doi:10.4085/1062-6050-0294.24

The relationship between knee joint effusion and quadriceps strength and activation after anterior cruciate ligament (ACL) injury and reconstruction.

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ABSTRACT

Context: Knee joint effusion and quadriceps strength and activation deficits are common consequences of anterior cruciate ligament (ACL) injury and reconstruction. The presence of an effusion may initiate or worsen the quadriceps dysfunction present after ACL trauma. In simulated effusion studies, evidence indicates an inverse relationship between effusion size and quadriceps dysfunction. While this relationship was not found in patients after ACL injury, prior research was limited by a subjective clinical assessment of effusion grade. **Objective:** The purpose of this study was to determine if the size of the knee joint effusion, measured via ultrasound, after ACL injury and reconstruction influences quadriceps strength and activation. **Design:** Descriptive Laboratory Study. **Setting:** Research Laboratory. **Patients or Other Participants:** 41 individuals (23 females, age=21.8±7.5years, height =171.7±7.9cm, mass =72.3±14.2kg), with an ACL injury reported for 2 sessions [one before reconstruction and one ~16 weeks after ACL reconstruction]. **Main outcome measures:** Three ultrasound images of the suprapatellar pouch and three trials of quadriceps strength and activation using the interpolated twitch technique were gathered from the ACL knee. Effusion cross-sectional area was measured using ImageJ, averaged and inputted into linear regression models to predict muscle strength and interpolated twitch activation. Analyses were considered significant at $p \leq 0.05$. **Results:** No relationship was found between effusion size and strength ($R^2 = 0.086$) or activation ($R^2=0.056$) after ACL injury ($p>0.05$). After reconstruction, however, there

was a small negative relationship between effusion size and activation (R^2=0.122; Standardized β=−0.349; p=0.025), while no relationship was found for effusion size and strength (R^2=0.000; p>0.05). **Conclusion:** The size of the effusion after ACL injury does not influence strength or activation. However, after ACL reconstruction, effusion size does have a small influence on quadriceps activation, with a larger effusion being related to lower activation. Prior research using simulated effusions appear to overestimate the effects of effusion on quadriceps function.

Key Terms: Swelling, Voluntary Activation, ITT, Muscle and Arthrogenic Muscle Inhibition

Word Count: 292

Manuscript Word Count: 2,890

Key points:

- Knee joint effusion, quantitatively assessed with ultrasound imaging, is not associated with quadriceps activation or strength after ACL injury
- A small negative relationship (i.e., larger effusions are related to less quadriceps activation) exists after ACL reconstruction.

INTRODUCTION

Quadriceps muscle strength is often drastically reduced after anterior cruciate ligament (ACL) rupture[1] and reconstruction[2,3]. Poor quadriceps strength prior to surgery is linked to poor strength and functional outcomes after surgery.[4,5] Further, weak quadriceps musculature after surgical reconstruction has not only been associated with short-term functional limitations[6] but also the development of post-traumatic osteoarthritis[7], which leads to long-term pain and dysfunction and currently has no cure. As such, understanding factors that lead to quadriceps weakness after ACL injury and reconstruction is paramount to combatting both its acute and chronic sequelae.

One mechanism by which quadriceps weakness develops after injury is via arthrogenic muscle inhibition (AMI) or a diminished ability to voluntarily activate the quadriceps.[8] AMI is thought to originate secondary to damage or altered signaling from joint mechanoreceptors resulting from direct trauma caused by the injury or surgery itself and/or from the pain, effusion, or inflammation occurring secondary to the trauma. AMI can contribute to profound muscle weakness and is an obstacle for rehabilitation, as it impairs force output during voluntary contraction rendering active exercise as a less potent stimulus for inducing strength gains.[9]

AMI can be artificially induced in the quadriceps muscle using a simulated knee effusion model, whereby sterile saline is injected into the knee joint capsule.[10-12] Simulated effusions greater than 20mL in size produce some level of quadriceps muscle shutdown immediately after induction.[13] This is thought to occur because of the pressure induced

by the saline in the joint capsule, triggering a mechanoreceptor response. Because these simulated effusions have the capability of inducing AMI, it has been assumed that effusions associated with joint injury, such as after an ACL injury or surgery, also lead to AMI. However, only one study has been done in ACL patients and the results refute this assumption. Lynch et al.[14] found that effusion size (measured/graded using the stroke/sweep test) was not correlated to AMI in patients that had sustained an ACL rupture. This finding would suggest that effusions, whether small or large, did not result in AMI in their study population. While these results are interesting, they are limited, in part, by how effusion was measured. The stroke test is a clinical examination technique and raters must subjectively assess effusion grade based on the size of the "bulge" produced during the test. A more quantitative approach, such as using ultrasound to image and calculate the cross-sectional area of the supra-patellar pouch, should allow for better sensitivity with regard to effusion size.[15] Furthermore, the work by Lynch et al.[14] only examined persons before any surgical intervention and it remains unknown if effusion size is related to AMI or quadriceps strength after ACL reconstruction. Therefore, the purpose of this study is to determine if the size of the suprapatellar knee joint effusion, measured via ultrasound, after ACL injury and reconstruction influences quadriceps AMI and strength. We hypothesized that greater suprapatellar joint effusion would be associated with greater quadriceps AMI (evaluated via the interpolated twitch technique) and lesser isometric quadriceps strength in the ACL reconstructed limb.

MATERIALS AND METHODS

Study Design

This is a longitudinal, cohort study where individuals who had sustained an ACL tear completed two testing sessions. One session occurred prior to surgery (PRE; within 90 days of injury) and the other occurred approximately four months after surgery (POST4M). At both visits, ultrasonographic effusion measurements, isometric quadriceps strength testing, quadriceps muscle activation testing, and patient-reported outcomes were gathered.

Participants

Forty-one individuals, aged 14-45 years old, who had experienced an ACL injury and were planning to undergo ACL reconstruction were recruited from a local sports medicine clinic following confirmation of injury via magnetic resonance imaging (Table 1). An a priori power calculation for simple linear regression (i.e., predictor variable = 1) in G*Power using an f2 effect of 0.25 and a statistical power of 0.8 indicated that 34 subjects would be needed to demonstrate a significant relationship at an alpha level of 0.05. Individuals were included in this study if they had sustained a primary unilateral ACL tear and were planning to use an ipsilateral autograft (bone-patellar-bone, hamstring, or quadriceps tendon) for their ACL reconstruction. Individuals were excluded if they: 1) sustained greater than a grade 3 concomitant collateral ligament injury indicating the need for a multi-ligamentous reconstruction, 2) experienced a knee dislocation at the time of their ACL injury, 3) underwent a knee aspiration following their ACL injury, and/or 4) were greater than 90 days from their injury at the time of recruitment.

Knee Effusion

Upon arriving to the lab, all participants lied supine on a table with the knees extended for 15 minutes prior to any images being recorded. After which, we placed a bolster under the knee providing 30° of knee flexion[16] in preparation for images to be recorded. A 12Mhz linear transducer connected to a ultrasound unit (Logiq e, General Electric, Waukesha, WI) was then placed longitudinally, approximately 2cm proximal to the patella to view the suprapatellar pouch (SPP) (Figure 1). The transducer settings were set to a gain of 50dB, a frequency of 17 Hz, and a depth of 4.5cm.[17] The ultrasound probe was placed as lightly as possible on the skin to avoid deforming the area. Three images of the SPP were taken on the ACL and contralateral limbs (contralateral limb data not reported). Two raters with 3+ years of ultrasound experience collected all the images for this study. The rater that collected the baseline image of a given participant always collected the 4-month image of the same participant.

DICOM images were then exported from the ultrasound machine and processed in Image J (National Institutes of Health). Echo-free space was measured (mm^2) and used to determine the cross-sectional area of the SPP (Figure 1). The areas of each of the three images were then averaged together. A single member of the study team was responsible for calculating the knee effusion area of the SPP from all images. The tracing of the knee effusion area was then confirmed by a senior team member. When there was disagreement between the team members, they met, discussed, and came to an agreement on the image measurements. The inter-rater reliability for our two raters was high ($ICC_{2,1}$ = .981; CI = .455, 1.00) suggesting strong agreement for measuring SPP effusion on our US images.

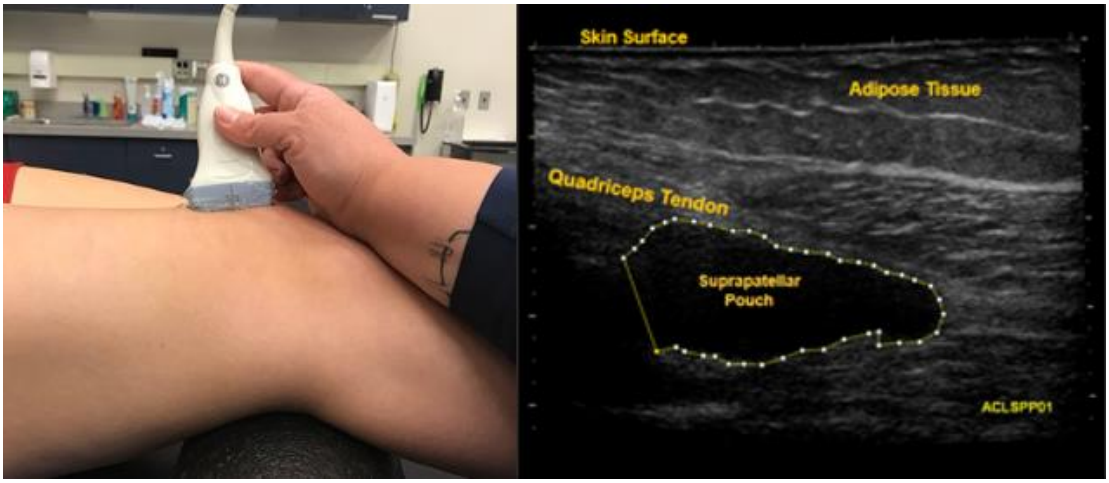
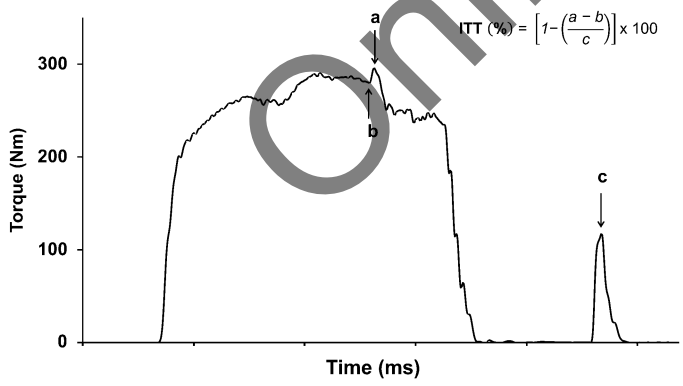


Figure 1.

Quadriceps Strength and Activation

Individuals completed isometric quadriceps strength testing and quadriceps voluntary muscle activation testing (a measure of AMI) using the interpolated twitch technique.[18] Briefly, individuals were seated in an isokinetic dynamometer (Humac NORM; CSMI, Stoughton, MA) per manufacturer guidelines, with their ACL leg positioned at 60º of flexion. Individuals were then outfitted with two self-adhesive electrodes, (2.75x5in Dura-Stick Chattanooga Group) one to the proximal vastus lateralis and the second to the distal vastus medialis. A series of warm-up trials at 25%, 50%, 75%, and 100% of perceived maximal effort with a 1-minute rest between efforts were completed. Individuals were then oriented to the electrical stimulus via the Digitimer DS7AH constant current stimulator with (Digitimer Ltd., Hertfordshire, UK) low intensity pulse trains (100Hz, 200-μs pulse duration, 3 pulse train, 400V, current intensity females: 290 mA, males: 360mA).[18] Participants were then instructed to perform three maximal voluntary isometric contractions (MVIC), lasting approximately five seconds each. During each MVIC, individuals would receive an electrical stimulus delivered via an automated torque-based triggering approach through a custom written LabVIEW

147 program (LabVIEW 11.0; National Instruments Corp., Austin, TX).[19] Following relaxation
148 from the first MVIC, an identical electrical stimulus was delivered to obtain a potentiated
149 evoked torque at rest (resting twitch torque). Individuals completed three MVICs and
150 muscle activation trials. Verbal encouragement and real-time feedback were provided
151 during each contraction.
152 The peak value from the isometric torque curve prior to the delivery of the interpolated
153 twitch was recorded as the MVIC and normalized to body mass. A limb symmetry index
154 (LSI) was also calculated for the MVIC ((ACL MVIC/Non-ACL MVIC)*100). The
155 superimposed twitch torque was recorded as the additional torque recorded after the
156 electrical stimulus was delivered, and the resting twitch torque was recorded as the
157 peak torque following the delivery of the resting twitch electrical stimulus. Overall
158 muscle activation was calculated as: % Muscle Activation = (1 − [superimposed twitch
159 torque / resting twitch torque]) × 100 (Figure 2). The average of the three trials is
160 reported for muscle activation, MVIC, and LSI.



161

162 **Figure 2.**

163 *Knee Osteoarthritis and Outcomes Scale (KOOS)*
164
165 The KOOS[20] was assessed at both study time points. This patient reported outcome
166 measure consists of 5 subscales: 1) Pain; 2) Other symptoms; 3) Function in daily

living; 4) Function in sport and recreation; and 5) Knee related quality of life. Standardized answer options are given (5 Likert boxes) and each question is assigned a score from 0 to 4. A normalized score (100 indicating no symptoms and 0 indicating extreme symptoms) is calculated for each subscale. Each KOOS subscale score was calculated and reported descriptively in Table 1.

Statistics

Four linear regression models were run in SPSS (Version 29, IBM Corp., Armonk, NY) to determine the relationship between effusion and strength and activation before and after ACL reconstruction. Effusion was entered as the independent variable and normalized MVIC or interpolated twitch activation ratio were inputted as the dependent variable. Supplementary multiple linear regression models were run to determine the relationship between KOOS pain score, effusion, and strength. Paired t-tests were done to determine differences pre-to-post ACL reconstruction for effusion size, normalized strength, LSI, activation, and KOOS pain. Analyses were considered significant at $p < 0.05$

RESULTS

Demographic data for participants and descriptive data for average strength, activation and effusion size can be found in Table 1. The values for each trial of activation and strength can be found in Appendix 1. Two of the 41 participants were missing strength data at baseline, and therefore, were not included in the baseline regression models.

No relationship was found between effusion size and isometric strength ($R^2 = 0.086$; $p = 0.068$) or activation ($R^2 = 0.056$; $p = 0.165$) prior to ACL reconstruction (Figure 3). After

reconstruction, however, there was a small relationship between effusion size and activation (R^2 = 0.122; Standardized β = -0.349; p = 0.025), while no relationship was found for effusion size strength (isometric R^2 = .000; p = 0.935) (Figure 4). Multiple linear regression models which considered pain and effusion on strength and activation revealed similar findings reported to the simple linear regression models above, whereby no relationships were noted between the variables prior to ACL reconstruction (p > 0.05), but after ACL reconstruction the model was significant for activation (R^2 = .157; Unstandardized β for pain = 0.27 and p = 0.22 ; Unstandardized β for effusion = -0.10 and p =.04), but not strength (Appendix 2). The size of the effusion and the quadriceps LSI decreased after ACL reconstruction compared to baseline (p < 0.05). The KOOS pain score increased significantly from pre-surgery to post surgery (p < 0.001). No significant differences were noted between the normalized ACL leg MVIC (p = 0.13) and quadriceps activation (p = 0.093) between the pre-surgical and post-surgical time points.

Table 1. Relevant Demographic Information for Participants Before and After ACL Reconstruction. Means (SD) unless otherwise denoted.

	PRE-ACL Reconstruction	POST-ACL Reconstruction
N	41	
Age (yrs)	21.44 (7.59) Range: 14-45	
Height (cm)	171.73(7.95) Range: 155.4-192.5	
Mass (kg)	72.21(14.22) Range: 49.7-110.7	

Sex (N)	F = 23 M = 18	
Injury to Pre-ACL testing (days)	46.37(25.69) Range: 16-90	
Surgery to Post-ACL testing (days)		128.74 (12.19) Range: 95-157
KOOS Pain*	74.19(11.90)	83.47 11.57)
KOOS Function in Daily Living	79.84(15.75)	92.51
KOOS Sport & Recreation	36.46(24.96)	44.88(22.40)
KOOS Knee-Related Quality of Life	30.95(16.99)	45.12(19.09)
KOOS – Other Symptoms	68.47(13.48)	80.49(11.98)
Graft Type		Bone Patellar Tendon Bone = 34 Hamstring = 5 Quadriceps = 2
Effusion (mm^2)*	136.18(92.44)	96.48(53.48)
ACL Limb MVIC (Nm/kg)	2.25 (0.73)	2.09 (0.63)
LSI*	83.17 (14.65)	72.22 (11.43)
Quadriceps activation (%)	68.76 (25.53)	69.27 (18.11)

* indicates significant different between pre-and post-ACL reconstruction time points

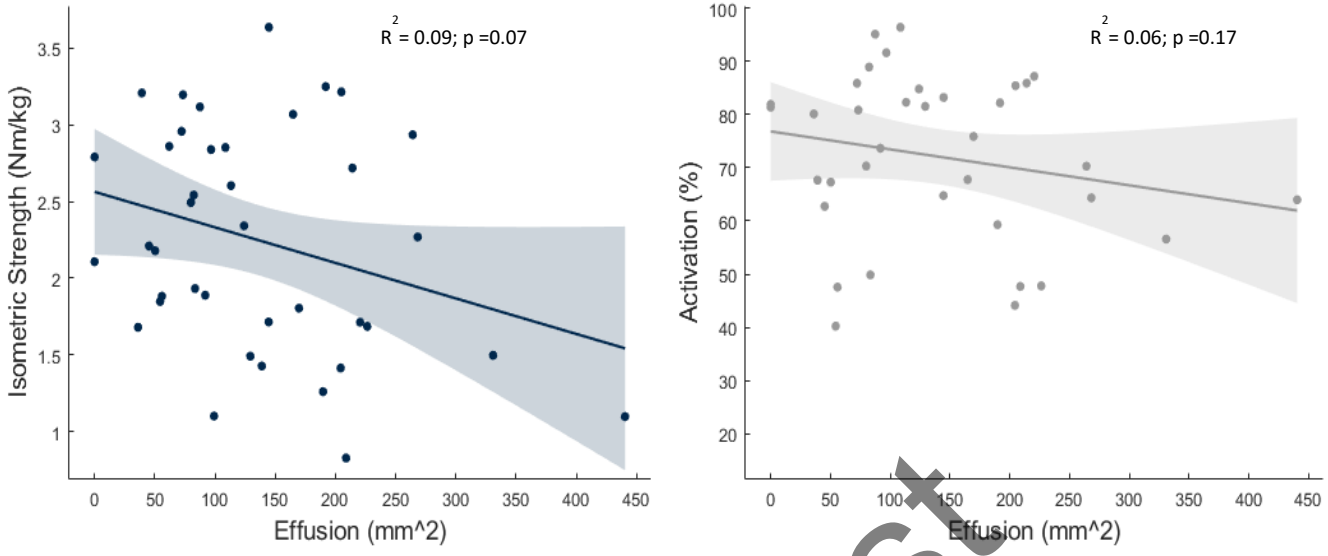


Figure 3.

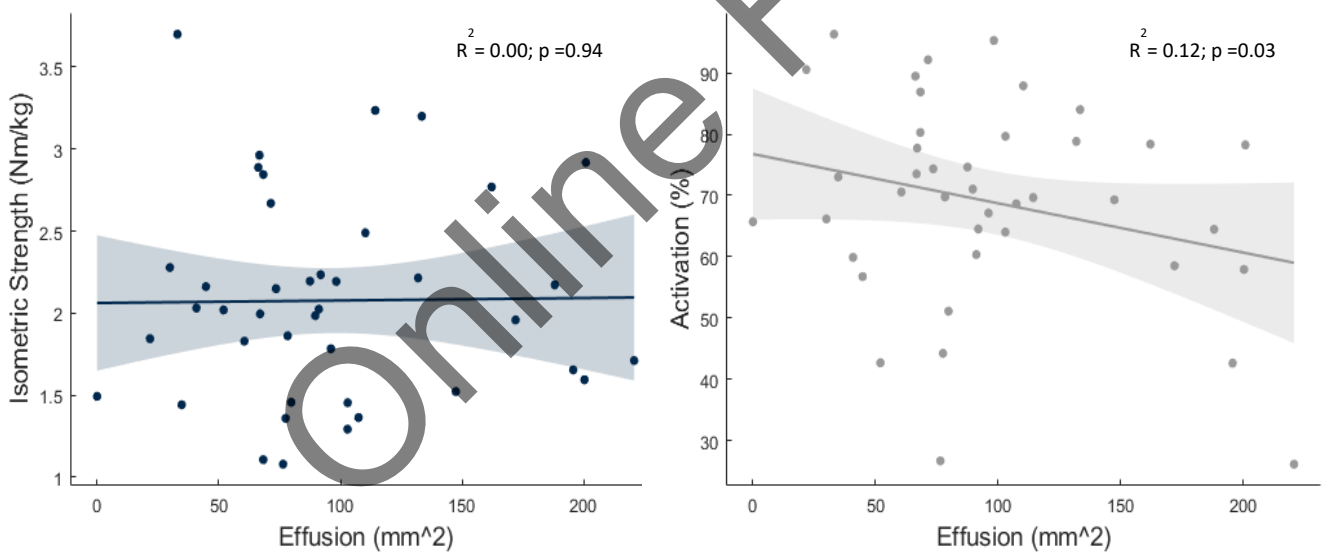


Figure 4.

DISCUSSION

This study aimed to examine the relationship between knee joint effusion size and quadriceps muscle strength and AMI/activation in patients before and after ACL reconstruction. Our results show that the size of the knee joint effusion after ACL injury

did not influence quadriceps strength or activation. However, after ACL reconstruction effusion size did influence quadriceps activation, with a larger effusion being related to lower quadriceps activation/more AMI. We also demonstrated no relationship between effusion size and quadriceps strength after ACL reconstruction.

The finding that knee effusion size is not related to quadriceps strength or activation after ACL injury agrees with prior literature. Work by Lynch et al.[14] showed that in subjects with ACL injury, clinical effusion grade measured by the stroke test was not related to quadriceps activation quantified using the central activation ratio. These results support that effusion grade was not related to the presence of AMI. Lynch et al.[14] also showed that the quadriceps index did not differ among the various effusion grades, suggesting patients with a variety of different effusion sizes (small, moderate, and large) were not different in terms of quadriceps strength. Our findings (and those of Lynch et al.[14]), however, are in conflict with research utilizing experimental effusion models. These experimental effusion studies[10-12] have demonstrated that injecting fluid into an otherwise healthy knee to mimic knee effusion directly results in AMI and strength declines. The neuromuscular response to the experimental effusion is thought to be the result of pressure applied to the mechanoreceptors from the injected fluid[21], and this pressure would also be present with effusions that develop naturally in patients after ACL injury. A likely explanation for the conflict is related to the duration of time the fluid is present in the joint in conjunction with the timing of when measurements were made. In the experimental effusion studies, strength and activation can be captured immediately after the fluid is placed inside the joint capsule, and thus, these studies capture the acute response to the effusion/increase in pressure. However, in the

current study, we are capturing a sub-acute/chronic response to the fluid, as the participants were tested on average 5-6 weeks after sustaining the injury. As such, the fluid inside of the knee joint resulting from the injury may have been placing pressure on the mechanoreceptors for weeks. Thus, the mechanoreceptors likely adapt to that stimulus over time and their response is muted. While there isn't direct evidence to support this claim inside the knee joint, research looking at cutaneous pressure thresholds shows that the greater amount of time pressure is applied to the skin of the hand the greater the pressure threshold becomes and supports our idea that the mechanoreceptors in the knee may blunt their response to longer-term application of pressure.[22] Similarly, it is possible in the days since injury the magnitude of the effusion inside of the knee joint for the ACL patients decreased, thereby resulting in a smaller pressure-inducing stimulus, and a decreased neuromuscular response. Regardless of the reason for the lack of an effect of effusion size on strength and activation, it is apparent that the presence of an effusion after ACL injury is not a major driving factor for initiating AMI or quadriceps strength deficits.

While effusion size was not related to quadriceps activation/AMI (or strength) prior to surgery, it was related to AMI after surgical reconstruction. This relationship, whereby a larger effusion was related to a lower activation ratio or greater AMI, was small however, with effusion size only accounting for about 12% of the variance in the model. It is unclear why effusion would be associated with AMI/activation after surgery, but not after injury (i.e., before surgery). The average size of effusion was greater prior to surgery in our cohort than it was post-surgery and as such, it is unlikely that there is a threshold effect, whereby a certain magnitude of effusion is necessary to induce a neuromuscular

response. Along these lines, it is improbable that firing of the joint mechanoreceptors responsible for pressure sensation (e.g. Ruffini endings) is responsible for the relationship we see between effusion and AMI/activation after surgery given the lack of relationship prior to ACL reconstruction when the pressure in the joint from the effusion should be similar if not greater after injury (given the larger average effusion size at baseline in our cohort). Another plausible explanation could be that pain is heightened after surgery and the firing of free nerve endings in conjunction with the firing of pressure receptors leads to a neuromuscular response/muscle shutdown. The KOOS pain scores are significantly higher after ACL reconstruction in our study group, however, when we explored the addition of pain to the activation regression model after reconstruction (Appendix 2) pain did not contribute significantly, and thus, suggests pain was not relevant to the relationship between effusion and AMI/activation. The only other possibility we can hypothesize is that the content/makeup of the effusion (e.g., the inflammatory markers, etc.) differs before and after ACL reconstruction and thereby alters the body's neuromuscular response leading to AMI. This idea can be supported by some literature which has shown a higher concentration of inflammatory and cartilage breakdown makers in the knee four weeks after ACL reconstruction compared with prior to surgery.[23] However, other research has reported no such differences.[24] It is also possible that this observation could have been influenced by the rehabilitation process, where patients with milder effusion could have been pushed harder to contract their quadriceps muscle maximally than those with larger effusion during the rehabilitation process. More research is necessary to understand why effusion is related to quadriceps AMI/activation after ACL reconstruction. From a clinical standpoint,

however, it is important to discuss that while effusion and activation were related after surgery the relationship was quite small, and thus, interventions that minimize effusion after ACL reconstruction are unlikely to make a substantial impact on the magnitude of AMI in patients who have undergone surgery. As such, researchers should continue to investigate the mechanistic factors that lead to AMI after ACL injury and reconstruction so that targeted intervention approaches can be developed.

This research is not without limitations. First, effusion was measured in the suprapatellar pouch (SPP). The SPP Is only one of several recesses, however, where fluid could collect with an ACL injury. As such, it is important to consider that our US measurements are only reflective of the fluid in the SPP and may not be reflective of entire state of effusion in the knee. Secondly, while US is superior to clinical examination in detecting effusion[25] it is not as strong as MRI[26]. Ultrasound, however, has been reported to have high specificity and sensitivity values of 100% and 66.7% for detecting effusion in the SPP. Additionally, subject characteristics could have influenced our results. For example, the majority of subjects had ACL reconstruction with a patellar tendon autograft and as such these findings might not be relevant to participants with other graft types. Next, the number of days from injury to baseline testing and from surgery to 4-month testing had some variability between subjects which may have also influenced our study outcomes. Lastly, the relationship between effusion and strength may have been different if values were recorded at different times post-injury and post-surgery.

In conclusion, knee joint effusion does not appear to be a driving mechanistic factor leading to quadriceps strength deficits or quadriceps AMI before or after surgery. While

329 a statistically significant relationship was found between effusion and AMI/activation
330 after surgery, this was quite small and its clinical relevance is questionable.
331 Interventions targeting removal or reduction of joint effusion after ACL injury and
332 reconstruction are unlikely to mediate/reduce the quadriceps AMI.
333
334 **REFERENCES**

335 1. Hart JM, Pietrosimone B, Hertel J, Ingersoll CD. Quadriceps activation following
336 knee injuries: a systematic review. *J Athl Train*. Jan-Feb 2010;45(1):87-97.
337 doi:10.4085/1062-6050-45.1.87

338 2. Lisee C, Lepley AS, Birchmeier T, O'Hagan K, Kuenze C. Quadriceps Strength
339 and Volitional Activation After Anterior Cruciate Ligament Reconstruction: A Systematic
340 Review and Meta-analysis. *Sports Health*. Mar/Apr 2019;11(2):163-179.
341 doi:10.1177/1941738118822739

342 3. Palmieri-Smith RM, Thomas AC, Wojtys EM. Maximizing quadriceps strength
343 after ACL reconstruction. *Clin Sports Med*. Jul 2008;27(3):405-24, vii-ix.
344 doi:10.1016/j.csm.2008.02.001

345 4. Logerstedt D, Lynch A, Axe MJ, Snyder-Mackler L. Pre-operative quadriceps
346 strength predicts IKDC2000 scores 6 months after anterior cruciate ligament
347 reconstruction. *Knee*. Jun 2013;20(3):208-12. doi:10.1016/j.knee.2012.07.011

348 5. Riesterer J, Mauch M, Paul J, Gehring D, Ritzmann R, Wenning M. Relationship
349 between pre- and post-operative isokinetic strength after ACL reconstruction using

hamstring autograft. *BMC Sports Sci Med Rehabil*. Oct 30 2020;12(1):68. doi:10.1186/s13102-020-00215-7

6. Hohmann E, Bryant A, Tetsworth K. Strength does not influence knee function in the ACL-deficient knee but is a correlate of knee function in the and ACL-reconstructed knee. *Arch Orthop Trauma Surg*. Apr 2016;136(4):477-83. doi:10.1007/s00402-015-2392-6

7. Tourville TW, Jarrell KM, Naud S, Slauterbeck JR, Johnson RJ, Beynnon BD. Relationship between isokinetic strength and tibiofemoral joint space width changes after anterior cruciate ligament reconstruction. *Am J Sports Med*. Feb 2014;42(2):302-11. doi:10.1177/0363546513510672

8. Pietrosimone B, Lepley AS, Kuenze C, et al. Arthrogenic Muscle Inhibition Following Anterior Cruciate Ligament Injury. *J Sport Rehabil*. Aug 1 2022;31(6):694-706. doi:10.1123/jsr.2021-0128

9. Hurley MV, Jones DW, Newham DJ. Arthrogenic quadriceps inhibition and rehabilitation of patients with extensive traumatic knee injuries. *Clin Sci (Lond)*. Mar 1994;86(3):305-10.

10. Palmieri-Smith RM, Villwock M, Downie B, Hecht G, Zernicke R. Pain and effusion and quadriceps activation and strength. *J Athl Train*. Mar-Apr 2013;48(2):186-91. doi:10.4085/1062-6050-48.2.10

11. Palmieri RM, Tom JA, Edwards JE, et al. Arthrogenic muscle response induced by an experimental knee joint effusion is mediated by pre- and post-synaptic spinal

mechanisms. *J Electromyogr Kinesiol*. Dec 2004;14(6):631-40. doi:10.1016/j.jelekin.2004.06.002

12. Hopkins JT, Ingersoll CD, Krause BA, Edwards JE, Cordova ML. Effect of knee joint effusion on quadriceps and soleus motoneuron pool excitability. *Med Sci Sports Exerc*. Jan 2001;33(1):123-6.

13. Spencer JD, Hayes KC, Alexander IJ. Knee joint effusion and quadriceps reflex inhibition in man. *Arch Phys Med Rehabil*. Apr 1984;65(4):171-7.

14. Lynch AD, Logerstedt DS, Axe MJ, Snyder-Mackler L. Quadriceps activation failure after anterior cruciate ligament rupture is not mediated by knee joint effusion. *J Orthop Sports Phys Ther*. Jun 2012;42(6):502-10. doi:10.2519/jospt.2012.3793

15. Karaszewski W, Pekanovic A, Streich NA, Herbort M, Petersen W, Schmidt-Lucke C. Ultrasonography for quantitative assessment of knee joint effusions-useful tool for objective evaluation of rehabilitation progress? *Int Orthop*. Apr 2023;47(4):955-961. doi:10.1007/s00264-023-05697-x

16. Mandl P, Brossard M, Aegerter P, et al. Ultrasound evaluation of fluid in knee recesses at varying degrees of flexion. *Arthritis Care Res (Hoboken)*. May 2012;64(5):773-9. doi:10.1002/acr.21598

17. Chiba D, Ota S, Sasaki E, Tsuda E, Nakaji S, Ishibashi Y. Knee effusion evaluated by ultrasonography warns knee osteoarthritis patients to develop their muscle atrophy: a three-year cohort study. *Sci Rep*. May 21 2020;10(1):8444. doi:10.1038/s41598-020-65368-4

18. Garcia SA, Rodriguez KM, Krishnan C, Palmieri-Smith RM. Type of measurement used influences central and peripheral contributions to quadriceps weakness after anterior cruciate ligament (ACL) reconstruction. *Phys Ther Sport*. Nov 2020;46:14-22. doi:10.1016/j.ptsp.2020.08.001

19. Krishnan C, Allen EJ, Williams GN. Torque-based triggering improves stimulus timing precision in activation tests. *Muscle Nerve*. Jul 2009;40(1):130-3. doi:10.1002/mus.21279

20. Roos EM, Roos HP, Lohmander LS, Ekdahl C, Beynnon BD. Knee Injury and Osteoarthritis Outcome Score (KOOS)--development of a self-administered outcome measure. *J Orthop Sports Phys Ther*. Aug 1998;28(2):88-96. doi:10.2519/jospt.1998.28.2.88

21. Deandrade JR, Grant C, Dixon AS. JOINT DISTENSION AND REFLEX MUSCLE INHIBITION IN THE KNEE. *J Bone Joint Surg Am*. Mar 1965;47:313-22.

22. van Vliet D, Novak CB, Mackinnon SE. Duration of contact time alters cutaneous pressure threshold measurements. *Ann Plast Surg*. Oct 1993;31(4):335-9. doi:10.1097/00000637-199310000-00010

23. Hunt ER, Jacobs CA, Conley CE, Ireland ML, Johnson DL, Lattermann C. Anterior cruciate ligament reconstruction reinitiates an inflammatory and chondrodegenerative process in the knee joint. *J Orthop Res*. Jun 2021;39(6):1281-1288. doi:10.1002/jor.24783

412 24. Mendias CL, Lynch EB, Davis ME, et al. Changes in circulating biomarkers of
413 muscle atrophy, inflammation, and cartilage turnover in patients undergoing anterior
414 cruciate ligament reconstruction and rehabilitation. *Am J Sports Med*. Aug
415 2013;41(8):1819-26. doi:10.1177/0363546513490651

416 25. Elsawy NA, Ibrahiem AH, Younis GA, Meheissen MA, Abdel-Fattah YH. Clinical
417 examination, ultrasound assessment and aspiration of knee effusion in primary knee
418 osteoarthritis patients. *J Orthop Surg Res*. Jun 10 2023;18(1):422. doi:10.1186/s13018-
419 023-03891-6

420 26. Draghi F, Urciuoli L, Alessandrino F, Corti R, Scudeller L, Grassi R. Joint effusion
421 of the knee: potentialities and limitations of ultrasonography. *J Ultrasound*. Dec
422 2015;18(4):361-71. doi:10.1007/s40477-015-0180-3

423 **Legends to Figure**

424 **Figure 1.** Placement of ultrasound probe to obtain knee effusion images (left).
425 Ultrasound image of the suprapatellar effusion (right).

426 **Figure 2.** Representative maximal voluntary isometric contraction (MVIC) trial during
427 activation testing. Letter b represents the time where the stimuli are applied at the peak
428 of the MVIC. Letter a shows the increase in torque that resulted from the stimuli. Letter
429 c represents the resting twitch torque.

430 **Figure 3.** Scatterplots depicting the relationship between effusion and quadriceps
431 isometric strength (left) and effusion and quadriceps activation
432 (right) in study participants after ACL injury.

433 **Figure 4.** Scatterplots depicting the relationship between effusion and quadriceps
434 isometric strength (left) and effusion and quadriceps activation(right) in study
435 participants after ACL reconstruction.

Appendix 1. Average Quadriceps Strength and Activation Data for Each of the Three Trials Recorded During Testing Before and After ACL Reconstruction. Reported as Mean (SD).

	PRE-ACL Reconstruction	POST-ACL Reconstruction
ACL Leg MVIC Trial 1	2.14 (0.73)	2.08 (0.63)
ACL Leg MVIC Trial 2	2.25(0.75)	2.06 (0.65)
ACL Leg MVIC Trial 3	2.23(0.74)	2.02 (0.62)
Quadriceps activation (%) Trial 1	66.94(28.45)	71.56(19.91)
Quadriceps activation (%) Trial 2	69.61(24.17)	68.13(19.28)
Quadriceps activation (%) Trial 3	67.96(27.86)	66.73(19.16)

Appendix 2. Scatterplots depicting the relationship between the unstandardized predicted value for KOOS pain score and effusion and its relationship to pre-ACLR quadriceps isometric strength (top left), pre-ACLR quadriceps activation (top right),post-ACLR quadriceps isometric strength (bottom left) and post-ACLR quadriceps activation.(bottom right).