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The Knee

The relationship between lower extremity swelling, quadriceps strength, and functional performance following total knee arthroplasty☆

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ABSTRACT

Background: The relationships between swelling after total knee arthroplasty (TKA) and quadriceps strength and functional performance are poorly understood.
Therefore, the aim of this study was to examine the relationships between lower extremity swelling, measured using bioelectrical impedance assessment (SF-BIA), and quadriceps strength and timed up and go (TUG) times following TKA.

Methods: 53 participants (64 ± 9.5 y/o, 43% male) undergoing primary unilateral TKA were recruited for the longitudinal observational study with repeated measures.
Quantities of swelling were examined for contribution to two and six-week outcomes of strength and TUG time using hierarchical regression controlling for age, sex, and the baseline value of the dependent variable. Swelling was assessed using bioelectrical impedance assessment and quantified as the peak level of swelling and cumulative swelling (integral) over the post-TKA time window. Maximum isometric quadriceps strength (MVIC) was measured using a electromechanical dynamometer and participant functional performance measured using the TUG.

Results: Neither peak swelling nor cumulative swelling significantly contributed to the variance of two-week quadriceps strength. At six weeks, peak swelling significantly improved the variance in maximal quadriceps strength by an additional four percent ($p = 0.05$), while cumulative swelling did not significantly contribute. Peak swelling significantly contributed to the variance in two-week (16%) and six-week (five percent) TUG times ($p < 0.05$), but the cumulative swelling did not.

Conclusions: Peak swelling represents a value of post-TKA swelling that is associated with strength and function. Reducing the peak level of swelling, occurring early after surgery, may improve patient functional recovery.

Level of evidence: Level II — Prospective observational study.

☆ Declarations of interest: none.

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1. Introduction

Limiting functional decline following total knee arthroplasty (TKA) is a high priority for patients and clinicians. Functional decline following surgery is common and includes, but is not limited to, decreased walking speed [1], difficulty rising from a chair [2,3], and reduced stair climbing ability [4,5]. Poor performance on more difficult activities has also been reported in patients many years after surgery [6,7]. Functional limitations following surgery are often attributed to the significant decline in quadriceps muscle strength following surgery [8–10]. Thus, increasing quadriceps strength and improving functional mobility remain a focal point of most post-TKA rehabilitation. As a result, research aimed at improving post-TKA outcomes has focused on identifying causes of quadriceps strength loss and decline in functional performance [10–15].

One hypothesized mechanism contributing to quadriceps strength loss and decline in functional performance following TKA is lower extremity swelling [7,13,16]. Swelling occurs substantially in and around the knee joint capsule in the majority of patients following TKA. The presence of swelling after TKA is thought to reduce muscle strength by decreasing voluntary muscle activation through a process referred to as arthrogenic muscle inhibition (AMI) [7,13,17]. Arthrogenic muscle inhibition results when sensory afferent signaling increases the influence of inhibitory interneurons on motor neuron excitability [13]. The relationship between swelling and AMI of the quadriceps has been shown to occur acutely with artificially-induced effusion of the knee [7,18]. These studies provide the theoretical framework for the investigation of the relation between swelling and motor function following TKA.

While there is growing evidence to support the hypothesis that swelling may be a contributor to post-TKA quadriceps strength loss [19,20], there remains a need to further explore this relationship. This can be explored by analyzing how changes in swelling after TKA relate to quadriceps muscle strength at different points in the recovery process and by examining different measures of swelling. Furthermore, the relationship between swelling and functional performance remains poorly understood. Swelling may result in decreased functional performance by contributing to strength loss in muscles throughout the lower extremity or by causing other impairments that influence functional performance, such as knee range of motion. Thus, the relationship between swelling and functional performance should be examined independent of quadriceps strength.

The purpose of this study was to determine the relationship between swelling and strength and functional performance after TKA. We hypothesized that swelling will be significantly related to quadriceps strength and patient performance on the timed up and go (TUG) test at two and six weeks following surgery. Identification of these relationships will help inform clinicians and researchers as they design interventions to target swelling with the intent of improving patient functional performance.

2. Methods

2.1. Participants

Data used in this analysis were collected as part of a longitudinal observational study examining post-TKA swelling and quadriceps strength, consisting of 53 participants consecutively recruited from three different orthopedic surgeons between December 2015 and April 2017. Data were collected at baseline (pre-TKA) and days zero, one, two, four, seven, two weeks, and six weeks (post-TKA). Inclusion criteria for the study included: undergoing a primary, unilateral TKA for osteoarthritis and ages 50 to 90 y/o. Exclusion criteria included: neurological conditions or unstable orthopedic conditions that limited function, history of orthopedic surgery or trauma within one year of study enrollment, or diagnosis of a condition known to result in lower extremity edema (i.e., heart failure and primary or secondary lymphedema). Informed consent was obtained from all participants. This study was approved by the Colorado Multiple Institutional Review Board (COMIRB #15-1419).

2.2. Outcomes assessments

2.2.1. Swelling

Lower extremity swelling was assessed using Bioelectrical Impedance Assessment (BIA). This approach has been validated for the measurement of swelling in patients with upper extremity lymphedema [21] and in patients following TKA [22,23]. All measurements were taken using an RJL systems Quantum II body composition analyzer© (Clinton Township, MI) and recorded in Ohms. Two electrodes were placed over the second ray on the dorsum of the foot separated by 10 cm and two were placed on the thigh, 10 and 20 cm proximal to the superior pole of the patella, a similar method for measuring swelling with bioelectrical impedance spectrometry has been previously used [24]. Swelling values are recorded as a percentage difference in the involved limb to the uninvolved limb using the formula:

$$\mathrm{BIA}_{\mathrm{ratio}} = (1-(\text{involved BIA}/\text{uninvolved BIA})) * 100$$

By normalizing the uninvolved limb, the $\mathrm{BIA}_{\mathrm{ratio}}$ controls for differences in body composition (i.e., BMI) between subjects and accurately measures changes in swelling between the limbs [21].

Utilizing the $\mathrm{BIA}_{\mathrm{ratio}}$, two different quantities of the swelling response were calculated: peak level of swelling and the cumulative swelling (integral) over time. Peak swelling is represented by the maximum value in involved limb swelling recorded at any of the post-TKA assessments. This value was chosen, as the authors hypothesize that the peak level may represent the time when swelling is likely to be the most damaging to the neuromuscular system. Cumulative swelling was calculated using the "sintegral" function in the Bolstad2 package in R (Bolstad2 1.0) [25]. This function calculates the trapezoidal area under the curve. Two integral values were calculated, one for the first two weeks and a second for the full six-week post-TKA period. Because swelling values were not always collected at exactly 14 and 42 days following surgery, significant variation in the integral of the swelling measures was possible. Therefore, when examining integral swelling values in the regression models time since surgery was controlled for. When examining the univariate correlations, swelling assessments occurring at 14 ± 2 days were used for the two-week swelling value, while assessments occurring at 42 ± 2 days were used for the six-week swelling value. For those two-week and six-week assessments that occurred beyond the accepted window, imputation was performed to estimate a swelling at day 14 or 42. This was done by assuming a linear relationship between the preceding and following swelling values and calculating the point corresponding with either the 14th or 42nd post-TKA day. If swelling values were not collected within or beyond the 14th and 42nd day, imputation could not be performed and those patient records were not used in the correlations. Cumulative swelling was chosen to represent the total amount of swelling experienced over the two windows of time (days 0–14 & 0–42). Examples of cumulative swelling (integrals) are provided in Figure 1.

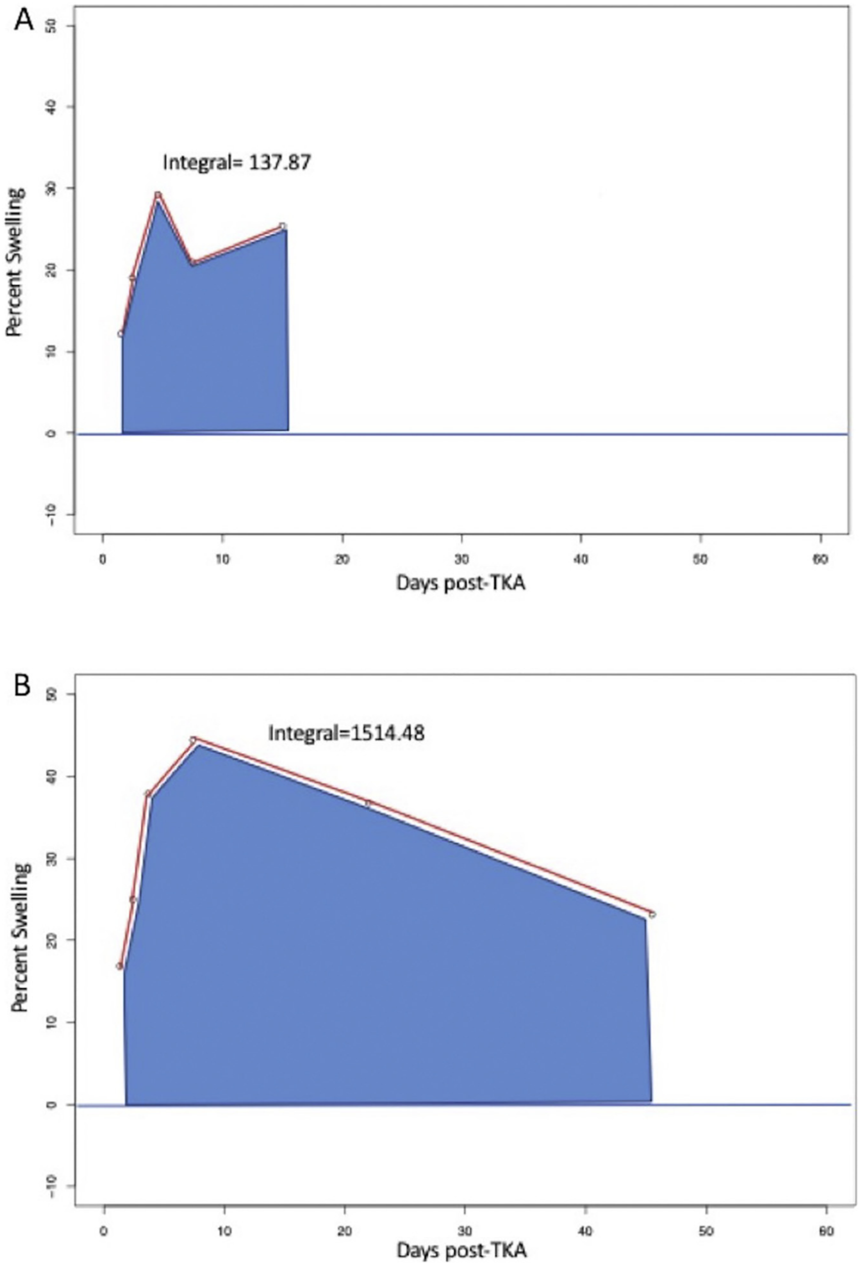

Figure 1. Examples of the calculation of A) Early cumulative swelling (integral of ~14 days) and B) full cumulative swelling (integral of ~42 days) using trapezoidal integration.

2.2.2. Quadriceps strength assessment

Quadriceps strength was measured as a maximum voluntary isometric contraction (MVIC) and recorded in Newton-meters (N-m) using an electromechanical dynamometer (Humac Norm) with the participant seated upright and positioned in 90 degrees of hip flexion and 60° of knee flexion. Each participant performed two warm up trials followed by maximal contractions as previously described [1]. If the force values produced in the first two maximal attempts were not within five percent of one another, additional trials were performed until two trials were within five percent of each other and the highest value of the two was used for analysis.

2.2.3. TUG test assessment

The TUG is a timed test of the patient ability to rise from an arm chair (seat height of 46 cm), walk three meters, turn, and return to sitting in the same chair without physical assistance [26]. TUG is a valid and reliable measure, and decreased performance on the TUG has been shown to correlate with increased risk of falls and higher rates of mortality in elderly patients [26]. This test has excellent inter-rater (Intraclass Correlation Coefficient (ICC) = 0.99) and intra-rater (ICC = 0.99) reliability, as measured in a group of older adults (mean age 80 years) [27]. In our study, participants performed the TUG test twice during each assessment, and the average of the two trials was used for analysis.

Assessments of swelling, strength, and TUG time were performed during the same sessions at each time point and were always performed in the same order, beginning with BIA measures of swelling, followed by the TUG test, and concluding with quadriceps strength assessments.

2.3. Calculation

General relationships between the peak and cumulative levels of swelling and the dependent variables of interest were established using Pearson product correlations at two and six weeks following surgery [28].

To estimate the effect of swelling on post-operative quadriceps strength and TUG time, hierarchical regression modeling was used. Hierarchical model building was chosen because it allows for determination of the individual contribution of the independent variable of interest to the variance in the dependent variable when controlling for other important covariates [29,30]. Step one consisted of modeling known covariates of interest (i.e., sex and age), and in the case of the swelling integral, time since surgery, on the dependent variable. In step two, pre-TKA values for the dependent variables were added to the model. In step three, the swelling value of interest is added to the model. In steps two and three, the coefficients and 95% Confidence Interval (CI) as well as the standardized coefficients were calculated for the independent variables of interest. Standardized coefficients were used to allow for easy assessment of the model contribution for each independent variable. In total, eight models were examined, one for each dependent variable regressed on each of the swelling values, at two and six weeks. Model fit was tested by examining the change in adjusted r-squared, the F-statistic, and level of model significance at each step. Model significance was defined as a p-value ≤0.05. The contribution of the independent variable to the model was examined using the variable p-value, parameter estimate, standardized coefficient, and the contribution to the adjusted r-squared.

3. Results

Patient characteristics as well as baseline swelling, strength, and TUG times are included in Table 1. Imputation was performed to calculate swelling values seven times and four participants did not have sufficient data for assessment of swelling, therefore, 49 participants were available for analysis. Additionally, from the 49 participants with usable swelling data two participants were unwilling to perform the TUG or strength testing at two weeks and at six weeks TUG and strength data were missing for five participants. Data missing at six weeks was a result of multiple factors including participants unable to perform the testing, testing equipment failure, and time restraints. This missing data was less than five percent of the useable data at two weeks and ~10% at six weeks.

3.1. Correlation between swelling, strength, and function

Pearson correlation coefficients, shown in Table 2, demonstrate that the peak swelling significantly correlated with quadriceps strength at two and six weeks, whereas cumulative swelling was only related to six-week strength. Peak swelling was significantly related to two-week TUG time, but had a weaker correlation at six weeks. Cumulative swelling was not correlated with TUG time at two or six weeks.

3.2. Hierarchical modeling of quadriceps strength

Table 3 presents the results of the hierarchical regression modeling for the outcome of two and six week quadriceps strength. When added as step three of the hierarchical regression, neither peak swelling or cumulative swelling were found to significantly contribute to the variance in the outcome of quadriceps strength at two weeks ($p = 0.22$ and $p = 0.98$, respectively)(Table 3). At six weeks, both full models were found to be significant, but the majority of the model variance was explained by pre-TKA strength. However, with the addition of peak swelling a significant contribution of an additional four percent of the variance was explained ($p = 0.05$), while cumulative swelling failed to reach significance at six weeks ($p = 0.47$).

Table 1
Demographic and baseline information for study participants.

Age mean (SD)	64.2 (9.5)
Sex (% female)	57%
BMI mean (SD)	31.9 (5.4)
Pre-TKA swelling % mean (SD)	1.7 (6.8)
Pre-TKA strength (N-m) mean (SD)	
Involved	105.7 (55.8)
Uninvolved	125.2 (54.3)
TUG time (s) mean (SD)	10.1 (2.8)
Comorbidity, frequency (%)	
HBP	29/53 (55%)
Diabetes	7/53 (13%)
Cancer	4/53 (8%)
RA	0/53 (0%)

BMI — Body mass index.
TUG — Timed up and go test.
HBP — High blood pressure.
RA — Rheumatoid arthritis.

3.3. Hierarchical modeling of TUG time

Table 4 presents the results of the hierarchical regression modeling for the outcome of two and six-week TUG time. Peak swelling was found to explain a significant portion of the variance in two-week TUG time ($p = 0.003$) (Figure 2). At the six-week time point, peak swelling significantly contributed to the variance in TUG time ($p = 0.04$) (Figure 2). The standardized beta coefficient for peak swelling was greater than pre-TKA TUG time at two weeks (0.45 vs 0.05), while at six weeks, the standardized beta coefficient for peak swelling was nearly equal to that of pre-TKA TUG time (0.27 vs 0.28). Cumulative swelling did not significantly contribute to two-week ($p = 0.14$) or six-week ($p = 0.47$) TUG time.

4. Discussion

This study was designed to examine the relationships between swelling following TKA, quadriceps strength, and functional performance. It was hypothesized that higher peak levels of swelling and greater cumulative swelling over time (integral) would be associated with lower quadriceps strength and slower TUG times. At both two and six weeks following surgery, peak swelling was found to significantly contribute to the variance in TUG time. Similarly, peak swelling significantly contributed to the variance in six-week quadriceps strength. Interestingly, cumulative swelling did not significantly contribute to the variance in two or six-week TUG time or quadriceps strength. The strength of the relationships between peak swelling and TUG time is compelling, especially at two weeks following surgery when peak swelling was a stronger predictor of functional performance than pre-TKA TUG time. While this full model only explained 20% of the variance in TUG time, 16% of the variance was explained by peak swelling, demonstrating the relative impact swelling has on functional recovery after TKA.

These findings add depth to our understanding of the swelling response after TKA by examining two different measurements of post-operative swelling. This quantitative information helps evaluate the relationship between swelling and quadriceps strength loss and examining the association of swelling to functional performance is critical to understanding the widespread impact swelling has on recovery from TKA.

The two swelling measures, peak swelling and cumulative swelling, were chosen based on physiologic rationale for influencing strength. Peak swelling represents the maximum level of recorded swelling for each participant. This value was chosen based on past literature showing continual decreases in knee extensor torque with increasing levels of knee joint effusion [31]. While the current study did not simultaneously test strength at the time of peak swelling, reductions in voluntary activation when swelling is at its highest could reduce the ability to benefit from strengthening activities. This is a result of an inability to achieve physiologic muscle overload with AMI, which could contribute to quadriceps disuse. Disuse is likely to contribute to both immediate

Table 2
Pearson correlation coefficients (95% CI) between swelling variables and strength outcomes.

	Maximal strength	p-Value	TUG time	p-Value
2 weeks (N = 49)				
Peak swelling (%)	r = −0.32 (−0.56, −0.04)	0.02*	0.43 (0.16, 0.65)	0.003*
Cumulative swelling (integral)	r = −0.18 (−0.44, 0.13)	0.23	0.26 (−0.04, 0.51)	0.08
6 weeks (N = 48)				
Peak swelling (%)	r = −0.45 (−0.65, −0.17)	0.002*	0.25 (−0.04, 0.51)	0.09
Cumulative swelling (integral)	r = −0.33 (−0.57,-0.04)	0.03*	0.23 (−0.07, 0.49)	0.12

TUG — Timed up and go test.
* Significant at $p < 0.05$.

Table 3
Hierarchical model building examining swelling measures and outcome of knee extensor strength.

Dependent variable	Independent variables	Added Variable Statistics			Model Statistics			
		Estimate (95% CI)	Standardized Coefficient	p-Value	Adj. R2	F-statistic	df	p-Value
Strength (2 weeks)								
Step 1	Age + sex	–		–	0.03	1.66	2, 45	0.2
Step 2	Age + sex + baseline strength	0.15 (0.006,0.29)	0.4	0.04	0.1	2.65	3, 44	0.06
Step 3	Age + sex + baseline strength + peak	−0.50 (−1.31 0.34)	−0.2	0.22	0.11	2.40	4, 43	0.06
	Age + sex + baseline strength + time since surgery + cumulative	−0.004 (−0.10 0.09)	−0.01	0.98	0.09	2.01	5, 42	0.09
Strength (6 weeks)								
Step 1	Age + sex	–		–	0.37	13.88	2, 42	<0.0001*
Step 2	Age + sex + baseline strength	0.38 (0.16, 0.60)	0.54	0.001	0.5	15.83	3, 41	<0.0001*
Step 3	Age + sex + baseline strength + peak	−1.17 (−2.37, 0.02)	−0.24	0.05	0.54	13.71	4, 40	<0.0001*
	Age + sex + baseline strength + time since surgery + cumulative	−0.008 (−0.04, 0.02)	−0.09	0.47	0.48	9.98	5, 39	<0.0001*

* Significant at $p < 0.05$; df — degrees of freedom; Adj. R2 — Adjusted r-squared.

and longer-term strength loss. Peak swelling might also reflect the magnitude of swelling at which muscle fibers experience damage. High levels of swelling have been shown to cause alterations in muscle cell water volume and internal pressure. These changes have been associated with strength loss in people following extreme endurance exercise [32]. The swelling integral was chosen as a measure of the cumulative swelling over time. The authors hypothesized that prolonged exposure to elevated levels of swelling may represent an abnormal or unhealthy response and may contribute to difficulty with recovery of strength and function. However, the lack of significant relationships between cumulative swelling and the outcomes of interest may be a result of the body's ability to accommodate to prolonged periods of elevated swelling. Unfortunately, prior lab based studies have only examined the acute influence of swelling and the impact of prolonged swelling is not yet understood.

The role of swelling in strength loss is supported by studies such as Palmeri-Smith et al. 2007 [16] and others [18,33], which demonstrated that the injection of saline into the knee results in significant AMI. These studies have shown that effusion in the knee joint capsule causes increased signaling from group II mechanoreceptors and, in large part, from group III and IV afferent fibers, which become sensitive to mechanical stimulation in the presence of swelling [34,35]. As afferent signaling increases from each of these fiber types, AMI occurs and a decline in muscle activation is observed [13,35–38]. Furthermore, studies have directly shown a reduction in quadriceps strength in the presence of artificial knee joint effusion [39–41]. In an attempt to link swelling to muscle activation in patients following TKA a couple studies have examined the influence swelling has on strength in this patient population [19,20]. Pua et al. 2015 [20] used methods similar to those used in the current study to examine the

Table 4
Hierarchical model building examining swelling measures and outcome of TUG time.

Dependent variable	Independent variables	Added variable statistics			Model statistics			
		Estimate (95% CI)	Standardized Coefficient	p-value	Adj. R2	F-statistic	df	p-value
TUG time (2 weeks)								
Step 1	Age + sex	–	–	–	0.07	2.399	2, 45	0.1
Step 2	Age + sex + baseline TUG time	0.07 (−0.4,0.5)	0.05	0.7	0.04	1.329	3, 44	0.2
Step 3	Age + sex + baseline TUG + Peak	0.23 (0.07,0.40)	0.45	0.003	0.2	3.757	4, 43	0.01*
	Age + sex + baseline TUG + time since surgery + cumulative	0.01 (−0.005,0.03)	0.22	0.14	0.06	1.578	5, 42	0.18
TUG time (6 weeks)								
Step 1	Age + sex	–		–	0.25	8.172	2, 42	0.001*
Step 2	Age + sex + baseline TUG	0.2 (0.02,0.39)	0.28	0.03	0.31	7.546	3, 41	0.0003*
Step 3	Age + sex + baseline TUG time + Peak	0.07 (0.002,0.14)	0.27	0.04	0.36	7.2	4, 40	0.0002*
	Age + sex + baseline TUG + time since surgery + cumulative	0.002 (−0.006,0.02)	0.17	0.48	0.28	4.462	5, 39	0.002*

* Significant at $p < 0.05$; TUG — timed up and go test.

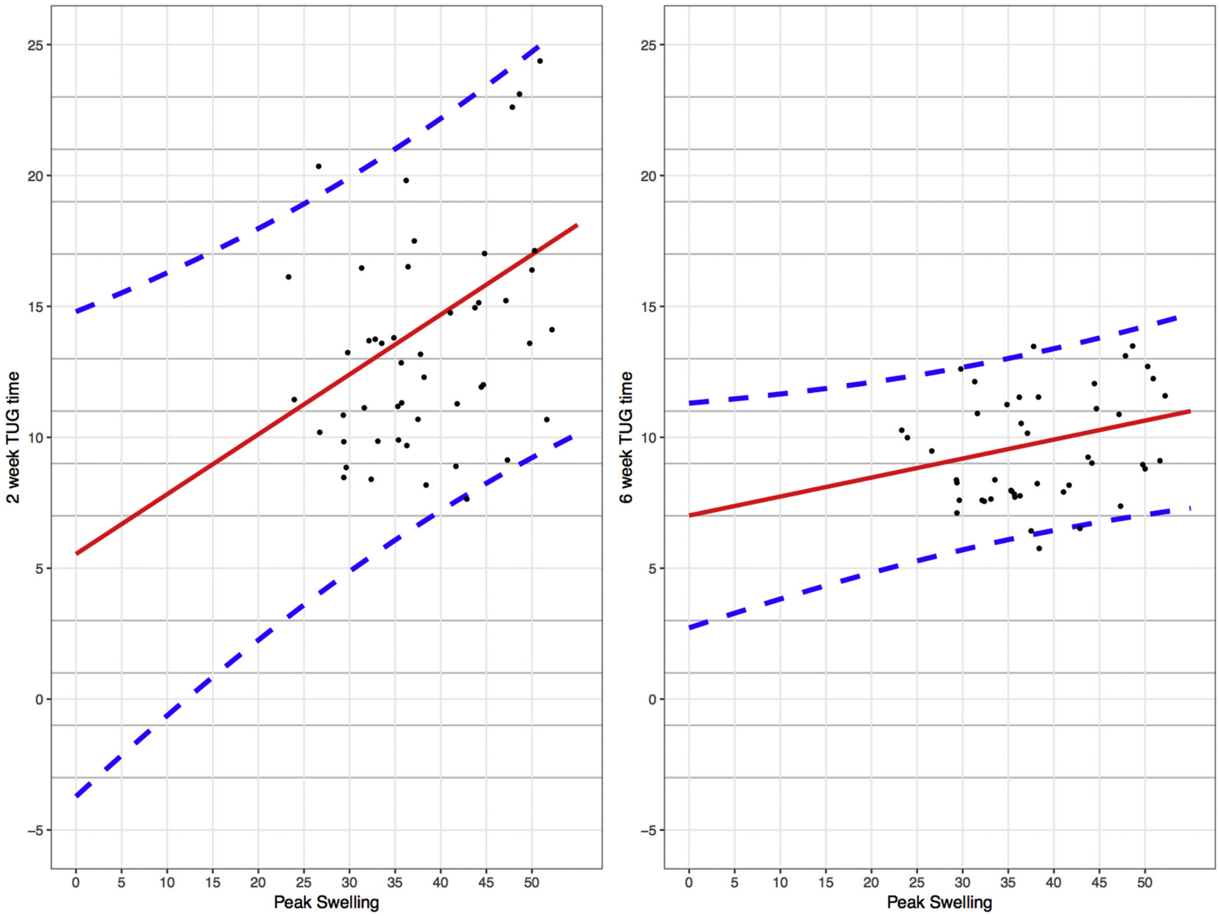

Figure 2. Relationship between peak swelling and A) two-week TUG time and B) six-week TUG time from the linear model when controlling for baseline TUG time, age, and sex.

relationship between swelling after TKA and quadriceps strength. In this study, swelling over the first 90 days after TKA, measured using BIA, was found to be significantly related to quadriceps strength over the same 90 days. Specifically, differences between those participants in the highest percentile of swelling and those in the lowest over the entire 90 days, when controlling for age, sex, pre-TKA strength, and pain, were found.

Findings from the current study echo those shown by Pua, but add further insight into the relation of swelling after TKA and quadriceps strength, specifically, by examining swelling levels as the peak acute level of swelling and the cumulative level of swelling. When added to the model, peak swelling reached significance ($p = 0.05$), demonstrating the incremental decline in six-week strength that occurs with increasing levels in peak swelling. Furthermore, in the previous work a dichotomy of the people with the highest and lowest levels of swelling was used. In this study swelling differences were viewed continuously allowing us to provide estimates of the affect incremental increases in peak swelling have on strength. Specifically, for each percentage point increase in peak swelling, a reduction of nearly 0.25 N-m in six-week strength occurred when controlling for age, sex, and pre-TKA quadriceps strength. Additionally, the standardized beta coefficient for peak swelling is of clinical consideration, as it is nearly half the magnitude of that of pre-TKA quadriceps strength (−0.27 vs. 0.54), suggesting that swelling contributes to post-TKA quadriceps strength loss in a clinically meaningful way. However, the authors note the need to be cautious in the interpretation of the standardized coefficient, with the positive skew in quadriceps strength this result has potential for over estimation. These findings add to the findings by Pua, demonstrating the individual contribution of peak swelling to the variance in quadriceps strength, above that explained by pre-operative strength, which is known to be the strongest predictor of post-TKA strength [9]. Reducing peak swelling may also be more clinically feasible than attempting to reduce mean swelling over the first 90 post-TKA days, as was the measure of swelling used by Pua.

Perhaps the most compelling finding from the current study was the strong contributions peak swelling made to TUG times at two and six weeks. Particularly, the finding that peak swelling was a significant predictor of two-week TUG performance, while pre-TKA TUG time was not. The TUG is a commonly used performance measure for determining patient's mobility status after TKA [42], and it is strongly correlated with patient independence [26]. It is also known to correlate with quadriceps strength following

TKA [8]. Despite a weaker relation between swelling and strength, a strong relation between swelling and TUG time supports the hypothesis that swelling is associated with recovery beyond reducing maximal quadriceps strength.

Swelling may result in strength declines in different muscles aside from the quadriceps that are also critical to performance-based outcomes. Declines in muscle strength of the plantar flexors, hip extensors, and hip abductors could be influenced by swelling occurring throughout the limb and detected by BIA. Each of these muscle groups contributes to functional mobility and is likely to contribute to TUG test performance [43–45]. The plantar flexor muscles have been found to experience significant strength loss following TKA [46], which is likely driven by decreased activation or disuse. The influence activation plays in plantar flexor strength has been demonstrated in patients after immobilization from ankle fracture [47,48]. Therefore, the significant declines in plantar flexor strength, observed following TKA, could be associated with declines in activation caused by swelling in different lower extremity compartments (e.g., calf and ankle). Swelling in and around the plantar flexor muscles has also been shown to result in fiber swelling and decreased force producing ability [32]. In a similar way, swelling throughout the lower extremity could contribute to the decline in strength of hip extensors and abductors, shown to occur following TKA and known to contribute to functional performance [45,49,50]. While evidence exists to support strength loss throughout the lower extremity following TKA [46], linking this loss to swelling will require investigations of these muscle, but will benefit from measuring swelling using BIA, which captures swelling throughout the entire limb.

Secondary hypotheses are that swelling impairs the quadriceps muscles by reducing submaximal force steadiness [51], rate of torque development, [52] and/or eccentric control [53], all of which may be impacted following surgery and may impair functional performance. Swelling may also alter functional recovery by contributing to factors such as limited joint mobility [8], decreased proprioception [54], or increased pain [55]. Specifically, early after surgery decreased ROM has been shown to correlate with slower TUG times [8]. Future work should examine these relationships and test whether they may mediate or moderate the relationship between swelling and functional performance.

This study has limitations that require further examination. The time points for strength assessment were chosen because the authors believed they would provide both an early and later assessment of strength outcomes and would capture swelling when it was greatest and most likely to contribute to strength loss. However, the lack of strong relationships between swelling and strength may be partially explained by the chosen time points that also did not account for time of day of swelling assessment. Two weeks following surgery patients are likely to be influenced by a number of factors that can lead to decreased strength or an inability to accurately perform strength assessments. These factors include pain, fatigue, stiffness, and fear of movement. Unfortunately, this study was not designed to examine all of these factors. Additionally, by using the linear interpolation method for calculating missing swelling values there is a potential that in some cases swelling may have been under estimated, potentially influencing the observed relationship between cumulative swelling and the outcomes. Secondarily, this analysis was limited by a small sample, reducing the number of covariates from what had been used previously [20]. Lastly, bioelectrical impedance assessment is a reliable and precise way of measuring swelling, but this measure captures changes across the entire lower extremity. This could lead to inaccurate representation of the swelling in the knee joint capsule—the location where swelling is most likely to contribute to AMI of the quadriceps and may explain the small affect detected between swelling and strength.

5. Conclusion

Total knee arthroplasty is the most commonly performed elective orthopedic surgery in the United States, and improving outcomes following TKA remains an important priority for clinicians and patients. While the post-TKA recovery is complex and associated with a number of factors, findings from past studies and this current study indicate that managing swelling following TKA may lend itself to improved outcomes. Specifically, this study has shown a strong relationship between peak swelling and TUG times at both two and six weeks following surgery. Peak swelling provides an ideal clinical target for management due to its time course and explicit value. Recent evidence suggests that peak swelling typically occurs between days six and 10 following surgery [56]. Intervention approaches designed to target peak swelling during this window may improve patient functional performance during the early and longer term following surgery.

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Conflict of interest statement

None of the authors report any conflicts of interest related to the submitted work titled “THE RELATIONSHIP BETWEEN SWELLING, QUADRICEPS STRENGTH, AND FUNCTIONAL PERFORMANCE FOLLOWING TOTAL KNEE ARTHROPLASTY”.

This study was approved by and followed all ethical standards of the Colorado Multiple Institutional Review Board (COMIRB #15-1419).

Ethical statement

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