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Preoperative Quadriceps Characteristics Predict Physical Activity Outcomes after Total Knee Arthroplasty

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Abstract

This single-center cohort study explored preoperative determinants—specifically physical function and the quantity and quality of the quadriceps femoris muscle—for physical activity (PA) status at 1 year following total knee arthroplasty (TKA). A total of 204 individuals with knee osteoarthritis scheduled for TKA were enrolled and subsequently stratified into groups based on PA increase or decrease. Variables exhibiting significant between-group differences, including non-operative-side quadriceps strength, the Knee Injury and Osteoarthritis Outcome Score (KOOS) Sport/Rec dimension, the cross-sectional area (CSA) of the vastus medialis (VM) on the operative side, and computed tomography attenuation values (CTV) of the vastus lateralis (VL) on the operative side, were incorporated into a multiple logistic regression model. Receiver operating characteristic (ROC) curve analysis was employed to establish the threshold for preoperative VM CSA required to surpass the necessary PA score at the one-year postoperative mark. The multivariate logistic regression demonstrated that non-operative-side quadriceps strength, KOOS Sport/Rec, operative-side VM CSA, and operative-side VL CTV each maintained a significant independent association with enhanced PA after TKA. The cutoff value determined by ROC analysis was 10.2 cm². The data suggest that preoperative muscle quantity and quality, particularly the VM, may be critical factors influencing postoperative PA outcomes following TKA.

Keywords: Knee osteoarthritis, Muscle quantity, Muscle quality, Physical activity, Quadriceps femoris, Total knee arthroplasty

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Introduction

Knee osteoarthritis (KOA) is a degenerative articular condition frequently encountered in older adults and is the principal cause of mobility restriction among adults [1, 2]. The discomfort and functional deficits provoked by KOA exert a detrimental influence on both physical activity (PA) and quality of life (QOL) [3]. The objective of total knee arthroplasty (TKA) is to restore physical capacity and PA, bolster health-associated QOL, and lengthen the span of healthy life [4-6]. Hence, postoperative PA emerges as a pivotal metric of success for TKA patients. Despite this, a subset comprising roughly 10–33% of TKA recipients reports enduring pain and challenges with routine tasks [7]. A major contributing element is muscular weakness, which is omnipresent before TKA, intensifies further after the procedure, and correlates with diminished physical function and activity [8, 9].

The quadriceps muscle complex is responsible for knee extension, acts as the chief dynamic stabilizer of the joint, and its adequate function is a strong determinant of patients' ability to resume PA post-TKA [10]. KOA induces quadriceps weakening, a phenomenon that may accelerate the degenerative cascade of osteoarthritis [11]. Research by Mizner *et al*. [12] established that preoperative quadriceps strength predicts functional performance on stair-climbing and timed "Up & Go" assessments 1 year after TKA. Additional studies have shown that the strength of the contralateral quadriceps before surgery predicts postoperative PA levels and ambulation velocity [13, 14]. With respect to imaging-based muscle evaluation via computed tomography (CT), the mid-thigh quadriceps cross-sectional area (CSA) is a reliable proxy for total-body skeletal muscle mass [15], and mid-thigh quadriceps CT attenuation values (CTV) exhibit an inverse relationship with PA [16]. CT can cleanly discriminate adipose from muscle tissue because fat yields negative CTV while muscle yields positive CTV [17]. Fatty infiltration within the quadriceps has a more profoundly adverse impact on PA and activities of daily living (ADL) than does a simple reduction in quadriceps mass [16]. Accordingly, preoperative deficits in quadriceps strength, CSA, and CTV could potentially affect postoperative PA. To date, however, the precise preoperative quantitative and qualitative characteristics of the quadriceps that shape PA after TKA have not been fully elucidated.

The present study was designed to pinpoint preoperative risk factors spanning physical function, along with quadriceps femoris quantity and quality, for PA at 1 year post-TKA. The underlying hypothesis posited that a decline in preoperative quadriceps strength, operative-side CSA, and CTV of the quadriceps would correspond with a reduction in postoperative PA.

Materials and Methods

Study design

This single-center cohort study recruited patients with KOA undergoing primary TKA. Consecutive enrollment of 247 individuals took place at the participating institutions between January 2019 and August 2023 **(Figure 1)**. Grounds for exclusion comprised revision TKA procedures, major cognitive impairment, a primary language other than Japanese, prior surgical intervention on a lower limb, and withdrawal of patient consent. Applying these parameters led to the exclusion of 43 individuals, yielding a final study cohort of 204 participants. Patients were categorized into two groups based on whether their score for item 4 on the Japanese version of the 2011 Knee Society Score (KSS) at 1 year postoperatively increased or decreased from their baseline preoperative score. Written informed consent was secured from every participant before study enrollment. The Ethics Review Committee of our institution approved this research (113,786).

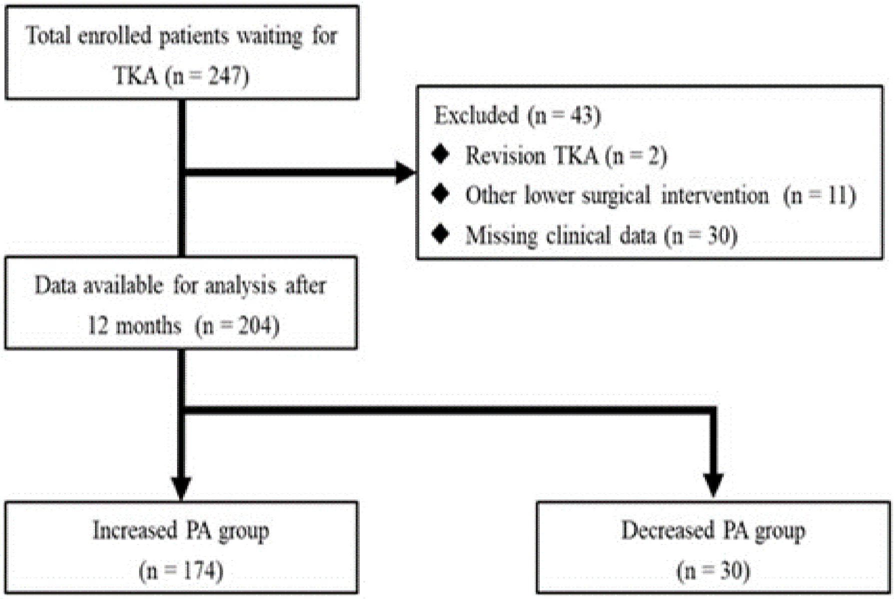

Figure 1. Flow chart of patient recruitment into this study.

Surgical technique and rehabilitation protocol

The TKA operations were performed by two orthopedic surgeons in a university hospital setting. Every procedure utilized either the subvastus or medial parapatellar approach, adhering to a mechanical alignment philosophy. Postoperative rehabilitation was initiated on the day after surgery, allowing full weight-bearing on the operated limb. The targeted rehabilitation milestone was independent walking with a cane by two weeks after the operation. The rehabilitation regimen included exercises to enhance knee flexion and extension range of motion, lower-extremity strengthening, gait re-education, and task-oriented practice of ADL movements.

Assessment variables

Data collected on clinical parameters consisted of fundamental patient information (sex, operative age, height, weight, body mass index, whether the contralateral knee had undergone TKA, surgical approach, Kellgren–Lawrence classification, time required for a 10 m walk, knee flexion and extension range of motion [ROM], quadriceps strength, duration of one-leg standing, and knee pain scored on a numerical rating scale [NRS]); the femorotibial angle; and the full set of Knee Injury and Osteoarthritis Outcome Scores (KOOS). Preoperative skeletal muscle evaluations covered the cross-sectional area (CSA) and computed tomography attenuation values (CTV) of the vastus medialis (VM), vastus lateralis (VL), vastus intermedius (VI), and rectus femoris (RF).

Physical function tests

Walking speed over 10 m was captured at a relaxed, self-selected pace on a 14 m straight course, incorporating an extra 2 m segment at both the start and finish to account for acceleration and deceleration [18]. A stopwatch recorded how long each patient needed to cover the central 10 m distance. Passive ROM was assessed with a goniometer (Toudaisiki Goniometer; OG Wellness Co., Ltd., Okayama, Japan). A handheld dynamometer (μTas F-1; ANIMA, Tokyo, Japan) was used to measure the force output of the quadriceps and hamstrings. This dynamometry method has been validated for quantifying quadriceps strength in prior work [19]. During testing, subjects sat with both hips and knees bent to 90°, and maximal voluntary isometric knee extension force was measured across two trials. The highest reading, recorded in newtons, was carried forward for analysis. Single-leg stance endurance was timed from the moment the subject lifted the foot until it made contact with the floor again, because the position could no longer be maintained; two attempts were allowed, with a 60-second ceiling. The longer of the two trials was used in the statistical evaluation. This one-leg standing test functioned as a clinical indicator of static balance impairment [20]. Pain intensity was rated on the NRS from 0 to 10, with 0 indicating no pain and 10 the worst pain imaginable.

Patient-reported outcome measures

Study participants completed the Japanese version of the KSS at two time points: before surgery and at the 1-year postoperative follow-up [21]. The forms were completed while patients were in the hospital. Physical activity (PA) level was captured before the operation and again 1 year after TKA using item 4 (PA) from the KSS instrument, scored from 0 to 100 points (where 100 reflects the greatest amount of PA) [22]. This scoring tool evaluates four domains—symptoms, expectations, satisfaction, and PA—in the post-TKA population [22].

The patient-reported outcome instruments employed in this study further included the KOOS, a 42-item knee-specific questionnaire designed for self-administration. It generates scores across five separate subscales: pain (nine items), symptoms (seven items), function in daily living (17 items), function in sport and recreation (five items), and knee-related quality of life (four items). For each question, patients chose one of five Likert-scale responses. Each subscale yields a score spanning 0 (extreme difficulties) to 100 (complete absence of problems) [23].

Skeletal muscle assessment

Muscle quantity and quality were determined by measuring CSA and evaluating CTV, respectively, from cross-sectional CT scans **(Figure 2)**. Measurements were taken at the mid-thigh, defined as the halfway point between the upper edge of the patella and the inguinal crease (acquisition parameters: 120 kV, 120 mA; rotation time: 1 s; field of view: 233 mm) [24], using EV Insite image analysis software (PSP Corporation, Tokyo, Japan). For each individual, regions of interest were outlined manually around the VM, VL, VI, and RF, after which CSA and CTV were computed for each of the four muscle heads [24]. CSA reflected overall muscle bulk, including intermuscular fat, whereas CTV served as a surrogate marker of muscle composition, capturing the extent of intramuscular and intramyocellular lipid deposition. Muscles normally exhibit CTVs between 40 and 100 Hounsfield Units (HU); lower HU values indicate reduced muscle density, indicating poorer muscle quality. Previous research has verified the feasibility, reliability, and validity of this measurement protocol [25].

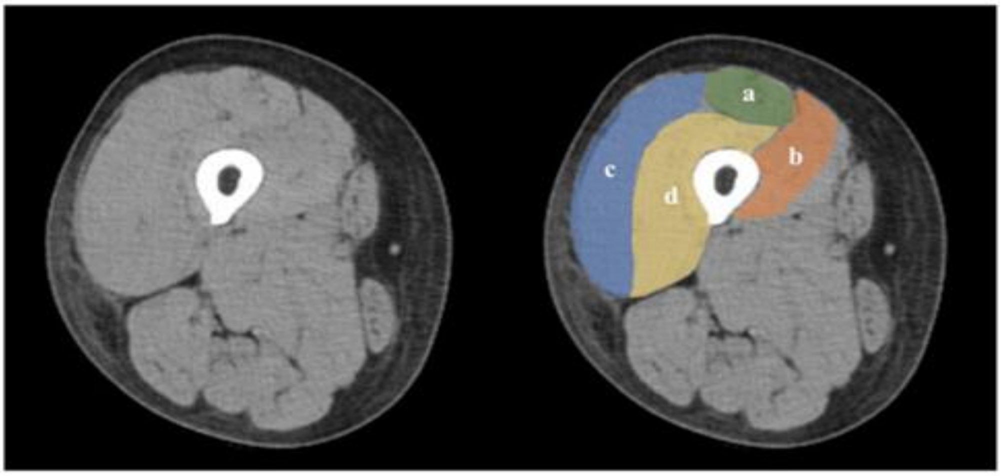

Figure 2. Measurement of quadriceps femoris using CT; Mid-thigh CT: a) Rectus femoris, b) Vastus medialis, c) Vastus lateralis, and d) Vastus intermedius. Abbreviation: CT = computed tomography.

Data analyses

The necessary sample size and statistical power were established using G Power 3.1.9.7 (Franz Paul, Kiel, Germany). An a priori power calculation for the univariate comparisons indicated that 142 patients would be required, with an effect size (d) of 0.50, an α of 0.05, and a power of 0.80. Separately, an a priori power estimate for the multiple logistic regression analysis determined that 129 patients were needed, assuming an effect size (f^2) of 0.15, an α of 0.05, a power of 0.95, and a model containing 4 predictor variables [26].

The Shapiro–Wilk test was applied to assess normality, and the F-test was used to examine equality of variances where appropriate. Comparisons between groups for normally and non-normally distributed variables were performed using the Student's t-test or Welch's t-test, and the Wilcoxon test or Pearson's chi-square test, respectively. Multivariate logistic regression was used to identify determinants of PA at 1 year postoperatively. Here, 1-year PA served as the outcome variable, and predictors were selected from factors that showed statistically significant differences between the two groups in the univariate analyses. Finally, the optimal preoperative VM CSA threshold required for PA to surpass the target score at 1 year after surgery was derived from a receiver operating characteristic (ROC) curve. All statistical analyses were conducted in SPSS Statistics (version 27.0.0.0; IBM, Armonk, NY, USA), with a significance threshold of $P < 0.05$.

Results and Discussion

Table 1 displays the baseline demographic characteristics of the sample. Among the study population, 30 patients in the decreased PA group experienced a greater decline in postoperative PA than their preoperative levels at 1 year after TKA. The increased PA group showed a marked rise in PA at the 1-year follow-up relative to the decreased PA group (increased PA: 68.6 ± 14.3 points; decreased PA: 40.8 ± 7.7 points; $P < 0.001$) **(Figure 3)**.

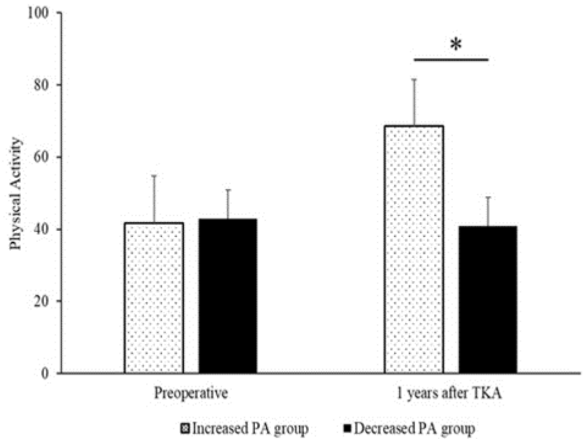

Figure 3. Changes in physical activity before TKA and at 1 year after TKA. There are significant differences between groups ($P < 0.001$). Abbreviation: TKA = total knee arthroplasty.

Table 1. Patient demographic data.

Characteristics	N or Mean
Sex (male/female)	49:155
Age at time of surgery (years)	73.5 (8.5)
Height (m)	155.0 (7.7)
Weight (kg)	61.8 (10.1)
BMI (kg/m²)	25.7 (3.9)
History of contralateral TKA (yes/no)	48/156
Surgical approach	
Subvastus	181 (88.7%)
Medial parapatellar	23 (11.3%)
Kellgren–Lawrence grade	
Grade III	31 (15.2%)
Grade IV	173 (84.8%)

Abbreviations: BMI = body mass index; TKA = total knee arthroplasty.

The univariate analysis uncovered notable disparities between groups for quadriceps strength on the nonoperative side, the KOOS Sport/Rec domain **(Table 2)**, operative-side VM CSA, and VL CTV **(Table 3)**. Upon entering these variables into a multivariate logistic regression model **(Table 4)**, four factors emerged as independently linked to sufficient PA at the 1-year post-TKA time point: nonoperative quadriceps strength (odds ratio (OR): 1.011; 95% confidence interval (CI): 1.004–1.018; P = 0.001); KOOS Sport/Rec (OR: 1.037; 95% CI: 1.003–1.073; P = 0.033); operative-side VM CSA (OR: 1.544; 95% CI: 1.124–2.119; P = 0.007); and operative-side VL CTV (OR: 1.222; 95% CI: 1.063–1.404; P = 0.005). Based on the ROC curve, the CSA of the VM on the operated side required to discriminate between those who did and did not reach target PA levels at one year was established at 10.2 cm², yielding a sensitivity of 0.79 and a specificity of 0.67; the calculated area under the curve was 0.70 **(Figure 4)**.

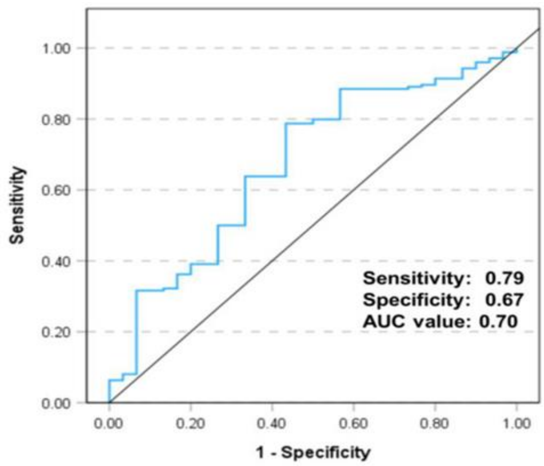

Figure 4. Calculation of cutoff values for preoperative-side and operative-side CSA of VM. The receiver operating characteristic curve demonstrates an area under the curve of 0.70 for increased and decreased 1-year postoperative PA. The optimal threshold to predict PA at 1 year postoperatively was the operative-side CSA of the VM at a preoperative angle of 10.2 cm² (sensitivity: 0.79; specificity: 0.67). Abbreviations: CSA = cross-sectional area; VM = vastus medialis; PA = physical activity; AUC = area under the curve.

Table 2. Comparison of preoperative parameters by increased or decreased 1-year PA.

Variable	P-value	95% CI	Decreased PA group (n = 30)	Increased PA group (n = 174)
Clinical parameters				
Gender (male: female)	0.496	−0.11, 0.23	6:24	43:131
Age at surgery (years)	0.921	−3.17, 3.51	73.0 (7.2)	72.8 (8.7)
Height (m)	0.103	−5.45, 0.50	152.9 (3.7)	155.4 (7.8)
Weight (kg)	0.322	−5.96, 1.97	60.1 (10.3)	62.1 (9.6)
BMI (kg/m²)	0.948	−0.11, 0.23	25.7 (4.0)	25.7 (3.6)
History of contralateral TKA	0.624	−0.21, 0.13	6	42
10 m gait time (s)	0.672	−1.64, 2.51	13.5 (5.2)	13.1 (5.2)
Operative side				
Knee flexion ROM (°)	0.390	−8.95, 3.51	108.0 (14.4)	110.7 (16.2)
Knee extension ROM (°)	0.831	−2.87, 2.31	−8.2 (7.1)	−7.9 (6.5)
Quadriceps strength (N)	0.086	−49.46, 3.27	146.7 (53.7)	169.9 (69.7)
One-leg standing time (s)	0.263	−10.32, 2.83	18.3 (16.2)	22.0 (17.0)
Knee pain	0.055	−1.23, 0.01	3.4 (1.9)	4.0 (1.5)
FTA	0.177	−3.53, 0.68	186.2 (5.3)	187.6 (5.4)
Nonoperative side				
Knee flexion ROM (°)	0.845	−4.34, 5.29	129.5 (11.5)	129.0 (12.5)
Knee extension ROM (°)	0.163	−0.52, 3.09	−1.3 (3.5)	−2.6 (4.8)
Quadriceps strength (N)	<0.001	−87.49, −30.17	154.4 (68.3)	213.2 (74.4)
One-leg standing time (s)	0.657	−7.79, 11.92	33.5 (24.9)	31.4 (23.3)
Knee pain	0.482	−0.57, 1.08	1.8 (2.1)	1.5 (1.8)
FTA	0.654	−0.21, 0.57	176.9 (1.5)	176.8 (1.4)
PROMs				
KOOS symptoms	0.882	−6.72, 7.81	49.5 (16.5)	48.9 (19.0)
KOOS pain	0.164	−13.05, 0.26	41.5 (19.1)	46.9 (19.6)

KOOS ADL	0.639	−9.69, 5.96	50.2 (18.4)	52.1 (20.3)
KOOS Sport/Rec	0.010	−14.72, −2.04	13.8 (11.6)	22.1 (16.9)
KOOS QOL	0.806	−7.90, 6.15	26.0 (19.7)	26.8 (17.7)

Abbreviations: PA = physical activity; BMI = body mass index; TKA = total knee arthroplasty; FTA = femorotibial angle; PROMs = patient-reported outcome measures; KOOS = knee injury and osteoarthritis outcome score; ADL = activities of daily living; QOL = quality of daily life; Sport/Rec = sports and recreation function; CI = confidence interval.

Table 3. Comparison of preoperative parameters by sufficient or insufficient 1-year PA.

Variable	P-value	95% CI	Decreased PA group (n = 30)	Increased PA group (n = 174)
Operative side				
Cross-sectional area				
Vastus medialis (cm²)	< 0.001	−1.53, −0.30	10.4 (1.5)	11.6 (1.8)
Vastus lateralis (cm²)	0.619	−0.55, 0.33	19.1 (1.0)	19.2 (1.1)
Vastus intermedius (cm²)	0.491	−0.79, 1.65	17.0 (1.0)	17.1 (1.1)
Rectus femoris (cm²)	0.384	−0.21, 0.31	6.5 (0.5)	6.4 (0.7)
CT-derived muscle density (HU)				
Vastus medialis (HU)	0.065	−2.19, 0.07	43.5 (2.9)	44.5 (2.9)
Vastus lateralis (HU)	< 0.001	−3.23, −0.84	43.9 (3.3)	45.9 (3.0)
Vastus intermedius (HU)	0.491	−0.79, 1.65	47.8 (3.6)	47.4 (3.3)
Rectus femoris (HU)	0.384	−0.71, 1.83	48.0 (3.1)	47.5 (3.3)
Nonoperative side				
Cross-sectional area				
Vastus medialis (cm²)	0.761	−0.34, 0.46	12.0 (1.1)	11.9 (1.0)
Vastus lateralis (cm²)	0.979	−0.63, 0.61	21.9 (1.7)	21.9 (1.6)
Vastus intermedius (cm²)	0.923	−0.29, 0.32	17.3 (0.8)	17.3 (0.8)
Rectus femoris (cm²)	0.945	−0.29, 0.31	7.0 (0.9)	7.0 (0.8)
CT-derived muscle density (HU)				
Vastus medialis (HU)	0.801	−0.62, 0.80	51.3 (2.2)	51.3 (1.7)
Vastus lateralis (HU)	0.915	−0.76, 0.68	51.3 (2.1)	51.4 (1.8)
Vastus intermedius (HU)	0.646	−0.75, 1.21	51.2 (2.9)	51.0 (2.5)
Rectus femoris (HU)	0.863	−0.77, 0.65	50.5 (1.8)	50.6 (1.8)

Abbreviations: CI = confidence interval; PA = physical activity; HU = Hounsfield unit.

Table 4. Preoperative predictive factors of increased PA 1 year after primary TKA.

Variable	95% confidence interval (lower–upper)	P-value	Odds ratio
Non-operative-side quadriceps strength (N)	1.004 – 1.018	0.001	1.011
KOOS Sport/Rec	1.003 – 1.073	0.033	1.037
CSA vastus medialis (operative side)	1.124 – 2.119	0.007	1.544
CTV vastus lateralis (operative side)	1.063 – 1.404	0.005	1.222

Abbreviations: KOOS = knee injury and osteoarthritis outcome score; CSA = cross-sectional area; CTV = computed tomography attenuation values; Sport/Rec = function in sports and recreation.

The present investigation identified a set of factors associated with the preoperative likelihood of a decline in PA at 1 year following TKA. The outcomes lent partial support to the original hypothesis—namely, that reduced preoperative quadriceps strength, along with diminished operative-side CSA and CTV of the quadriceps, would be accompanied by lower postoperative PA. From a clinical standpoint, these findings imply that increasing the preoperative quantity of the VM and the quality of the VL may enhance PA after TKA.

The results revealed that individuals with weaker quadriceps strength on the nonoperative side were more likely to fail to improve PA by the 1-year mark. In line with earlier work [8, 13, 27], our data confirmed that preoperative quadriceps strength in the nonoperative leg was associated with postoperative functional status. Moreover, prior studies have indicated that preoperative contralateral quadriceps strength forecasts post-TKA PA, stair negotiation capacity, and gait speed [13, 14]. Among patients undergoing TKA, the contralateral limb frequently compensates for the compromised operated leg throughout rehabilitation and everyday tasks. Those with stronger non-operative-side quadriceps were presumably better able to support body weight during ambulation, stair ascent, and other physical endeavors, thereby facilitating more effective recovery and superior mobility. These observations underscore the value of prehabilitation regimens that target strengthening not only the surgical limb but also the opposite leg to maximize overall recuperation.

This study demonstrated that preoperative VM CSA and VL CTV influenced postoperative PA. Furthermore, the cutoff for anticipating meaningful PA improvement at 1 year was a preoperative VM CSA of 10.2 cm². Earlier research has documented that VM muscle thickness in cohorts with advanced KOA was substantially reduced relative to healthy counterparts [28]. Intramuscular adipose tissue within the quadriceps, particularly in the VM, was significantly elevated in early-stage KOA compared with asymptomatic controls [29]. With respect to age-driven changes, the accumulation of intramuscular fat in the quadriceps appears to precede the frank loss of muscle bulk [16]. The VM, as part of the quadriceps complex, plays an essential role in maintaining knee stability during motion, particularly during demanding tasks such as walking, ascending stairs, and squatting [30, 31]. Consequently, a buildup of intramuscular fat in the VM may have contributed to compromised knee steadiness and a subsequent drop in PA. Prior investigations have reported that resistance exercise can enhance both muscle quantity and quality [32, 33].

Additionally, high-intensity preoperative strengthening protocols have been shown to improve lower extremity muscle force and knee ROM before surgery, leading to shorter hospital stays and more rapid physical and functional recovery post-TKA [34, 35]. From a practical clinical perspective, these insights highlight the potential importance of preoperative rehabilitation; future studies should explore whether muscle volume and fatty infiltration can indeed be ameliorated after TKA. Prior research has suggested that high-velocity resistance training may outperform low-velocity protocols specifically for improving muscle quality [36]. Hence, incorporating high-velocity resistance exercise into preoperative care could yield gains not only in muscle size but also in tissue composition.

This study also established that patients with poorer preoperative KOOS Sport/Rec scores had elevated odds of no PA improvement at 1 year after TKA. The KOOS Sport/Rec subscale specifically assesses the capacity to perform higher-demand physical pursuits such as squatting, running, and jumping—activities that require substantial knee function and muscular power [37, 38]. Individuals scoring low on this subscale preoperatively were more likely to experience more pronounced restrictions during these rigorous tasks, reflecting greater knee functional deterioration. Some systematic reviews have indicated that PA can recover within the first 3 months post-surgery and surpass preoperative benchmarks at 6 to 12 months [39, 40]. Nonetheless, the majority of TKA recipients continue to engage in less PA compared with age-matched peers throughout the initial postoperative year [39-41]. Such constraints may be symptomatic not only of the operated knee's condition but also of an overall reduced capacity for physical exertion, encompassing deficits in contralateral limb strength, coordination, and general conditioning. Therefore, patients presenting with lower KOOS Sport/Rec scores before surgery might encounter a more arduous path to regaining mobility and attaining higher levels of PA.

Several limitations of the current study warrant acknowledgment. First, PA was evaluated solely through self-reported instruments, namely the KSS. The PA data gathered here diverge from measurements obtained via objective tools such as three-axis accelerometers or pedometers. Second, the single-center design may limit the generalizability of the findings to other populations or healthcare settings. Multicenter investigations are needed to corroborate these results across varied demographic and clinical contexts. Finally, the study concentrated primarily on the quadriceps femoris muscle group. Beyond the quadriceps, other musculature—such as the hamstrings—likely plays a pivotal part in knee joint stability, mobility, and overall physical activity. The hamstrings function as antagonists to the quadriceps, supplying dynamic stabilization by restraining anterior tibial translation and alleviating strain on the reconstructed joint during gait and other movements. Although other periarticular knee muscles, including the hamstrings, were not assessed in this study, they too may have influenced postoperative PA and functional recovery.

Conclusion

Preoperative non-operative-side quadriceps strength, operative-side VM CSA and VL CTV, and baseline KOOS Sport/Rec scores emerged as significant determinants for attaining higher PA at 1 year following TKA. These findings indicate that preoperative quadriceps strength, along with muscle quantity and quality—especially within the VM—may play important roles in shaping postoperative PA outcomes after TKA.

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Conflict of interest: None

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Ethics statement: This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Kanazawa University (113786, 18 August 2021).
Informed consent was obtained from all participants involved in the study.

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