


Differences in psychological readiness for return to sport after anterior cruciate ligament injury is evident in thigh musculature motor unit characteristics

Nathan D Schilaty ^{1,2,3,4}, April L McPherson,^{4,5,6} Takashi Nagai,^{4,7}
Nathaniel A Bates^{4,5}

To cite: Schilaty ND, McPherson AL, Nagai T, *et al.* Differences in psychological readiness for return to sport after anterior cruciate ligament injury is evident in thigh musculature motor unit characteristics. *BMJ Open Sport & Exercise Medicine* 2023;**9**:e001609. doi:10.1136/bmjsem-2023-001609

► Additional supplemental material is published online only. To view, please visit the journal online (<http://dx.doi.org/10.1136/bmjsem-2023-001609>).

Accepted 26 June 2023



© Author(s) (or their employer(s)) 2023. Re-use permitted under CC BY-NC. No commercial re-use. See rights and permissions. Published by BMJ.

For numbered affiliations see end of article.

Correspondence to
Dr Nathan D Schilaty;
nschilaty@usf.edu

ABSTRACT

Background Following anterior cruciate ligament (ACL) injury, many athletes that undergo surgery and 6–9 months of rehabilitation struggle to return to sport. Evidence suggests that psychological factors contribute to this failure to return-to-sport.

Objective Determine the motor control relationship between thigh musculature motor unit characteristics and psychological readiness to return to sport between ACL-injured and healthy controls.

Study design A longitudinal cohort study.

Methods Athletes longitudinally completed the ACL Return to Sport after Injury (ACL-RSI) survey and isometric strength measures with a measurement of electromyography (EMG) of the vastus lateralis, vastus medialis, biceps femoris, and semitendinosus. A score cut-off of 61 on the ACL-RSI was used to divide ACL-injured groups. EMG was decomposed to provide each identified motor unit's characteristics (amplitude, average firing rate, etc).

Results Data demonstrated increased average firing rate for hamstrings ($p < 0.001$), decreased average firing rate for vastus lateralis ($p < 0.001$) and decreased motor unit size for both the quadriceps and hamstrings at return-to-sport post-ACL reconstruction compared with sex-matched and age-matched healthy controls ($p < 0.001$). Furthermore, there were marked differences in disparate ACL-RSI scores between ACL-injured athletes.

Conclusions At return to sport, ACL-injured athletes have major alterations of thigh musculature motor control, with smaller motor units used by those with low ACL-RSI scores. This study uniquely demonstrates objective thigh muscle motor unit characteristics that coincide with subjective reports of psychological readiness. This information will be important to address psychomotor complexes of injury for future rehabilitation protocols.

INTRODUCTION

Following anterior cruciate ligament (ACL) injury, ACL reconstruction (ACLR) and rehabilitation, only 33%–61% of athletes return to their same level of play.^{1–4} Despite rehabilitation, quadriceps strength deficits persist after ACL injury and ACLR.^{3 5 6} Knee joint trauma

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Some athletes fail to return-to-sport after anterior cruciate ligament (ACL) injury due to psychological issues, including kinesiophobia, anxiety and confidence. This study explores associations between psychological components and associated objective data of thigh musculature motor units (MUs).

WHAT THIS STUDY ADDS

⇒ Our study links subjective psychological outcomes with objective motor output. We demonstrate the underlying changes that have occurred in the musculature that is associated with these psychological outcomes.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Dramatic neuroplasticity of the synaptic region occurs in thigh musculature due to ACL injury. Our results may support future personalised rehabilitation that targets MU activation and provide objective effectiveness of psychological counselling to recover from traumatic injury.

induces a presynaptic reflex inhibition of musculature surrounding the joint, termed arthrogenic muscle inhibition (AMI).^{6 7} This inhibition is initially protective of the joint as deactivation of the muscle can protect the joint from large forces; however, AMI ultimately prevents complete muscle activation and can impede recovery and return to sport (RTS).⁶ The mechanism for persistent muscular strength deficits remains unclear and could be due to sensorimotor or psychological corticomotor inhibition. A plethora of data demonstrates that many athletes report fear of RTS after ACL injury.^{1 8–18} Furthermore, fear of re-injury is highly associated with secondary injury.^{1 9 13 17} Fear of re-injury could be attributed to decreased activation of the musculature or contrarily, fear could induce cortical inhibition of voluntary strength and motor unit (MU) activity.

Regardless of the causation of lowered muscle activation, it is evident that psychological readiness is an important factor for RTS.^{13 18 19}

Psychological responses to injury include fear of re-injury,^{8 9 16 17 20 21} lack of self-confidence,²² kinesiophobia,^{9 12 17 20} depression^{23 24} and anxiety.^{22 25 26} Psychological readiness for RTS after ACLR is commonly assessed with the ACL Return to Sport after Injury (ACL-RSI) survey,^{27 28} a validated questionnaire to measure psychological responses, particularly confidence in the injured body part and risk appraisal.²⁸ As psychological readiness may affect motor control (CTRL), potentially with the induction of neuroplasticity,^{29 30} it is vital to understand the motor CTRL deficits related to these psychological responses. In addition, combining objective measures that correlate with subjective questionnaires is vital for appropriate clinical care decisions.³¹ Future patient-centric health approaches will require holistic integration of physical, psychological, cultural and metaphysical dimensions.³² Thus, it is important to characterise the function of MUs with psychological readiness.

This work aimed to assess the effect of psychological readiness for RTS with measures of motor CTRL. Understanding motor CTRL characteristics is vital to avoid future injury occurrences (and potentially primary injury). Approximately 1 in 3 ACL-injured individuals will suffer a secondary ACL injury within 2 years, wherein both ipsilateral and contralateral limbs are at risk.^{33 34} Furthermore, individuals with a smaller increase in ACL-RSI scores were more likely to experience a second ACL injury.¹³ Contrarily, another study with a smaller sample size has also demonstrated that females with higher ACL-RSI scores were more likely to have a second ACL injury.³⁵ Thus, with the discrepancy of ACL-RSI scores with re-injury, this study was uniquely designed to differentiate objective MU characteristics of thigh musculature between those with disparate ACL-RSI scores (RSI-high and RSI-low) at 6 months and 12 months post-injury and healthy CTRLs.^{31 36}

This study aimed to determine the relationship of a subjective psychological readiness metric to RTS to objective measures of bilateral motor CTRL. Specifically, we measured MU common drive, MU recruitment, MU rate coding, MU action potential (MUAP) peak-to-peak amplitude and delta frequency (ΔF).^{37 38} The last two metrics are surrogate measures of MU size^{39 40} and synaptic activity,^{41–43} respectively. We hypothesised that ACL-injured athletes with lower ACL-RSI scores would recruit smaller MUs and have increased synaptic neuromodulation (ΔF) values across the recruitment of MUs compared with athletes with higher ACL-RSI scores and CTRLs. Demonstrating objective neural deficits that directly associate with psychological responses may help improve future physical, psychological, and emotional health outcomes.³¹

METHODS

Fifty-six subjects were recruited and consented (see [table 1](#) for demographics). Subject inclusion criteria were healthy, active individuals between the ages of 14 years and 25 years from both sexes. Exclusion criteria were lower extremity injury (other than ACL) or surgery in the past 6 months, neurological disorders, paralysis, neuromuscular disease, cardiovascular disease, exercise-induced injury, asthma and pregnancy. ACL-injured subjects were recruited either before surgery (data captured the day before ACLR; n=25) or at 6 months post-surgery (± 1 month; n=5). Of the ACL-injured subjects, 7 (23%) had experienced a 2nd ACL tear before recruitment, a percentage consistent with existing literature.^{33 44} The ACL-injured participants were followed longitudinally for testing intervals of 6 months (± 1 month), which could include 6 months post-surgery (n=19) and/or 12 months (± 1 month) post-surgery (n=11).⁴⁵ A decrease in numbers longitudinally occurred as a result of attrition. ACL-injured participants that did not return for longitudinal data collection past the ACL pre-surgical data collection were excluded from the analysis.

Anterior cruciate ligament return to sport after injury

The ACL-RSI was administered longitudinally to all subjects at each data collection.²⁷ With the ACL-RSI, a higher score indicates a greater psychological readiness for RTS (scored from 0 to 100). Based on previously published literature, a cut-off score of 61 on the ACL-RSI was used as this was the average 12 months post-ACL injury score for athletes who experienced a second ACL injury.¹⁹ Furthermore, this cut-off value was mid-range to other publications that demonstrated a cut-off score of 55 at 6 months to predict RTS at 1 year⁴⁶ and a cut-off score of 65 at 12 months.⁴⁷

Isometric setup

A custom load cell apparatus (MLP-300; Transducer Techniques, Temecula, CA, USA) was affixed to the dynamometer torque arm (HumacNORM; CSMi, Stoughton, MA, USA) and used to measure the subject's force production required for the electromyography (EMG) software for decomposition (EMGWorks (V.4); Delsys, Boston, MA, USA). For isometric knee extension testing, subjects were seated with their leg at a gravity-selected, comfortable, flexed position. Subjects were secured with straps at the shoulder and waist to minimise whole-body movement during seated testing. For isometric knee flexion testing, subjects were prone with their leg positioned at 30° knee flexion (0°=full extension) and strapped to the dynamometer arm. A randomised protocol was generated for each subject to determine the test order. Limb side (right vs left), muscle group (hamstring vs quadriceps) and order of trials (10%–50%) were all randomised.

Maximal voluntary isometric contraction (MVIC)

Before data acquisition, subjects were allowed to walk on a treadmill at their own self-selected pace for at

Table 1 Population demographics (divided by sex and group)

		Height (cm)	Mass (kg)	Age (years)	Activity level	Graft type	ACL-injured (n)	Non-contact mechanism of injury (n)	
Sex	M (n=19)	180.5±6.1	79.5±13.9	18.8±2.9	Comp: 13 Rec: 6 Sed: 0	AutoBTB: 6 AutoHam: 2 Allo: 0 None: 11	8	6 (75%)	
	F (n=24)	168.6±6.7	66.7±13.8	19.0±3.3	Comp: 13 Rec: 10 Sed: 1	AutoBTB: 7 AutoHam: 3 Allo: 1 None: 13	11	8 (73%)	
	Significance	<0.001	0.005	0.837	0.627	1.000	0.807	0.912	
Group	CTRL (n=24)	174.0±8.7	68.2±13.4	18.9±3.1	Comp: 13 Rec: 11 Sed: 0	---	---	---	
	Significance	0.903	0.039	0.932	0.265				
	ACL-injured	RSI-low (n=9)	175.5±5.5	84.9±9.6	20.0±3.3	Comp: 5 Rec: 4 Sed: 0	AutoBTB: 6 AutoHam: 2 Allo: 1	9	6 (66%)
		RSI-high (n=10)	172.0±11.4	71.2±18.0	18.1±2.8	Comp: 8 Rec: 1 Sed: 1	AutoBTB: 7 AutoHam: 3 Allo: 0	10	8 (80%)
Significance	0.402	0.058	0.197	0.211	1.000	---	0.510		

Significant p-values are indicated in bold.
 ACL, anterior cruciate ligament; Allo, allograft; AutoBTB, autograft bone–tendon–bone; AutoHam, autograft hamstring; Comp, competitive; CTRL, control; Rec, recreational; RSI, return to sport after injury; Sed, sedentary.

least 5 min. Three isometric knee flexion and extension maximal voluntary isometric contractions (MVICs) were performed first to determine the force associated with 100% effort from each subject. From this MVIC, 5 levels of effort were extrapolated (0%, 10%, 25%, 35% and 50% MVIC) for each leg. Each trial was repeated two times to coordinate MU CTRL with ultrasound stiffness (separate study).⁴⁵ Subjects were verbally encouraged to ‘push as hard as possible’ for 3 s and were permitted to view the computer monitor during the MVIC trials for visual feedback and motivation. After MVICs, the randomised protocol was followed to complete the 10 %MVIC effort trials. Each test followed a trapezoidal waveform (3-second ramp up, 10-second sustained contraction and 3-second ramp down) in which the sustained contraction was at the designated %MVIC. The subject was instructed to follow the trapezoid waveform as closely as possible, with real-time visual feedback of the force production displayed on a computer monitor.

EMG and decomposition

Surface five-pin array electrodes (Delsys, Natick, MA, USA) were placed on the muscle belly of the vastus medialis (VM), vastus lateralis (VL), semitendinosus (ST) and biceps femoris (BF) muscles according to SENIAM standards.⁴⁸ Before electrode placement, the skin was shaved and cleansed with an alcohol swab to ensure adequate

skin–electrode contact and enhance the signal-to-noise ratio.

EMG decomposition was calculated via post-processing to obtain MU characteristics (dEMG Analysis, Delsys, MA, USA).^{49–51} Identified MUs that were ≥90% accuracy were included for further evaluation. Data variables extracted for MUs included: MUAP, average firing rate (AvgFR), interpulse interval, initial firing rate (FR), terminal FR, interpulse-interval coefficient of variation and common drive coefficient.⁵¹ The common drive coefficient is an assessment of coherence cross-correlation and was calculated according to methods already published^{52 53} during the hold phase of the isometric contraction. Recruitment thresholds (%MVIC and time of MU recruitment) were also extracted.

ΔF was calculated with custom LabVIEW software (NI, Austin, TX) according to the description in the literature.^{41 43 54 55} Briefly, ΔF values were calculated for every possible pair of MUs in each contraction for a designated ‘CTRL MU’ and every other MU treated as a ‘test MU’. The instantaneous FRs of both MUs were smoothed by fitting a fifth-order polynomial, and the ΔF values were calculated on the polynomials by taking the difference between the values of the CTRL MU at recruitment and derecruitment of the test unit. ΔF is a paired MU analysis and an indirect technique for estimating synaptic activity due to the magnitude of persistent inward currents

(PICs) in human motor neurons.⁴³ For ΔF analysis, MUs were only included that achieved $\geq 0.5 R^2$ values with the referent MU and ≥ 0.5 impulses/s.^{41 43 56}

Rehabilitation protocol

For rehabilitation, each subject followed the standard of care protocol at Mayo Clinic and the treatment recommendations of their respective physical therapist. The researchers did not influence any of the physical therapy recommendations. All the athletes were allowed to RTS between 9 months and 11 months once they achieved the standard of care thresholds of the medical team (physical therapist and orthopaedic surgeon).

Data analysis

All statistical analyses were performed with JMP V.16 Pro (SAS Institute, Cary, NC, USA). Inferential statistics were calculated for sex and group via Student's t-test and Fisher's Exact test and reported as mean (SD) or *n* values (table 1). As MU strategies are non-linear,^{36 57} log (MUAP) and cube root (common drive coefficient and recruitment threshold) transformations were used to provide parametric data for linear regressions (as parametric data are a statistical assumption for linear analysis). In addition, we performed an interaction of AvgFR \times log (MUAP) by recruitment to demonstrate total 'MU force contribution'. Both common drive coefficient and ΔF were normalised to %MVIC. Least-square means were reported as summary data between subjects and group (CTRL, ACL-injured with ACL-RSI $<$ 61 (RSI-low), ACL-injured with ACL-RSI \geq 61 (RSI-high)). For MUAP, the data were normalised to mass as MU size is affected by body size.⁵⁸ We were specifically interested in RTS for ACL-injured (typically 9–11 months), so the 6-month and 12-month visit data were used for the analysis. This criterion excluded the pre-surgical time point and thus excluded some of the original subjects from the study (table 1). Linear regressions with Tukey's least squares means, and analysis of variance (ANOVA) with Tukey's post hoc comparisons were used for statistical assessment. If the data were non-parametric, Kruskal-Wallis rank sums were performed with Steel-Dwass post hoc comparisons. Significance was set a priori at $p < 0.05$.

RESULTS

From the complete dataset, there were 41 473 MUs identified. However, with RTS being the primary focus of this study, the ACL pre-surgery visit was excluded, resulting in a dataset of 29 800 MUs for CTRLs and 6-month and 12-month measures from ACL-injured. For sex or group (table 1), there were no differences between age, activity level, graft type or activity level by graft type ($p=0.165$). There were differences in mass for both sex and group and differences in height and mass for sex (table 1). Time from surgery for all ACLR was a median of 37 days (25 days, 94 days).

Maximal voluntary isometric contraction

For the quadriceps, the MVIC was highest for RSI-low (570 (IQR: 445, 786) N), which was not different from

RSI-high (524 (420, 729) N; $p=0.167$), and both were different from CTRL (488 (394, 587) N; $p<0.001$). For the hamstrings, the MVIC was highest for RSI-low (335 (260, 417) N), which was not different from RSI-high (334 (248, 385) N; $p=0.401$). However, both were different from CTRL (241 (196, 312) N; $p<0.001$).

MU recruitment thresholds

Median MU recruitment thresholds for the quadriceps for CTRL was 5.2 (1.8, 13.2) %MVIC, which was lower than RSI-high at 7.2 (2.0, 14.9) %MVIC ($p<0.001$). RSI-high was also higher than RSI-low at 5.3 (1.6, 14.5) %MVIC ($p<0.001$). For the hamstrings, CTRL was 10.6 (3.3, 22.2) %MVIC, which was higher than RSI-High at 9.9 (3.0, 20.1) %MVIC ($p=0.03$). Neither group differed from RSI-low at 10.5 (3.8, 20.6) %MVIC.

MU rate coding

AvgFR was observed for each of the four major thigh muscles (ie, VL, VM, BF and ST) with a linear relationship. For the VL, all groups were different from one another ($p<0.001$), with CTRL (16.3 \pm 0.2 pulses per second (pps)) having the highest AvgFR, followed by RSI-low (15.5 \pm 0.2 pps) and RSI-high the lowest AvgFR at (14.3 \pm 0.2 pps; figure 1). There were no differences between groups for the VM: 16.1 \pm 0.2, 16.5 \pm 0.2 and 16.1 \pm 0.2 pps for RSI-high, RSI-low, and CTRL, respectively ($p>0.069$; figure 1). For the BF, both RSI-low (17.0 \pm 0.2 pps) and RSI-high (16.1 \pm 0.2 pps) had higher AvgFR than healthy CTRL (15.7 \pm 0.2 pps; $p<0.001$; figure 1). For the ST, both RSI-low (19.0 \pm 0.2 pps) and RSI-high (18.1 \pm 0.2 pps) had higher AvgFR than healthy CTRL (17.5 \pm 0.2 pps; $p<0.001$; figure 1).

MU action potentials

A linear regression of MUAP by recruitment threshold for quadriceps ($R^2=0.46$) revealed differences in all groups ($p<0.001$). For the VL specifically, a linear regression of MUAP by recruitment threshold ($R^2=0.48$) revealed that CTRL had higher MUAP than RSI-low ($p<0.001$) and RSI-high ($p<0.001$; figure 2). RSI-high also had higher MUAP than RSI-low ($p<0.001$). For the VM specifically, a linear regression of MUAP by recruitment threshold ($R^2=0.44$) demonstrated that both CTRL and RSI-high had higher MUAP from RSI-low ($p<0.001$; figure 2). RSI-high also had higher MUAP than RSI-low ($p<0.001$). A linear regression of MUAP by recruitment threshold for hamstrings ($R^2=0.35$) revealed differences for all groups ($p<0.001$). Specifically for the BF, a linear regression of MUAP by recruitment threshold ($R^2=0.33$) revealed that CTRL had higher MUAP than RSI-low ($p<0.001$) and RSI-high ($p<0.001$; figure 2). RSI-high also had higher MUAP than RSI-low ($p<0.001$). Specifically for the ST, a linear regression of MUAP by recruitment threshold ($R^2=0.42$) demonstrated that CTRL had higher MUAP from RSI-low ($p<0.001$) and RSI-high ($p<0.001$; figure 2). RSI-high also had higher MUAP than RSI-low ($p<0.001$).

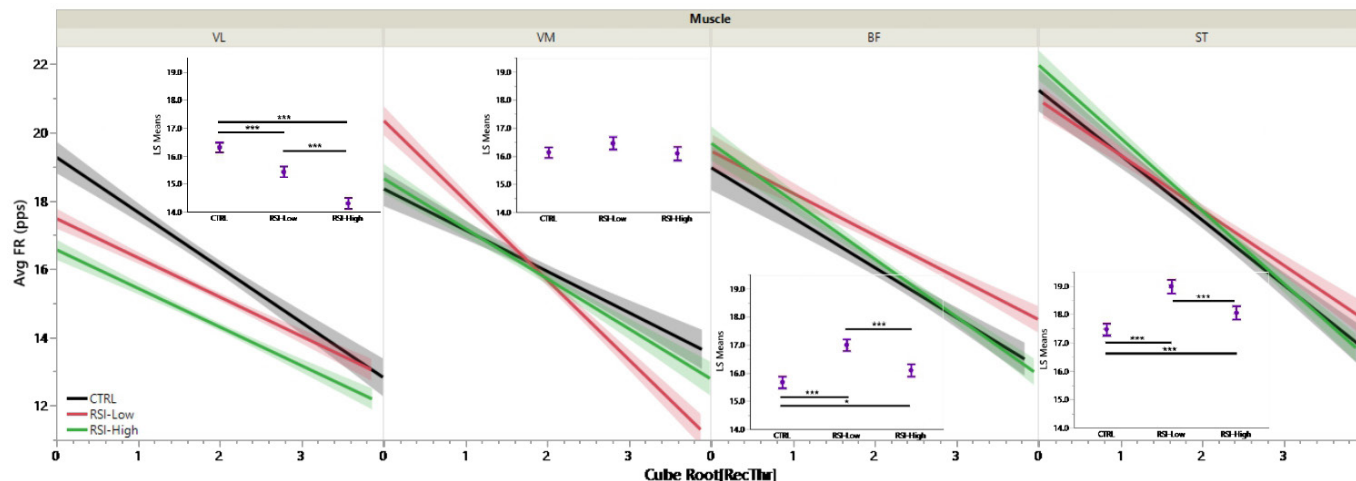


Figure 1 Linear regression of AvgFR by recruitment of thigh musculature at RTS. For the VL, the least squares mean (inset plot) demonstrates that the AvgFR for RSI-low and RSI-high was decreased compared with healthy CTRL. There were no differences between groups for the VM. Both RSI-low and RSI-high were significantly higher than healthy CTRL for the BF. For the ST, RSI-low and RSI-high were significantly higher than healthy CTRL (* denotes $p < 0.05$, *** denotes $p < 0.001$; line shading and error bars denote 95% CI of the mean). AvgFR, average firing rate; BF, biceps femoris; CTRL, control; RSI, return to sport after injury; RTS, return to sport; ST, semitendinosus; VL, vastus lateralis; VM, vastus medialis.

MU total force contribution

A linear regression of MU force contribution by recruitment threshold for quadriceps ($R^2=0.43$) revealed differences for all groups. Specifically for the VL, MU force contribution by recruitment threshold ($R^2=0.43$) revealed that CTRL had a higher MU force contribution than RSI-low ($p < 0.001$) and RSI-high ($p < 0.001$; [figure 3A](#)), with RSI-low being lower than RSI-high ($p < 0.001$). For the VM, MU force contribution by recruitment threshold ($R^2=0.43$) demonstrated the exact relationship as the VL with CTRL higher than RSI-low and RSI-high ($p < 0.001$; [figure 3B](#)), with RSI-low being lower than RSI-high ($p < 0.001$). For the BF, a linear regression of MU force contribution by recruitment

threshold ($R^2=0.27$) revealed that CTRL had higher MU force contribution than RSI-low ($p < 0.001$) and RSI-high ($p < 0.001$; [figure 3C](#)), with RSI-low lower than RSI-high ($p = 0.002$). For the ST, a linear regression of MU force contribution by recruitment threshold ($R^2=0.32$) demonstrated that CTRL had higher MU force contribution from RSI-low ($p < 0.001$) and RSI-high ($p < 0.001$; [figure 3D](#)). RSI-high also had higher MU force contribution than RSI-low ($p < 0.001$).

Common drive

Common drive (normalised by %MVIC) demonstrated differences between groups for the quadriceps ($F_{2,41716} = 66.784$; $p < 0.001$) and hamstrings

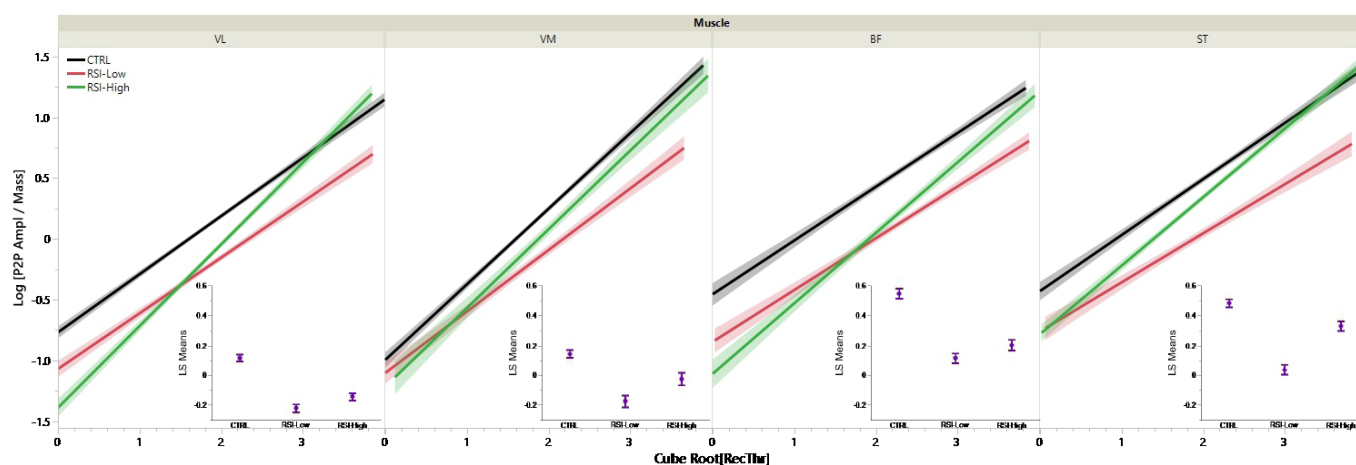


Figure 2 Linear regression of MUAP peak-to-peak amplitude by recruitment threshold at RTS. MUAPs are a surrogate for MU size. For each muscle, all groups were different ($p < 0.001$), with CTRL having larger least squares mean (inset plot) MUAP than both ACL-RSI-low and RSI-high; RSI-high similarly had larger MUAP than RSI-low. ACL, anterior cruciate ligament; CTRL, control; MUAP, motor unit action potential; RSI, return to sport after injury; RTS, return to sport.

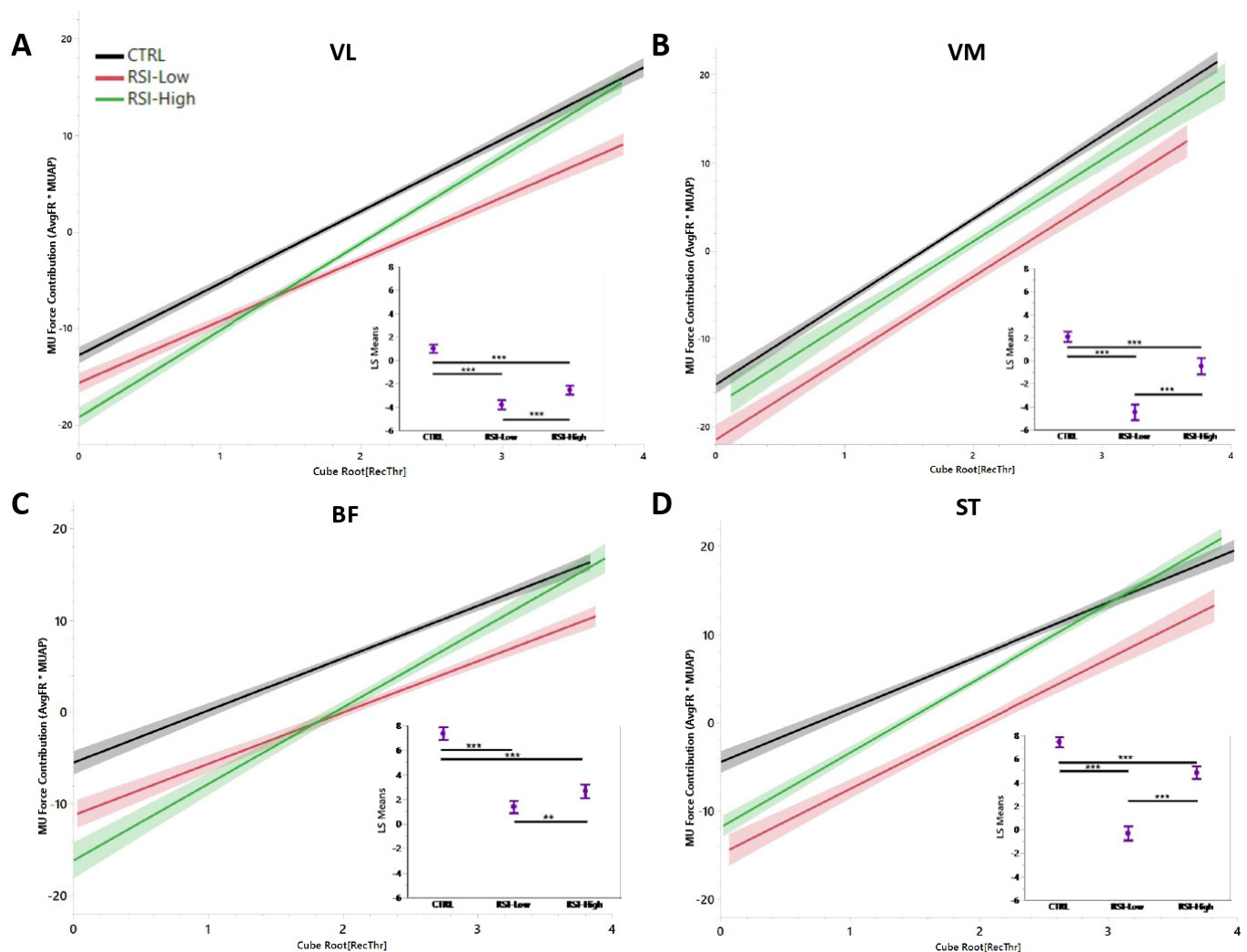


Figure 3 Linear regression of MU total force contribution by recruitment threshold at RTS. MUAPs are a surrogate for MU size. The interaction of AvgFR and MUAP provides the relative contribution of each MU to the total force production. Inset plots (A)–(D) least squares means analysis of variance (ANOVA) demonstrates lower interaction for RSI-low and RSI-high compared with CTRL, with RSI-low lower than RSI-high (** denotes $p < 0.01$; *** denotes $p < 0.001$; line shading and error bars denote 95% CI of the mean). AvgFR, average firing rate; BF, biceps femoris; CTRL, control; MU, motor unit; MUAP, MU action potential; RSI, return to sport after injury; RTS, return to sport; ST, semitendinosus; VL, vastus lateralis; VM, vastus medialis.

($F_{2,33133} = 549.335$; $p < 0.001$). For quadriceps, the Tukey's post hoc comparison demonstrated a common drive coefficient for CTRL of 0.257 (0.256, 0.258), which was higher than RSI-low at 0.249 (0.248, 0.251; $p < 0.001$) and RSI-high at 0.247 (0.245, 0.249; $p < 0.001$). There were no differences between RSI-low and RSI-high ($p = 0.080$). For hamstrings, the Tukey's post hoc comparison demonstrated a common drive coefficient for CTRL of 0.320 (0.319, 0.321), which was higher than RSI-low at 0.306 (0.304, 0.308; $p < 0.001$) and RSI-high at 0.278 (0.276, 0.280; $p < 0.001$). There was a difference between RSI-low and RSI-high ($p < 0.001$).

Delta frequency

An ANOVA of ΔF for the VL ($n = 4317$) demonstrated higher values of RSI-high (−0.003 (−0.014, 0.007)) from CTRL (−0.005 (−0.021, 0.011); $p = 0.021$). For the VM ($n = 3157$), ANOVA of ΔF demonstrated higher values

of both RSI-high (0.000 (−0.016, 0.015)) and RSI-low (−0.001 (−0.010, 0.012)) compared with CTRL (−0.008 (−0.031, 0.008), $p < 0.001$). For the BF ($n = 3374$), ANOVA of ΔF demonstrated higher values for RSI-high (−0.007 (−0.021, 0.014); $p < 0.001$) and RSI-low (−0.003 (−0.020, 0.020); $p < 0.001$) compared with CTRL (−0.018 (−0.043, 0.008)). For the ST ($n = 3750$), ANOVA revealed higher values of RSI-high (0.006 (−0.007, 0.020)) compared with both CTRL (−0.012 (−0.048, 0.023); $p < 0.001$) and RSI-low (−0.004 (−0.022, 0.015); $p < 0.001$). In addition, CTRL had higher values than RSI-low ($p = 0.021$).

DISCUSSION

There is compelling evidence that AvgFR, a common drive, MU size and synaptic activity differ between CTRL and ACL-injured at 6 months and 12 months post-ACLR (time of RTS). ACL-injured demonstrated altered

AvgFR that was decreased for the VL and increased for the hamstrings (figure 1). Similarly, ACL-injured demonstrated overall smaller MUAP (figure 2) MU force contribution compared with CTRL (figure 3). Smaller MUAPs were even more dramatic with RSI-low compared with RSI-high, especially for the hamstrings and with the median recruitment threshold being similar for CTRL and RSI-low. Furthermore, ΔF (MU synaptic activity) demonstrated increased values for ACL-injured compared with CTRL for both the quadriceps and the hamstrings. Our hypotheses were supported that MUAPs were smaller and alterations of ΔF were apparent for ACL-injured compared with CTRL. Thus, ACL injured rely more on smaller MUs than CTRLs.

MU characteristics and common drive

The MU characteristics are similar to those reported previously, such as the demonstration of the VL with lower FR than the VM.⁵⁹ Across rehabilitation, the current evidence demonstrates that ACL-injured is dramatically different from CTRL. AvgFR appears to follow what has been demonstrated about AMI—inhibited quadriceps and facilitated hamstrings.^{6 60} Changes in MU recruitment threshold have previously been demonstrated with pathology.³⁷ Similarly, a previous study has shown that intervention in strength training could change the MU recruitment threshold.⁶¹ However, it is imperative to consider the entire range of recruitment (regression with least squares mean; figures 1–3). MU recruitment is not clustered; it differs based on the task's demand, the MU size's capability and MU rate coding. The importance of MU observation across recruitment is evident by observation of averaged MUs that tend to demonstrate little or no differences in MU behaviour. Yet, it is known that the early-recruited MUs have higher FR than later-recruited units (observed in figure 1).⁶² Therefore, variables were considered across recruitment as the strategy between groups can be disparate due to MU recruitment strategies.

The common drive is a common excitation from an upper motor neuron to all MUs in the pool of a muscle.^{52 63 64} Each MU can modulate FR in unison according to individualistic thresholds.⁶⁴ This collective CTRL allows for unique firing patterns of individual MUs yet eliminates the burden of monitoring and regulating each MU separately.⁶⁴ Cross-correlation of the firing rates of all possible MU pairs demonstrates firing patterns similarities within a certain delay time frame.^{52 64} Further increases in drive level from the upper motor neuron will recruit other MUs and increase the FR of MUs already active. The results of this study demonstrated that ACL-injured had lower common drive than CTRL. This denotes that ACL-injured had inhibited common drive from the upper motor neuron; however, this does not preclude other neural adaptations, such as post-synaptic potentiation, that could result in changes in recruitment thresholds.

Total MU force contribution

After normalising the MUAP by body mass (as mass contributes to the size of MUs and MUAP is a surrogate of MU size^{39 65}), ACL-injured had overall smaller MUs recruited than CTRL (figure 2), and this occurred across all levels of recruitment (0%–50% MVIC; figures 2 and 3), with RSI-low using overall smaller MUs than RSI-high (see inset plots). The overall smaller MUs recruited may be due to decreased common drive (described previously) and threshold alterations at the MU level that cause the MUs to be recruited at higher levels of MVIC. This threshold alteration would be a synaptic method for larger MUs to be recruited later in a contraction and avoid potential overproduction of force or rate of force development of the muscle. This threshold alteration strategy may be a mechanism in which AMI initially protects the joint. Still, the ability to recruit larger MUs provides additional CTRL to musculature with the development of high force and quickness,⁶⁶ especially with unexpected perturbation, which is necessary for RTS and sports performance. As the ACL-injured groups had lower overall common drive, the larger MUAPs they demonstrate (see linear regression slopes) may be due to the altered recruitment thresholds that would allow for larger MU recruitment as sensorimotor recovery occurs.⁵⁷ Whether the sensorimotor recovery is psychologically driven or the psychological readiness is due to proprioceptive awareness of the muscle condition remains to be determined. However, the data demonstrate that the MUAPs recruited may differ greatly in psychological confidence or lack of fear of motion (figures 2 and 3). Interestingly, the MUAPs at the pre-surgery visit were similar between CTRL and ACL-injured (data not shown; median time from injury=37 days (23 days, 94 days)). Thus, the inhibition of larger MUAPs progressed with time from injury (figure 3).

Delta frequency

ΔF is a surrogate method for measuring the effect of PICs for neuromodulation.⁴¹ Higher ΔF values equate to increased monoaminergic excitability at the dendrites of the synapse.⁴¹ In this study, we observed that RSI-low and RSI-high demonstrated higher ΔF than CTRL. This is even more dramatic for the VM and ST RSI-high group. Others have demonstrated that extensors have higher ΔF excitability than flexors with the upper extremity.⁴¹ This was not a pattern observed with the thigh musculature, as the flexors had higher ΔF excitability than the extensors.

Clinical relevance

Previous studies on neuroplasticity following ACL injury have determined that intervention targeting cortical levels may not improve neuromuscular CTRL following injury.^{67 68} Furthermore, immediate aberrant cutaneous sensory did not affect the motor function of ACL-injured.⁶⁸ Thus, the region of the central nervous system most likely to adapt to injury would be the synapse between the upper and lower motor neurons, with



Table 2 Summary of MU adaptations of ACL injury compared with CTRLs

	RSI-low	RSI-high
AvgFR		
Quadriceps	↓	↓↓
Hamstrings	↑	↑
MUAP	↓↓	↓
Common drive	↓	↓
Total force contribution (AvgFR × MUAP)	↓↓	↓
ΔF	↑	↑

ACL, anterior cruciate ligament; AvgFR, average firing rate; CTRLs, controls; MU, motor unit; MUAP, MU action potential; RSI, return to sport after injury; ΔF, delta frequency.

changes in MU recruitment threshold, a common drive and facilitated or inhibited synaptic activity (ΔF) of the motor neuron pool.⁶¹

Table 2 summarises the observed MU differences of the ACL-RSI groups compared with CTRLs. Specifically, ACL-injured had lower common drive, a smaller size of recruited MUs, and altered ability of MU recruitment. These MU changes were compensated for by the increased synaptic excitability of these MUs (also evident in figure 1).

The data demonstrate that dramatic neuroplasticity of the synaptic region has occurred for thigh musculature in response to ACL injury. Furthermore, these differences are also dissimilar between the two groups of psychological readiness, most dramatically with MU force contribution. This information may help inform future studies that test whether personalised rehabilitation can target specific MUs⁶³ and (1) change psychological readiness to RTS and (2) provide an objective demonstration of psychological counselling effectiveness to recover from traumatic injury.³¹

The current evidence-based RTS criteria are limited to the assessment of the physical performance (ie, strength, symmetry and functional tasks) of an athlete, even though psychological factors can impact performance and future injury risk. This study demonstrates that differences in psychological readiness may be directly related to the neuromuscular adaptations of an athlete. Thus, psychological readiness for RTS should raise awareness of the non-physical needs of the athlete, especially with their potential effects at a neuromotor CTRL level.

STRENGTHS AND LIMITATIONS

This study used a large, longitudinal dataset of MUs (n=29 800) from healthy CTRL and ACL-injured subjects from 4 thigh muscles. Due to the large dataset and data extracted from MUs, this study has demonstrated mechanistic changes in neuromodulation from ACL injury,^{36 57} including recruitment threshold, common drive, MUAP and ΔF . Another strength is this study uniquely demonstrates objective neuromuscular changes that categorise

significant differences in subjective psychological states¹³ that influence returns to sport following injury.³¹

As noted in table 1, the CTRL population were not as massive as the ACL-injured population. This could be due to a lack of physical conditioning compared with the ACL-injured group, although activity level was not different between groups. However, increased mass is a relative risk factor for ACL injury and could be the reason for the increased mass in the injured group.

Although MUAP is a surrogate for MU size as larger units will produce larger signal amplitudes than smaller MU,^{40 58} smaller MUs that are closer to the surface of the skin (and thus closer to the electrodes) will also produce larger amplitudes.³⁹ However, as MUs are uniformly distributed throughout the muscle, this normalises and minimises this concern.⁶⁵

Interpretation and limitations of the ΔF method have been scrutinised by several groups, who concluded that ΔF is subject to a high degree of variability, partly from mechanisms other than PICs. Factors that can increase the variability of ΔF include which MU is chosen as the ‘CTRL MU’, difference in recruitment time between test and CTRL MU, maximum rate modulation of the CTRL MU, possible effects of spike frequency adaptation and the presence and timing of secondary range firing.⁴¹ For this study, the CTRL MU selection was automated and not biased by the examiners.

CONCLUSION

Many aspects of neuromuscular CTRL are affected by ACL injury. Specifically, ACL-injured had lower common drive, lower MUAP values, lower total MU force contribution and increased synaptic excitability (ΔF). Even though athletes may return to ‘normal’ levels of strength or symmetry, all ACL-injured cleared for RTS demonstrated substantial differences in MU CTRL compared with healthy CTRL. There are marked differences in MU CTRL for ACL-injured with those that scored below the cut-off (RSI-low) compared with those above (RSI-high). This study uniquely demonstrates objective thigh muscle MU characteristics that coincide with subjective reports of psychological readiness. This valuable information will be important to address psychomotor complexes of injury, especially for neuromotor CTRL, for future rehabilitation efforts.

Author affiliations

¹Department of Neurosurgery & Brain Repair, University of South Florida Tampa Campus, Tampa, Florida, USA

²Medical Engineering, University of South Florida, Tampa, Florida, USA

³Center for Neuromusculoskeletal Research, University of South Florida, Tampa, Florida, USA

⁴Department of Orthopedic Surgery, Mayo Clinic, Rochester, Minnesota, USA

⁵Department of Orthopaedics, The Ohio State University, Columbus, Ohio, USA

⁶Emory Sports Performance and Research Center, Emory University, Atlanta, Georgia, USA

⁷Division of Military Performance, USARIEM, Natick, Massachusetts, USA

Twitter Nathan D Schilaty @NathanSchilaty

Contributors NDS: Conceptualisation; guarantor; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; software and roles/writing - original draft. ALMP, TN and NAB: conceptualisation; data curation; investigation; methodology and writing - review and editing.

Funding The authors acknowledge the support of NIH (grant numbers: R01AR056259, K12HD065987 and L30AR070273), the Mayo Clinic Ultrasound Research Center and the University of South Florida Center for Neuromusculoskeletal Research.

Competing interests None declared.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants and was approved by Mayo Clinic Institutional Review Board (16-010600). Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available upon reasonable request.

Supplemental material This content has been supplied by the author(s). It has not been vetted by BMJ Publishing Group Limited (BMJ) and may not have been peer-reviewed. Any opinions or recommendations discussed are solely those of the author(s) and are not endorsed by BMJ. BMJ disclaims all liability and responsibility arising from any reliance placed on the content. Where the content includes any translated material, BMJ does not warrant the accuracy and reliability of the translations (including but not limited to local regulations, clinical guidelines, terminology, drug names and drug dosages), and is not responsible for any error and/or omissions arising from translation and adaptation or otherwise.

Open access This is an open access article distributed in accordance with the Creative Commons Attribution Non Commercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited, appropriate credit is given, any changes made indicated, and the use is non-commercial. See: <http://creativecommons.org/licenses/by-nc/4.0/>.

ORCID iD

Nathan D Schilaty <http://orcid.org/0000-0002-6038-7126>

REFERENCES

- Kvist J, Ek A, Sporrstedt K, *et al.* Fear of re-injury: A hindrance for returning to sports after anterior Cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2005;13:393–7.
- Ardern CL, Taylor NF, Feller JA, *et al.* Fifty-five per cent return to competitive sport following anterior Cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and Contextual factors. *Br J Sports Med* 2014;48:1543–52.
- Nawasreh Z, Logerstedt D, Cummer K, *et al.* Functional performance 6 months after ACL reconstruction can predict return to participation in the same Preinjury activity level 12 and 24 months after surgery. *Br J Sports Med* 2018;52:375.
- Webster KE, McPherson AL, Hewett TE, *et al.* Factors associated with a return to Preinjury level of sport performance after anterior Cruciate ligament reconstruction surgery. *Am J Sports Med* 2019;47:2557–62.
- Harkey MS, Luc-Harkey BA, Lepley AS, *et al.* Persistent muscle inhibition after ACL reconstruction. *Med Sci Sports Exerc* 2016.
- Hart JM, Pietrosimone B, Hertel J, *et al.* Quadriceps activation following knee injuries: a systematic review. *J Athl Train* 2010;45:87–97.
- Hopkins JT, Ingersoll CD. Arthroscopic muscle inhibition: A limiting factor in joint rehabilitation. *J Sport Rehabil* 2000;9:135–59.
- Ardern CL, Webster KE, Taylor NF, *et al.* Return to sport following anterior Cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. *Br J Sports Med* 2011;45:596–606.
- Paterno MV, Flynn K, Thomas S, *et al.* Self-reported fear predicts functional performance and second ACL injury after ACL reconstruction and return to sport: A pilot study. *Sports Health* 2018;10:228–33.
- Walker N, Thatcher J, Lavalley D. Review: psychological responses to injury in competitive sport: a critical review. *J R Soc Promot Health* 2007;127:174–80.
- Coronado RA, Sterling EK, Fenster DE, *et al.* Cognitive-behavioral-based physical therapy to enhance return to sport after anterior Cruciate ligament reconstruction: an open pilot study. *Physical Therapy in Sport* 2020;42:82–90.
- Hartigan EH, Lynch AD, Logerstedt DS, *et al.* Kinesiophobia after anterior Cruciate ligament rupture and reconstruction: Noncopers versus potential Copers. *J Orthop Sports Phys Ther* 2013;43:821–32.
- McPherson AL, Feller JA, Hewett TE, *et al.* Smaller change in psychological readiness to return to sport is associated with second anterior Cruciate ligament injury among younger patients. *Am J Sports Med* 2019;47:1209–15.
- Smith AM. Psychological impact of injuries in athletes. *Sports Med* 1996;22:391–405.
- Webster KE, Nagelli CV, Hewett TE, *et al.* Factors associated with psychological readiness to return to sport after anterior Cruciate ligament reconstruction surgery. *Am J Sports Med* 2018;46:1545–50.
- Ardern CL, Taylor NF, Feller JA, *et al.* Fear of re-injury in people who have returned to sport following anterior Cruciate ligament reconstruction surgery. *J Sci Med Sport* 2012;15:488–95.
- Hsu C-J, Meierbachtol A, George SZ, *et al.* Fear of Reinjury in athletes: implications for rehabilitation. *Sports Health: A Multidisciplinary Approach* 2016.
- Ashton ML, Kraeutler MJ, Brown SM, *et al.* Psychological readiness to return to sport following anterior Cruciate ligament reconstruction. *JBJS Rev* 2020;8:e0110.
- McPherson AL, Feller JA, Hewett TE, *et al.* Psychological readiness to return to sport is associated with second anterior Cruciate ligament injuries. *Am J Sports Med* 2019;47:857–62.
- Chmielewski TL, Jones D, Day T, *et al.* The Association of pain and fear of movement/Reinjury with function during anterior Cruciate ligament reconstruction rehabilitation. *J Orthop Sports Phys Ther* 2008;38:746–53.
- Tagesson S, Kvist J. Greater fear of re-injury and increased Tibial translation in patients who later sustain an ACL graft rupture or a contralateral ACL rupture: a pilot study. *Journal of Sports Sciences* 2016;34:125–32.
- Podlog L, Eklund RC. Returning to competition after a serious injury: the role of self-determination. *Journal of Sports Sciences* 2010;28:819–31.
- Freedman KB, Glasgow MT, Glasgow SG, *et al.* Anterior Cruciate ligament injury and reconstruction among university students. *Clin Orthop Relat Res* 1998;208–12.
- Sullivan MJL, Bishop SR, Pivik J. The pain Catastrophizing scale: development and validation. *Psychological Assessment* 1995;7:524–32.
- Walker N, Thatcher J, Lavalley D. A preliminary development of the re-injury anxiety inventory (RIAI). *Phys Ther Sport* 2010;11:23–9.
- Kyle BN, McNeil DW. Autonomic arousal and experimentally induced pain: a critical review of the literature. pain research & management: the Journal of the Canadian pain society. *Journal de La Société Canadienne Pour Le Traitement de La Douleur* 2014:159–67.
- Webster KE, Feller JA, Lambros C. Development and preliminary validation of a scale to measure the psychological impact of returning to sport following anterior Cruciate ligament reconstruction surgery. *Phys Ther Sport* 2008;9:9–15.
- Webster KE, Feller JA. Development and validation of a short version of the anterior Cruciate ligament return to sport after injury (ACL-RSI) scale. *Orthopaedic Journal of Sports Medicine* 2018;6:232596711876376.
- Wise RA. Dopamine, learning and motivation. *Nat Rev Neurosci* 2004;5:483–94.
- Needle AR, Lepley AS, Grooms DR. Central nervous system adaptation after Ligamentous injury: a summary of theories, evidence, and clinical interpretation. *Sports Med* 2017;47:1271–88.
- Schilaty ND, Nagelli C, Hewett TE. Use of objective Neurocognitive measures to assess the psychological States that influence return to sport following injury. *Sports Med* 2016;46:299–303.
- Ross CL. Integral Healthcare: the benefits and challenges of integrating complementary and alternative medicine with a conventional Healthcare practice. *Integr Med Insights* 2009;4:13–20.
- Paterno MV, Rauh MJ, Schmitt LC, *et al.* Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport. *Am J Sports Med* 2014;42:1567–73.
- Webster KE, Feller JA, Leigh WB, *et al.* Younger patients are at increased risk for graft rupture and contralateral injury after anterior Cruciate ligament reconstruction. *Am J Sports Med* 2014;42:641–7.
- Zarzycki R, Cummer K, Arhos E, *et al.* Female athletes with better psychological readiness are at higher risk for second ACL injury after primary ACL reconstruction. *Sports Health* 2023;19417381231155120.

- 36 Gorassini M, Yang JF, Siu M, *et al.* Intrinsic activation of human motoneurons: possible contribution to motor unit Excitation. *J Neurophysiol* 2002;87:1850–8.
- 37 Schilaty ND, Savoldi F, Nasr Z, *et al.* Neuromotor control Associates with muscle weakness observed with Mcardle sign of multiple sclerosis. *Ann Clin Transl Neurol* 2022;9:515–28.
- 38 Schilaty ND, McPherson AL, Nagai T, *et al.* Arthrogenic muscle inhibition Manifests in thigh musculature motor unit characteristics after anterior Cruciate ligament injury. *Eur J Sport Sci* 2023;23:840–50.
- 39 Hu X, Rymer WZ, Suresh NL. Motor unit pool organization examined via spike-triggered averaging of the surface Electromyogram. *J Neurophysiol* 2013;110:1205–20.
- 40 Pope ZK, Hester GM, Benik FM, *et al.* Action potential amplitude as a noninvasive indicator of motor unit-specific hypertrophy. *J Neurophysiol* 2016;115:2608–14.
- 41 Wilson JM, Thompson CK, Miller LC, *et al.* Intrinsic excitability of human motoneurons in biceps brachii versus Triceps brachii. *J Neurophysiol* 2015;113:3692–9.
- 42 Boccia G, Martinez-Valdes E, Negro F, *et al.* Motor unit discharge rate and the estimated synaptic input to the Vasti muscles is higher in open compared to closed kinetic chain exercise. *J Appl Physiol (1985)* 2019;127:950–8.
- 43 Stephenson JL, Maluf KS. Dependence of the paired motor unit analysis on motor unit discharge characteristics in the human tibialis anterior muscle. *J Neurosci Methods* 2011;198:84–92.
- 44 Schilaty ND, Nagelli C, Bates NA, *et al.* Incidence of second anterior Cruciate ligament tears and identification of associated risk factors from 2001 to 2010 using a geographic database. *Orthop J Sports Med* 2017;5:2325967117724196.
- 45 McPherson AL, Bates NA, Haider CR, *et al.* Thigh musculature stiffness during active muscle contraction after anterior Cruciate ligament injury. *BMC Musculoskelet Disord* 2020;21:320.
- 46 Kitaguchi T, Tanaka Y, Takeshita S, *et al.* Importance of functional performance and psychological readiness for return to Preinjury level of sports 1 year after ACL reconstruction in competitive athletes. *Knee Surg Sports Traumatol Arthrosc* 2020;28:2203–12.
- 47 Sadeqi M, Klouche S, Bohu Y, *et al.* Progression of the psychological ACL-RSI score and return to sport after anterior Cruciate ligament reconstruction: A prospective 2-year follow-up study from the French prospective anterior Cruciate ligament reconstruction cohort study (FAST). *Orthop J Sports Med* 2018;6:2325967118812819.
- 48 Hermens HJ, Frenks B, Disselhorst-Klug C, *et al.* Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol* 2000;10:361–74.
- 49 Nawab SH, Chang S-S, De Luca CJ. High-yield decomposition of surface EMG signals. *Clin Neurophysiol* 2010;121:1602–15.
- 50 Hu X, Rymer WZ, Suresh NL. Accuracy assessment of a surface Electromyogram decomposition system in human first dorsal Interosseus muscle. *J Neural Eng* 2014;11:026007.
- 51 De Luca CJ, Adam A, Wotiz R, *et al.* Decomposition of surface EMG signals. *J Neurophysiol* 2006;96:1646–57.
- 52 De Luca CJ, LeFever RS, McCue MP, *et al.* Control scheme governing concurrently active human motor units during voluntary contractions. *J Physiol* 1982;329:129–42.
- 53 Marsden JF, Farmer SF, Halliday DM, *et al.* The unilateral and bilateral control of motor unit pairs in the first dorsal Interosseus and Paraspinal muscles in man. *J Physiol* 1999;521 Pt 2(Pt 2):553–64.
- 54 Kim EH, Hassan AS, Heckman CJ. Changes in motor unit discharge patterns following strength training. *J Physiol* 2019;597:3509–10. 10.1113/JP278137 Available: <https://onlinelibrary.wiley.com/toc/14697793/597/14>
- 55 Johnson MD, Thompson CK, Tysseling VM, *et al.* The potential for understanding the synaptic organization of human motor commands via the firing patterns of motoneurons. *J Neurophysiol* 2017;118:520–31.
- 56 Oya T, Riek S, Cresswell AG. Recruitment and rate coding Organisation for Soleus motor units across entire range of voluntary Isometric Plantar flexions. *J Physiol (Lond)* 2009;587:4737–48.
- 57 Franklin DW, Wolpert DM. Computational mechanisms of sensorimotor control. *Neuron* 2011;72:425–42.
- 58 Trevino MA, Sterczala AJ, Miller JD, *et al.* Sex-related differences in muscle size explained by amplitudes of higher-threshold motor unit action potentials and muscle fibre typing. *Acta Physiol (Oxf)* 2019;225:e13151.
- 59 de Souza LML, Cabral HV, de Oliveira LF, *et al.* Motor units in Vastus Lateralis and in different Vastus Medialis regions show different firing properties during low-level, Isometric knee extension contraction. *Hum Mov Sci* 2018;58:307–14.
- 60 Kim H-J, Lee J-H, Ahn S-E, *et al.* Influence of anterior Cruciate ligament tear on thigh muscle strength and hamstring-to-quadriceps ratio: A meta-analysis. *PLoS ONE* 2016;11:e0146234.
- 61 Del Vecchio A, Casolo A, Negro F, *et al.* The increase in muscle force after 4 weeks of strength training is mediated by adaptations in motor unit recruitment and rate coding. *J Physiol* 2019;597:1873–87. 10.1113/JP277250 Available: <https://onlinelibrary.wiley.com/toc/14697793/597/7>
- 62 De Luca CJ, Contessa P. Hierarchical control of motor units in voluntary contractions. *J Neurophysiol* 2012;107:178–95.
- 63 De Luca CJ, Kline JC, Contessa P. Transposed firing activation of motor units. *J Neurophysiol* 2014;112:962–70.
- 64 De Luca CJ, Erim Z. Common drive of motor units in regulation of muscle force. *Trends Neurosci* 1994;17:299–305.
- 65 Del Vecchio A, Negro F, Felici F, *et al.* Distribution of muscle fibre conduction velocity for representative samples of motor units in the full recruitment range of the tibialis anterior muscle. *Acta Physiol (Oxf)* 2018;222:1–9.
- 66 Márquez G, Alegre LM, Jaén D, *et al.* Sex differences in kinetic and neuromuscular control during jumping and landing. *J Musculoskelet Neuronal Interact* 2017;17:409–16.
- 67 Ward SH, Pearce A, Bennell KL, *et al.* Quadriceps cortical adaptations in individuals with an anterior Cruciate ligament injury. *The Knee* 2016;23:582–7.
- 68 Ageberg E, Björkman A, Rosén B, *et al.* Principles of brain plasticity in improving sensorimotor function of the knee and leg in healthy subjects: a double-blind randomized exploratory trial. *BMC Musculoskelet Disord* 2009;10:99.