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Minimally Invasive Total Knee Arthroplasty Improves Early Knee Strength but Not Functional Performance: A Randomized Controlled Trial

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Abstract

A prospective, randomized investigation compared early clinical outcomes of total knee arthroplasty (TKA) using conventional (CONTROL) or minimally invasive surgical (MIS) approaches (n=44). Outcome measures included isometric quadriceps and hamstrings strength, quadriceps activation, functional performance, knee pain, active knee range of motion (AROM), muscle mass, the SF-36, and WOMAC, assessed preoperatively and 4 and 12 weeks after TKA. Four weeks after TKA, the MIS group had greater hamstring strength (p=0.02) and quadriceps strength (p=0.07), which did not translate to differences in other outcomes. At 12 weeks, there were no clinically meaningful differences between groups on any measure. Although MIS may lead to faster recovery of strength in patients undergoing TKA, there was no benefit on longer-term recovery of strength or functional performance.

Keywords

total knee arthroplasty; joint arthroplasty; quadriceps; muscle strength; minimally invasive surgery

INTRODUCTION

Almost 700,000 total knee arthroplasties (TKA) are performed each year in the United States to alleviate pain and disability associated with knee osteoarthritis.[1] Future projections suggest that by the year 2030, 3.48 million TKAs will be performed annually.[2] While TKA reliably reduces pain in patients with knee osteoarthritis, quadriceps strength and function often lag behind healthy, age-matched adults many years after surgery.[3] Reductions of about 20% in walking speed and 50% in stair climbing speed compared to

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age-matched groups without knee pathology have been reported a year after surgery and have been largely attributed to quadriceps weakness.[3]

Quadriceps muscle weakness is most pronounced within the first month after surgery and declines 50–60% from preoperative values.[4–6] This early quadriceps weakness is largely explained by muscle activation failure, presumably secondary to extensive trauma to the quadriceps muscle during surgery.[4,5, 7] This trauma is largely a combined result of patellar eversion, extreme knee flexion, and cutting of the quadriceps muscle and tendon to improve visualization. The eversion of the patella required for conventional TKA (often > 1 hr) stretches the quadriceps by over 16% compared to retraction of the patella, which stretches the quadriceps by only 8%.[8] In addition to patellar eversion, conventional TKA requires extreme knee flexion that further stretches the quadriceps mechanism and requires partial dissection of the quadriceps muscle or tendon. The substantial tension and trauma to quadriceps muscle during conventional TKA may contribute to permanent quadriceps dysfunction, as evidenced by long-term post-operative weakness and activation failure.[3,9, 10]

Traditionally, successful outcomes with TKA have been measured by long-term implant performance and low revision rates, rather than a rapid recovery of function.[11] As a result, conventional TKA surgical approaches have been designed to allow for good visualization to achieve predictable primary fixation, restore alignment, optimize ROM, and maintain ligament balance.[11] But good visualization requires compromise of the quadriceps muscle and tendon by splitting or detaching portions of each to allow for eversion of the patella.[8,10, 12] Recently, minimally invasive surgical (MIS) techniques for TKA have been introduced as promising alternatives to conventional TKA and have been purported to improve function more quickly, decrease the length of hospital stays, and reduce pain.[10,11, 13–19] Compared to conventional TKA, MIS techniques employ smaller skin incisions and smaller instrumentation and avoid patellar eversion and joint dislocation.[8,10, 20–22] Most importantly, these techniques avoid disruption of the extensor mechanism and suprapatellar pouch and minimize extreme knee flexion during surgery.[8,10, 13, 20, 21] The combined effects of these modifications may diminish damage to the quadriceps muscle[4,5, 7] and, therefore, decrease post-operative muscle weakness and activation failure, but there is little evidence to support these expectations.

Early retrospective cohort comparisons indicated that TKA MIS reduced hospital stays, decreased postoperative pain, and enabled patients to return to functional activities more quickly than conventional TKA.[8,10, 13, 23–25] More recently, small-scale randomized trials were not as universally supportive of whether the benefits of MIS TKA outweigh the risks of decreased visualization during surgery and increased length of operating time.[14,17, 24–26] Yet, many of these studies focused on self-report and surgical outcomes without including functional performance measures or specific measures of quadriceps strength and activation. Patient self-report measures such as the Western Ontario and McMaster University Osteoarthritis Index (WOMAC)[27] or the Knee injury and Osteoarthritis Outcome Score (KOOS)[28] do not reflect the magnitude of performance deficits present post-operatively, especially within the first two months after TKA.[29, 30] In large part, this is because self-reported outcomes closely parallel pain relief after surgery. Therefore, investigations of TKA outcomes should include a more comprehensive combination of performance measures (including muscle strength) and self-report to more completely evaluate intervention effectiveness. Furthermore, few studies have involved blinding of both patients and evaluators (i.e., because incisions lengths are different between MIS and conventional TKA) and very few studies have standardized rehabilitation.

The purpose of this investigation was to evaluate the efficacy of MIS TKA in a blinded, prospective, randomized controlled trial. We hypothesized that MIS for TKA would decrease quadriceps strength loss (primary outcome) and hamstrings strength loss, attenuate quadriceps activation deficits, improve function performance, increase knee range of motion, decrease post-operative knee pain, and attenuate muscle mass loss (confirmatory measures) when compared with conventional TKA surgery.

MATERIALS AND METHODS

Design Overview

This was a randomized, controlled trial to evaluate potential benefits of MIS TKA. Eligible patients were randomized with concealed allocation to a MIS or conventional (CONTROL) TKA group. Randomization included stratification for sex and decade of age. Patients were assessed 1–2 wk before surgery and 4 and 12 wk after TKA at the Clinical and Translational Research Center at the University of Colorado. The study was approved by the Colorado Multiple Institutional Review Board. Informed consent was obtained from all participants.

Setting and Participants

Patients anticipating a primary, unilateral knee replacement for OA, aged 50–85 years who met the following inclusion criteria were recruited by a single surgeon between December 2006 and June 2010: 1) no significant neurologic impairments, 2) no uncontrolled hypertension, 3) minimal contralateral knee OA (as defined by pain greater than 5/10 with activity), and 4) no other unstable lower-extremity orthopedic conditions. In addition, although only half of the patients were randomized for MIS, all patients met additional criteria for MIS eligibility: 1) minimum of 80° degrees of active knee flexion, 2) no greater than 15° knee varus, 15° valgus, and 3) body mass index $\leq 40 \text{ kg/m}^2$.

Randomization and Interventions

Blocked randomization was used to assure balanced assignment of subjects to the two intervention groups by sex and decade of age, with random block sizes of 4, 6, or 8. Group assignment occurred after enrollment criteria were met and after the preoperative testing session. Except for the surgeon performing the TKA, patients, investigators, and treating physical therapists were all blinded to group assignment because identical skin incision lengths were used for both groups.

Surgical approach

Both conventional (CONTROL) and MIS TKA approaches were performed through an anterior midline incision using a medial parapatellar approach. In the CONTROL group, the incision extended from the level of the distal tibial tubercle to approximately 6 cm proximal to the superior border of the patella. In the MIS group, the deep capsular exposure extended from the level of the superior tibial tubercle to no more than 1 cm proximal to the superior border of the patella. For both study groups, the sequence began with patellar resurfacing, then preceded with proximal tibial resection, followed by resurfacing of the femur with distal cut, then anterior, posterior, chamfer and notch cuts. Patella eversion was not used for MIS procedures and the MIS group had extensor mechanism dissection length strictly limited to the distance from superior patella distal to the proximal tibial tubercle.

In all cases, a tensioner device was used to establish balanced, symmetrical flexion and extension spaces. All TKA procedures sacrificed the posterior cruciate ligament (PCL). Furthermore, all TKA procedures utilized mobile-bearing, cemented implants using a P.F.C. Sigma Rotating Platform Knee System by DePuy (Johnson & Johnson). Closure was performed using absorbable sutures for capsule, subcutaneous tissue, and skin. Intra-

articular drains were placed for 24 hours in all knees, regardless of study group. Importantly, identical superficial incision lengths for both groups allowed for patient blinding to surgical group because cosmetically, neither patients nor investigators were able to discern differences between groups.

Rehabilitation

All patients were provided the same standard rehabilitation protocol for TKA, consisting of a standard set of core exercises as previously described.[31, 32] Briefly, inpatient rehabilitation began on postoperative day 1 and continued twice daily for 3 days. Following hospital discharge, patients were treated at home for 6 visits over 2 weeks and then began outpatient physical therapy consisting of 10–12 visits over 6 weeks. Exercises consisted of passive knee range of motion (ROM) stretching; patellofemoral mobilization (as needed); incision mobility; cycling for range of motion; lower extremity flexibility exercises for the quadriceps, calf, and hamstrings muscle group; modalities (ice or heat as needed); gait training; and functional training for transfers and stair climbing. For strengthening, both weight-bearing and non-weight-bearing exercises were utilized with 2 sets of 10 repetitions and progressed to 3 sets of 10 repetitions. Physical therapists were given instructions to increase weights to maintain a 10-repetition maximum intensity level. Resistance exercises included quadriceps sets, seated knee extensions, straight-leg raises, side-lying hip abduction, and standing hamstring curls. Body-weight exercises included step-ups, lateral step-ups, step-downs (all 5- to 15-cm step), terminal knee extensions, single-limb stance, and wall slides.

All patients were given a home exercise program to be performed twice daily during the first 4 weeks of recovery and then daily until discharge from therapy. The home exercise program included ROM exercises in addition to weight-bearing and non-weight-bearing strengthening exercises for the quadriceps, hamstrings, hip abductors, hip extensors, and plantar flexors. The intensity and type of exercises for the home program were similar to those completed during the supervised home and outpatient physical therapy sessions.

Physical therapists reported on treatment sessions via a detailed flow sheet that was reviewed by the study team to monitor treatment consistency. Patients were also given home exercise logs to track progress with home exercises.

Outcomes and Follow-up

Isometric Quadriceps Torque and Activation Testing—Maximal isometric quadriceps muscle torque (primary outcome) and activation testing were performed using a doublet interpolation test, as described previously.[31, 32] A HUMAC NORM (CSMi, Stoughton, MA) electromechanical dynamometer was utilized to measure torque. Data were collected using a Biopac Data Acquisition System at a sampling frequency of 2000Hz (Biodex Medical Systems, Inc., Shirley, NY) and analyzed with AcqKnowledge software, Version 3.8.2 (Biodex Medical Systems). A Grass S48 stimulator with a Grass Model SIU8T stimulus isolation unit (Grass Instruments, West Warwick, RI) was used for testing voluntary muscle activation via self-adherent, flexible electrodes (7.6 × 12.7 cm, Supertrodes, SME, Inc). Subjects were positioned and stabilized in the dynamometer with 60° of knee flexion. Voluntary activation of the quadriceps muscle was assessed using the doublet interpolation technique, where a supramaximal stimulus (2-pulse, 600-μs pulse duration, 100-Hz electrical train) was applied during an MVIC and again, immediately afterwards, while the quadriceps muscle was at rest.[31,33, 34] A value of 100% represents full voluntary muscle activation and anything less than 100% indicates incomplete motor unit recruitment or decreased motor unit discharge rates.[33–35]

Isometric Hamstrings Torque—Isometric hamstrings torque was measured using the same positioning described above, although no hamstrings muscle activation testing was performed. Both quadriceps and hamstrings measures were performed twice, with a third trial performed if maximal torque differed by more than 5%.

Functional Performance Measures—The stair climbing test (SCT) and 6-minute walk test (6MW) were used to assess functional performance as previously described.[32] The SCT measures the total time to ascend, turn around, and descend a flight of stairs.[36] Patients were tested on 1 of 2 staircases during the study due to a change in facilities. Two patients in the CONTROL and two patients in the MIS group were consistently tested on a 10-step stair case with 6.75-inch step height. All other patients were tested on a 12-step stair case with 6.75-inch step height. This did not impact analysis because within-subject changes were measured over time. The 6MW measures the total distance walked in meters over 6 minutes to evaluate endurance and has been validated as a measure of functional mobility following knee arthroplasty.[37] Pain during the 6MW test was measured utilizing an 11-point verbal numeric pain rating scale (NPRS). Patients were asked to rate their pain towards the end of the 6MW on a scale of 0 to 10 with 0 representing *no pain* and 10 representing *the worst pain imaginable*.

Range of Motion—Active ROM (AROM) of the knee was measured in supine using a long-arm goniometer as previously described.[38] For active knee extension, the heel was placed on a 4-inch block while the participant actively extended the knee. For active knee flexion, the participant actively flexed the knee as far as possible keeping the heel on the supporting surface.

Health Status Questionnaires

Short Form-36: Health status was assessed using the Physical Component Score (PCS) of the Short Form-36 (SF-36). The SF-36 has been shown to capture improvements in 7 of its 8 domains in patients after TKA in the first 3 months after surgery[39] and continues to indicate improvements in health-related quality of life over the next 6 to 12 months.[40] The SF-36 is reliable and internally consistent.[40–42]

Western Ontario and McMaster Universities Osteoarthritis Index: The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) was used to evaluate self-reported knee-specific impairment.[43] It assesses the pain, joint stiffness, physical, social & emotional function of a person with OA to determine the overall level of disability. The WOMAC is a valid, reliable, and responsive self-administered instrument for short-term and long-term follow-up of knee injury, including OA.[43]

Dual-energy X-ray absorptiometry—Muscle mass of the surgical leg was estimated using dual-energy X-ray absorptiometry (DXA). Measurements before and after surgery were made using a DXA-enhanced body analysis (v5.64, Hologic Delphi-W; Waltham, MA) as previously described.[44] Standard manufacturer recommendations for line placement were used to delineate regions of interest. Coefficients of variation for total fat-free mass and leg fat-free mass were 1.2% and 2.0% respectively.[44] Non-bone fat-free tissue, which is a good surrogate of extremity muscle mass, was measured for the entire surgical leg as well as a customized region of interest (ROI) for the thigh.[45] The estimation of skeletal muscle mass by DXA has been validated against MRI.[45,46] The ability of DXA to predict skeletal muscle mass as described by Kim et al.[45, 46] was 0.96–0.97 (R^2). For the thigh ROI muscle mass measurements, the proximal border of the ROI was the most proximal aspect of the femoral head. The distal border of the ROI was the lateral joint line. Medial

and lateral borders were positioned outside the boundaries of the leg from distal border and extended upward to the proximal border.

Data Analysis

The study was designed to achieve 80% power with 23 patients per group based on quadriceps **strength data** from a study comparing a median parapatellar TKA approach (41.4 ± 19.0 Nm) and a less invasive midvastus technique (27.6 ± 12.6 Nm) at 3 weeks.[47] The primary outcome, difference in quadriceps torque between intervention (MIS) and CONTROL TKA at 4 weeks, was tested using an ANCOVA model; the 4-week change from baseline was regressed on sex, age, and baseline quadriceps torque with 42 complete cases (22 MIS, 20 CONTROLS). Confirmatory measures were evaluated at 4 and 12 weeks after surgery in the same way. Baseline characteristics of the treatment groups were compared using two-sample *t* tests for continuous measures or a chi-square test for independent proportions for categorical measures. SAS version 9.2 (SAS Institute Inc., Cary, NC) was used for all statistical analyses. All analyses followed the intent-to-treat principle. A two-sided alpha level of 0.05 was designated for statistical significance.

RESULTS

One hundred seventy-five patients scheduled for TKA at UCH were assessed for eligibility when they were scheduled for TKA surgery. Based on clinical evaluation, 96 patients (55%) did not meet study enrollment criteria due to proximity for close follow-up or established eligibility criteria. Of the remaining 79 patients (45%), 28 patients (16% of 175) did not meet the MIS-specific eligibility criteria, and 7 patients (4% of 175) either declined to participate or could not be contacted. Therefore, 44 patients (22 males, 22 females) aged 50–85 years (64.3 ± 8.4 years) were enrolled in the study (Figure 1). There were no differences between groups in sex, age, height, weight and body mass index (BMI) (Table 1). There were no significant group differences in baseline self-reported function or performance measures.

Four weeks after TKA, the MIS group had greater hamstrings strength than the CONTROL group ($p=0.02$; Table 2; Figure 2) and a trend towards better quadriceps strength ($p=0.07$). Quadriceps activation also demonstrated a weaker trend towards improvements ($p=0.11$) with MIS. However, differences in muscle strength with MIS did not translate into differences in functional performance (SCT or 6MW). Furthermore, there were no significant differences between groups in the changes in 6MW knee pain, AROM (flexion or extension), WOMAC, or surgical leg and thigh muscle mass. Although SF-36 MCS scores declined significantly more in the CONTROL group ($p<0.001$), changes in SF-36 PCS scores were not different between surgical groups.

Twelve weeks after TKA, there were no significant differences in hamstrings or quadriceps strength, quadriceps activation, functional performance (SCT or 6MW), 6MW knee pain, AROM (flexion or extension), or DXA muscle mass. There were still significantly lower SF-36 MCS scores in the CONTROL group than the MIS group, but no differences between groups in the SF-36 PCS scores. Furthermore, there was a significant improvement in WOMAC score with MIS compared to CONTROLS.

Although not the focus of the present manuscript, there were no significant differences between groups in tourniquet times, blood loss, and length of inpatient hospital stay. Furthermore, there was no greater incidence of surgical complications (e.g retained cement, femoral notching, intra-operative fractures, etc) or improper radiographic alignment in either group.

DISCUSSION

Minimally invasive surgical techniques led to a faster recovery of muscle strength 4 weeks after TKA compared to conventional TKA, but this effect did not translate into better functional performance and was not paralleled by improvements in AROM, knee pain, or muscle size. Specifically, the lack of concurrent improvements in function (both self-report and performance measures) suggest that strength gains were not sufficient to impact functional performance. Strength gains 12 weeks after MIS were no longer enhanced relative to conventional TKA. Interestingly, WOMAC scores were better in the MIS group than controls at 12 weeks, but differences between groups were smaller than previously established clinically meaningful differences.[49] Also notable was the improved SF-36 MCS score for MIS at 4 and 12 weeks, although improvements were not clinically meaningful at 12 weeks.[49] Therefore, although the use of MIS techniques for TKA led to faster recovery of strength in patients undergoing TKA, the differences did not persist over time. Furthermore, there was no apparent benefit of MIS on other outcomes, suggesting that the benefits of MIS TKA may not outweigh the risks associated with poor surgical visualization.

Most investigations of MIS TKA have not included functional performance measures other than those self-reported through health status questionnaires.[14, 17] Yet, performance-based assessments, such as speed on a timed stair climbing test, have preferred responsiveness when measuring the impact of changes in muscle strength as compared to changes in self-report questionnaires, which tend to be more closely linked to pain relief.[29, 30] Furthermore, none of the aforementioned studies evaluated the impact of MIS TKA on the function of the quadriceps muscle by including muscle activation as a possible mechanism for improved outcomes. Also, no studies have blinded patients and testers fully to group assignment by standardizing incision lengths. Finally, few studies describe a standardized post-operative rehabilitation program to further decrease variability in outcome measures.

Currently, surgeons make decisions regarding minimally invasive surgery with limited scientific evidence to guide the decision. At the same time, patients often believe that less invasive should be better, without fully understanding the potential risks associated with this new procedure. While it seems promising that minimally invasive techniques may improve outcomes, a more comprehensive understanding of the impact of surgical trauma on muscle strength and functional performance is important for establishing future clinical practice recommendations. Therefore, the results of this investigation, which included a comprehensive evaluation of post-operative outcomes (muscle strength, functional performance, AROM, pain, and muscle mass), are important for advising the medical community with respect to MIS TKA recommendations.

Advocates of MIS TKA have suggested that it allows for faster recovery time, greater early post-operative quadriceps strength, shorter hospital stays, less pain, less need for inpatient rehabilitation, less narcotic usage, less need for assistive devices, better knee flexion during the early post-operative period, and improvements in function. [14, 17] Critics of MIS TKA have raised concerns over more complications with poor visualization during the surgery that could affect long-term outcomes (e.g., component malalignment)[14, 17] and the learning curve required for successful execution of MIS techniques.[50]

An increasing number of randomized controlled trials comparing MIS and conventional TKA techniques are emerging, although until recently, the majority of studies included retrospective cohort comparison studies. Early results from retrospective cohort comparisons indicated great promise with MIS surgery outcomes, yet more recently, small scale

prospective randomized controlled trials (RCTs) have been less universally supportive of whether the benefits of MIS surgery outweigh the risk of decreased visualization during surgery.[14, 15, 17, 26] A systematic review of RCTs comparing MIS and conventional TKA found that MIS surgery resulted in longer operating times, early improvements in Knee Society Scores (6 and 12 weeks, but not after 6 months), early improvements in knee ROM (6 days after TKA), and a greater incidence of delayed wound healing and infection with MIS, although no greater incidence in overall complications and component malalignment.[14] More recently, a meta-analysis of RCTs comparing clinical and radiological outcomes following MIS and conventional TKA found that knee flexion range of motion was significantly greater following MIS and there were trends for statistically significant improvements in quadriceps muscle strength during early follow-up, but not with later follow-up.[17] Therefore, the present study corroborates the increasing body of evidence that short-term benefits of MIS TKA surgery may not persist long term.

A limitation of the present study was the small sample size. Despite this, the results of this carefully controlled investigation with blinding to surgical approach, standardized rehabilitation, and comprehensive assessment of outcomes emphasize the need to scrutinize the purported benefits of MIS TKA and help inform future, large-scale clinical trials. Future clinical trials should include more than one surgeon to further validate the findings of this study. Another limitation is a relatively short follow-up time because it remains to be seen if there are differences in the durability of TKA with MIS surgery.

In conclusion, although the use of MIS techniques for TKA may lead to faster recovery of strength in patients undergoing TKA, there is no apparent benefit of MIS on the longer-term recovery of strength or functional performance. Therefore, the benefits of MIS TKA may not outweigh the risks associated with poor surgical visualization.

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Figure 1. Recruitment, enrollment and adherence of study participants

Enrollment numbers and withdrawals or those lost to follow-up are indicated in the boxes between time points. Overall, the total number of participants lost to follow-up through 12 weeks was one in the CONTROL group and none in the MIS group.

Figure 2. Quadriceps torque (A), hamstrings torque (B), and quadriceps activation (C) for MIS and CONTROL groups over time

Mean (SEM). ** indicates the difference between means had $p < 0.05$; * indicates the difference between means had $p < 0.10$.

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Table 1

Baseline Characteristics of the MIS and Control Groups^a

Variable	MIS		Control		p value ^b
	N	%	N	%	
Sex F	12	54.5%	10	45.5%	0.55
M	10	45.5%	12	54.5%	
	Mean (SD)		Mean (SD)		
Age	22	64.6 (8.5)	22	64.0 (8.4)	0.80
Height (cm)	22	166.5 (9.0)	22	171.2 (9.2)	0.09
Weight (kg)	22	84.4 (16.0)	22	92.1 (18.6)	0.15
BMI(kg/m ²)	22	30.5 (5.6)	22	31.3 (5.1)	0.63

^aMIS=minimally invasive surgery, BMI=body mass index

^bp values are based on chi-square test for independent proportions or a 2-sided, 2-group *t* test for difference in group means. Baseline data include all patients that were randomized pre-operatively.

Variable	Change from Baseline to 4wks Mean (SE) ^b		Difference in the Change from Baseline: MIS - Control (95% CI)		Change from Baseline to 12wks Mean (SE) ^b		Difference in the Change from Baseline: MIS - Control (95% CI)	
	MIS	Control		p value	MIS	Control		p value
Normalized Quadriceps Strength ^c (N-m/kg)	-0.51 (0.06)	-0.68 (0.07)	0.17 (-0.01, 0.35)	0.07	-0.05 (0.07)	-0.16 (0.08)	0.11 (-0.10, 0.33)	0.30
Normalized Hamstrings Strength ^c (N-m/kg)	-0.18 (0.04)	-0.32 (0.04)	0.14 (0.02, 0.25)	0.02	-0.04 (0.04)	-0.003 (0.05)	-0.04 (-0.17, 0.09)	0.54
Quadriceps Activation (percentage)	4.2 (4.2)	-5.9 (4.6)	10.2 (-2.5, 22.8)	0.11	12.0 (2.0)	9.8 (2.3)	2.3 (-3.9, 8.4)	0.46
6 minute walk (meters)	-109 (20.9)	-112 (24.5)	3.2 (-61.8, 68.2)	0.92	17.0 (1.8)	8.3 (16.4)	8.7 (-36.3, 53.8)	0.70
6 minute walk involved pain (points)	-1.1 (0.5)	-0.2 (0.5)	-0.9 (-2.4, 0.5)	0.20	-3.3 (0.3)	3.2 (0.3)	-0.1 (-1.0, 0.9)	0.90
Stair Climb (sec)	16.7 (3.0)	12.9 (3.4)	3.8 (-5.4, 12.9)	0.41	-2.7 (1.3)	-1.7 (1.4)	-1.0 (-4.8, 2.8)	0.60
Extension Active Range of Motion (degrees)	4.2 (1.0)	5.4 (1.1)	-1.2 (-4.2, 1.8)	0.43	1.6 (1.1)	-2.5 (1.2)	-0.9 (-4.2, 2.4)	0.59
Flexion Active Range of Motion (degrees)	-20.4 (2.6)	-23.1 (2.7)	2.7 (-4.9, 10.2)	0.48	-6.3 (1.8)	-6.9 (2.0)	0.6 (-4.9, 6.1)	0.83
WOMAC Total (points)	-2.8 (2.8)	-0.8 (3.1)	-1.9 (-10.3, 6.4)	0.64	-25.9 (2.6)	-16.5 (3.1)	-9.4 (-17.7, -1.1)	0.03
SF-36 PCS (points)	-3.9 (1.5)	-1.6 (1.8)	-2.3 (-7.0, 2.4)	0.33	8.0 (1.7)	-0.0 (-5.5, 5.4)	-0.0 (-5.5, 5.4)	0.99
SF-36 MCS (points)	-0.4 (2.3)	-15.3 (2.7)	15.0 (7.6, 22.3)	0.001	5.0 (1.4)	1.2 (1.6)	6.2 (1.8, 10.6)	0.01
DXA Thigh FFM (g)	-221 (125.8)	-21.1 (130.8)	-200 (-579, 179.4)	0.29	NT	NT	NT	NT
DXA Leg FFM (g)	-32.0 (192.7)	181.9 (200.2)	-214 (-795, 367.3)	0.45	NT	NT	NT	NT

^a CI=confidence interval, SF-36=36-Item Short-Form Health Survey questionnaire, WOMAC=Western Ontario and McMaster Universities Osteoarthritis Index, PCS=Physical Component Score, MCS=Mental Component Score, DXA= dual-energy X-ray absorptiometry

NT = not tested

^b Values are +/- standard error of the estimate. Negative values reflect a deficit from baseline; positive values reflect an improvement from baseline. P values are from the estimated between-group difference in change from baseline, conditioned on baseline and controlling for age and sex. The model is change from baseline regressed on baseline and treatment assignment.

^c Normalized to weight.

Variable	Pre-Op		4wks Post-Op		12wks Post-Op	
	MIS	Control	MIS	Control	MIS	Control
Quad strength (N·m/kg)	1.27 (0.56) N = 22	1.37 (0.56) N = 22	0.79 (0.39) N = 22	0.66 (0.23) N = 20	1.24 (0.40) N = 22	1.20 (0.42) N = 19
Ham strength (N·m/kg)	0.80 (0.34) N = 22	0.80 (0.24) N = 22	0.61 (0.29) N = 21	0.49 (0.18) N = 20	0.75 (0.29) N = 2	0.82 (0.27) N = 19
Quad Activation (%)	71.9 (20.3) N = 22	74.6 (15.7) N = 21	77.6 (15.6) N = 22	67.5 (22.6) N = 20	85.1 (8.3) N = 22	83.3 (10.4) N = 19
6 Minute Walk (m)	464.0 (124.9) N = 22	434.7 (147.8) N = 21	345.9 (111.2) N = 22	326.6 (125.7) N = 20	474.6 (105.4) N = 22	448.5 (124.8) N = 19
6 Minute Walk Pain	4.4 (2.7) N = 21	3.8 (2.9) N = 21	2.9 (2.2) N = 22	3.8 (2.2) N = 20	0.8 (1.5) N = 22	0.9 (1.6) N = 19
Stair Climb Test Total (sec)	18.1 (9.7) N = 22	19.4 (17.2) N = 22	35.0 (18.7) N = 22	32.2 (17.3) N = 20	15.9 (8.7) N = 22	16.4 (7.8) N = 18
Extension Active ROM	0.5 (4.7) N = 22	2.4 (7.5) N = 22	5.6 (4.6) N = 22	7.0 (4.5) N = 20	2.9 (4.4) N = 22	4.1 (5.5) N = 19
Flexion Active ROM	120.0 (16.7) N = 22	119.3 (15.8) N = 22	98.6 (12.3) N = 22	96.9 (13.9) N = 20	113.5 (10.6) N = 22	112.4 (9.4) N = 19
WOMAC Total	43.3 (15.0) N = 21	40.5 (16.6) N = 21	37.3 (11.4) N = 19	39.6 (12.7) N = 20	17.1 (11.7) N = 19	24.9 (13.0) N = 13
SF-36 PCS	36.9 (6.9) N = 21	37.3 (8.9) N = 19	32.9 (6.6) N = 19	35.7 (6.2) N = 20	44.7 (6.3) N = 18	44.7 (6.6) N = 13
SF-36 MCS	51.3 (10.7) N = 21	52.9 (9.7) N = 19	51.4 (10.2) N = 19	41.0 (12.4) N = 20	56.5 (7.1) N = 18	50.5 (8.7) N = 13

^aWOMAC=Western Ontario and McMaster Universities Osteoarthritis Index, SF-36=36-Item Short-Form Health Survey questionnaire, PCS=Physical Component Score, MCS=Mental Component Score, DXA= dual-energy X-ray absorptiometry