foot-pounds; <sup>§</sup>TKA, n = 50 (mean age, 65.8 years); healthy age-matched, n = 50 (mean age, 63.2 years); <sup>||</sup>TKA, n = 30 (mean age, 74.0 years); <sup>¶</sup>TKA, n = 68 (mean age, 63.0 years), values were converted from foot-pounds; <sup>#</sup>TKA, n = 40 (mean age, 64.0 years); <sup>\*\*</sup>TKA, n = 30 (mean age, 67.5 years); three training groups (TG1, TG2, Control) were averaged across all three groups, and values were delineated from graphs since no values were provided; postop = postoperative; preop = preoperative.

coactivation in 30 healthy control subjects and found hamstrings coactivation during a maximal isometric quadriceps effort in healthy control subjects was  $0.23 \pm 0.04$  (mean  $\pm$  SE of the mean), which is similar to our average value for control subjects ( $0.17 \pm 0.04$ ). Baratta et al. [3] reported hamstrings coactivation during an isometric quadriceps contraction ranged from 0.11 to 0.15 in young, healthy sedentary males (n = 20; mean age 22.1 years). Similarly, in 12 healthy control subjects (aged 25–59 years), antagonist hamstrings activity during a

maximal isometric contraction of the quadriceps muscle was approximately  $0.13 \pm 0.06$  [10]. We may have underestimated the level of hamstrings coactivation because the presence of hamstrings coactivation may be further magnified during weightbearing activities to increase the functional stability of the knee [4, 9, 22]. Antagonistic muscle activity of the hamstrings during open-chain, nonweightbearing exercise is less than during closed-chain, weightbearing exercise [9, 22]. For example, Busse et al. [9] found coactivation of the hamstrings during

isometric knee extension was  $0.12 \pm 0.06$  (mean  $\pm$  SD) compared with  $0.21 \pm 0.13$  during a sit-to-stand activity. Therefore, additional investigation is necessary to evaluate the degree and impact of hamstrings coactivation during weightbearing activities such as walking or sit-to-stand, especially during the acute and subacute periods after TKA. One study examining muscle coactivation using gait analysis 6 months to 2 years after TKA suggested patients still had prolonged muscle activation of antagonists to stabilize the knee during stance. This pattern of prolonged muscle activation persisted through the 2-year followup in most patients, further supporting the need for earlier evaluation of the impact of muscle coactivation during functional activities [4].

Our observations suggest that although quadriceps dysfunction after TKA typically is recognized and addressed in postoperative therapy protocols, hamstrings dysfunction also is present and should be addressed. Muscle weakness and overuse can cause tendinopathy [31], and if left untreated, hamstrings weakness and coactivation may contribute to persistent hamstrings tendinopathy and related dysfunction of the postoperative knee, resulting in increased pain. In addition to the importance of rehabilitation for the hamstrings, quadriceps muscle strength is important because persistent deficits in quadriceps muscle strength have been documented in this study and others. Therefore, quadriceps and hamstrings muscle strengthening should be the focus of future rehabilitation programs. Finally, additional investigation of quadriceps and hamstrings muscle function during dynamic, functional activities is necessary to expand on these results to better evaluate postoperative deficits.

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