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Case Studies

Alterations in physical and neurocognitive wellness across recovery after ACLR: A preliminary look into learned helplessness

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ABSTRACT

Objectives: Neural alterations after anterior cruciate ligament reconstruction (ACLR) may initiate a maladaptive neurocognitive response (learned helplessness [LH]). Understanding the interrelationships between neural inhibition, quadriceps function and psychological responses can provide clinicians areas to target during recovery. The purpose was to longitudinally evaluate neural excitability, strength and self-reported LH after ACL injury and to explore the relationship between these measures and knee mechanics and patient reported function.
Design: Case-series.
Setting: University.
Participants: Eight patients were evaluated across recovery after ACL injury.
Main outcome measures: Neural activity, quadriceps function, and self-reported LH were evaluated at pre-surgery, 3-months post-ACLR and at the time of return to play (RTP).
Results: Patients presented with higher helplessness between 3-months and RTP. Neural excitability and quadriceps function were variable and associated with various aspects of LH. These findings indicate a systemic inability to generate appropriate neural signaling to the quadriceps and highlights how these changes may influence perceived helplessness and overall function after ACLR.
Conclusions: LH is related to both measures of physical function and neural outcomes and varies across recovery. This may provide clinicians with a feasible clinical tool that has the potential to identify a variety of impairments arising after ACLR.

1. Introduction

Persistent quadriceps weakness following anterior cruciate ligament reconstruction (ACLR) is a widely-accepted barrier to the successful resumption of physical activity, in part, because it is associated with negative outcomes in knee function (Lohmander, Englund, Dahl, & Roos, 2007) and biomechanics (Palmieri-Smith & Lepley, 2015). Strength deficits have been cited as a consequence of the vast neural impairments that are common after ACLR. These wide-spread neural impairments impede rehabilitation outcomes well into the chronic phases of recovery (Palmieri-Smith & Thomas, 2009; Pietrosimone, Lepley, Ericksen, Gribble, & Levine, 2013). Specifically, alterations in the excitability of motor generating pathways, such as the spinal-reflexive (Pietrosimone et al., 2015) and corticospinal pathways (Heroux & Tremblay, 2006; Lepley et al., 2014, 2015a; Norte, Pietrosimone, Hart, Hertel, & Ingersoll, 2010; Pietrosimone et al., 2013), are factors that have been identified as large drivers of suboptimal outcomes after ACLR.

In order to compensate for the presence of altered peripheral input and changes in reflexive alterations, emerging hypotheses propose that cortical reorganization and neuroplasticity occurs, leading to chronic motor impairments observed years after ACLR (Needle, Lepley, & Grooms, 2017). Additionally, there is mounting evidence that nervous system impairments may also be associated with impaired psychological and behavioral wellness. This psychobehavioral manifestation is known as learned helplessness (LH) (Salomons et al., 2012; Maier & Seligman, 1976). LH is a

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psychological paradigm that has been well demonstrated in both animal and chronic disease literature (Kim et al., 2016; Salomons et al., 2012; Taub et al., 2006) in response to traumatic injury, neural alterations, and uncontrollable situations. LH can manifest clinically as impaired motor patterns, reduced motivation and psychological deficits (Klein, Fencil-Morse, & Seligman, 1976; Salomons et al., 2012; Samwel, Evers, Crul, & Kraaimaat, 2006; Smallheer et al., 2017). While LH has been well-established following classic neuropathologies, the application of LH to an ACLR population is a novel concept. A recent theoretical framework (Burland et al., 2019) has proposed that neural alterations arising after ACLR have the ability to initiate a maladaptive LH psychological response, fueling a negative cyclical relationship between post-surgical outcomes. Specifically, the framework suggests that these neural alterations can promote LH in one of two ways: 1) an individual's inability to successfully execute a task (due to neural inhibition) negatively influences a variety of clinical outcomes and fosters an environment of uncontrollability that leads to the development of LH or 2) protracted changes in neural activity lead to distinct whole-brain neuronal changes that can influence brain regions devoted to processing of emotional responses associated with helpless behaviors (Burland et al., 2019). In support of this concept, preliminary evidence has suggested that in patients who are greater than 2 years removed from ACLR, reduced neural signaling (via motor cortex pathways) to the quadriceps muscle is associated with greater perceived helplessness (Burland et al., 2019). Additionally, this study found that greater helplessness was associated with reduced knee flexion angles during a forward hop task, indicating the potential for these alterations to negatively influence physical function after ACLR.

To date however, no study has longitudinally investigated changes in neural activity collectively with quadriceps strength, knee mechanics and the presence of self-reported LH after ACL injury and reconstruction. In order to understand how neural inhibition, quadriceps strength and psychological responses progress and interact throughout recovery, the purpose of this case series was to generate preliminary insight and longitudinally evaluate spinal-reflexive and corticospinal excitability, strength and self-reported LH prior to and after ACLR. Secondly, to improve the clinical applicability of LH, we sought to evaluate the relationship between longitudinal measures of neural excitability and helplessness and more common clinical assessments such as knee mechanics and patient reported function.

2. Methods

2.1. Patients

Eight patients (5 males, 3 female) who sustained a primary, unilateral ACL rupture and who were scheduled to undergo ACLR were recruited (Table 1). All ACLR surgeries were performed by a single orthopaedic surgeon at the University of Connecticut Health Center within the Department of Orthopaedic Surgery. The surgeon employed an arthroscopic assisted ACLR technique, using an autograft (bone patellar tendon bone graft or a semitendinosus graft) of the patients choosing. Patients were excluded if they had a previous history of knee surgery other than the current ACLR, sustained a contralateral lower extremity injury within the past 6 months, had a history of seizures or concussion in the past 6 months, and if they had a past medical diagnosis of cancer under areas where magnetic or electrical stimulation would be conducted. All patients were enrolled into a physician recommended rehabilitation program. Participants were enrolled in the study once clearance for unrestricted levels of functional activates were obtained. All patients had planned to resume pre-injury activity levels. Written and informed consent was obtained, and all procedures were approved by the University's institutional review board.

2.2. Protocol

A longitudinal, case-series, study design that involved three separate testing sessions: pre-surgery (after injury but prior to ACL reconstruction surgery, average of 69.12 ± 90.12 days post-injury and 6.00 ± 3.46 days pre-ACLR), 3-months post-surgery (average of 95 ± 16.22 days post-ACLR) and when cleared by physician for resumption of unrestricted physical activity (average of 223.0 ± 42.34 days post-ACLR) was utilized. Spinal-reflexive and corticospinal excitability and quadriceps strength and activation were collected bilaterally across the three time points. Self-reported LH was evaluated using a validated self-reported outcome measure and an exploratory knee specific LH outcome measure at all three time points. Knee mechanics and functional hop tasks were performed bilaterally at the final test session, following clearance to functional activities. Supplementary measures of patient perceived function were also evaluated at all three time points to improve translation of our findings to clinical practice. Percent change scores were calculated between testing time points for each outcome measure to interpret the direction and magnitude of change.

2.3. Quadriceps spinal-reflex excitability

Quadriceps spinal-reflex excitability was quantified using the Hoffmann reflex (H-reflex) normalized to maximal muscle responses (H:M), as previously published (Hopkins, Ingersoll, Krause, Edwards, & Cordova, 2001; Lepley et al., 2015b; Palmieri et al., 2004). Quadriceps H-reflex is an electrically induced physiological

Table 1
Patient demographics.

Patient	Age (yrs)	Height (m)	Weight (kg)	Gender	ACLR Limb	Tegner activity level				ACLR Details	Test session time from ACLR (# of days)		
						Pre-injury	Pre-surgery	3-month	RTP		Pre-surgery	3-month	RTP
1	16	1.87	97.52	Male	Left	7	2	3	6	BTB autograft	8	82	201
2	17	1.60	68.03	Female	Left	9	3	4	8	BTB autograft	6	76	179
3	22	1.85	85.27	Male	Left	8	4	4	9	BTB autograft	10	89	195
4	19	1.77	84.09	Male	Left	7	5	4	5	BTB autograft	1	99	217
5	17	1.63	63.63	Female	Left	7	2	2	7	BTB autograft	5	89	310
6	18	1.57	54.55	Male	Left	9	4	2	6	Hamstring autograft	11	93	259
7	35	1.68	70.45	Male	Left	7	4	4	5	Hamstring autograft	3	103	221
8	20	1.65	68.18	Female	Left	9	2	4	6	BTB autograft	4	109	202

Abbreviations: BTB, bone-patellar tendon bone autograft; RTP, clearance to return to play time point.

equivalent of the stretch reflex and is a representation of the ability to reflexively recruit the quadriceps muscle (Hart, Pietrosimone, Hertel, & Ingersoll, 2010; Rosenthal, Moore, Stoneman, & DeBerardino, 2009). Patients were positioned supine with their knee's slightly flexed (~10–15°) using a pillow. Collection sites and recording electrode were shaved (when necessary), debrided and cleaned with alcohol prior to collection. Two 10 mm, pregelled Ag-AgCl (EL503, BIOPAC Systems Inc., Goleta, CA, USA) disc-shaped surface electromyographic (EMG) electrodes were positioned 1.75 cm apart over the medial quadriceps muscle belly (Palmieri & Ingersoll, 2005). EMG signals were band-pass filtered from 10 to 50 Hz and collected at 1024HZ with a common-mode-rejection ratio of 110 dB. A 2 mm shielded disc stimulating electrode (EL252RT, BIOPAC Systems Inc.) was placed over the femoral nerve. A round, self-adhesive dispersive electrode was positioned over the ipsilateral hamstring muscle belly. A 1 ms square wave stimulus produced with a BIOPAC stimulator module (STM100C, BIOPAC Systems, Inc.) and a 200 V maximum stimulus adaptor (STMISOC, BIOPAC Systems Inc) was delivered to the femoral nerve (Hopkins, Ingersoll, Krause, Edwards, & Cordova, 2001). The stimulus was increased until a maximum H-reflex was elicited and visualized. Three maximal H-reflexes were then collected at that voltage. The stimulus was increased until a maximal muscle response (M-response) was elicited, in which three maximal M-responses were elicited. The average peak-to-peak values of the three H-reflexes were normalized to the average peak-to-peak values of the three M-responses (H:M ratio). Spinal-reflexive excitability was collected bilaterally at all three testing timepoints (pre-surgery, 3-months, RTP).

2.4. Quadriceps corticospinal excitability

Transcranial magnetic stimulation (TMS) determined the active motor thresholds (AMT) and amplitude of motor evoked potentials (MEP) elicited at 120% of AMT. Two 10-mm EMG electrodes were positioned in the same manner as during spinal-reflex excitability testing. Debridement and cleaning of the collection and recording electrode site was also performed as needed. Subjects were seated in a testing chair (MagVenture Treatment Chair, 9016B008 MagVenture Inc., Atlanta, GA) and muscle force was monitored using a handheld dynamometer (micro FET; Hoggann Scientific LLC, West Jordan UT). A Lycra swim cap, with a 0.5 cm grid, was positioned on the subjects head by using straight lines drawn vertically in the sagittal (center of the occiput to the nose) and frontal planes (connecting each external auditory meatus) allowing for identification of the approximate motor cortex location (Lepley et al., 2015b; Norte et al., 2010). A double cone angled TMS coil (D-B80, MagVenture Inc., Atlanta, GA) was positioned over the intersected lines and moved in increments of 0.5 cm in anterior-to-posterior and medial-to-lateral directions until the optimal stimulating point was detected; defined as the location producing the greatest MEP amplitude in the quadriceps (Livingston & Ingersoll, 2008). The stimulator (MagPro R30 with Magoption, MagVenture Inc.) was secured over that spot using a flexible mount (Pietrosimone & Gribble, 2012) (Super Flex Arm, MagVenture Inc.). AMT was determined once the optimal stimulating point was located. The AMT is defined as the lowest TMS intensity required to evoke a measurable (>100 μV) MEP in five out of 10 trials (Lepley et al., 2015b; Pietrosimone et al., 2013). Once the AMT was established, five MEPs were elicited at 120% of AMT. Five peak-to-peak MEP amplitude values were averaged and normalized to the average of three maximal muscle responses elicited during H-reflex excitability testing (Groppa et al., 2012; Lepley et al., 2014, 2015b). Corticospinal excitability was collected bilaterally at all three testing time points. Two subjects, patients 3 and 5, did not complete corticospinal excitability testing at the final RTP testing timepoint due to equipment malfunction.

2.5. Quadriceps strength

Quadriceps maximum voluntary isometric contraction (MVIC) was used to assess quadriceps muscle strength. Patients were seated in a Biodex System IV Pro Dynamometer (Biodex Medical Systems, Shirley, New York, USA) with their knee and trunk in 90° of flexion (Pietrosimone et al., 2008, 2009; Pietrosimone & Ingersoll, 2009). Restrictive straps were secured at the lap and over the trunk to control accessory movement during the maximum effort knee extension task. The distal tibia was secured to a pad on the arm of the dynamometer with Velcro straps. Patients were instructed to grab the handles on the side of the dynamometer during all contractions to avoid unwanted upper extremity involvement (Pietrosimone et al., 2008, 2009; Pietrosimone & Ingersoll, 2009). Patients were asked to perform several practice MVICs to ensure that maximal effort was being given. Patients performed three MVICs with visual feedback and verbal encouragement with 60 s between trials. Quadriceps isometric MVIC were obtained bilaterally at all test sessions and normalized to body mass (Nm/kg) for analysis.

2.6. Quadriceps activation

Immediately following MVIC testing, two 7 × 13cm self-adhesive stimulating electrodes were placed on the proximal vastus lateralis and distal vastus medialis (Pietrosimone et al., 2008, 2009; Pietrosimone & Ingersoll, 2009). A custom program (LabView, National Instruments, Austin, TX) was used to automatically trigger 150 V of electrical stimulation (100 ms train of 10 stimuli, at 100 pps, with a pulse duration of 600 μs, and a 0.01 ms pulse delay, 150 V via the Grass S48 dual channel electrical stimulation unit with an SIU8T isolation unit attached [Grass Products, Natus Neurology]) to the quadriceps muscle belly, contracting any muscle not voluntarily recruited. To quantify quadriceps activation failure, the central activation ratio (CAR) was calculated: Central Activation Ratio = MVIC/MVIC + Superimposed Burst. A CAR of 1.00 represented complete quadriceps activation (Barber, Noyes, Mangine, McCloskey, & Hartman, 1990). Quadriceps activation was obtained bilaterally at all 3 test sessions.

2.7. Learned helplessness

In order to quantify self-reported LH, patients completed the validated Learned Helplessness Scale (LHS) and a modified ACL Helplessness Index (ACL-HI) at all time points (Supplementary File 1). The Learned Helplessness Scale (LHS) is a validated 20-item measure that has been previously used assess helplessness behaviors (Quinless & Nelson, 1988). The LHS is scored on a 4-point Likert scale with scores ranging from 20 to 80 and has been validated in an adult population (Cronbach's alpha = 0.82). The ACL-HI is a 15-question survey, modified from a previously validated Arthritis Helplessness Index (AHI) (Brady, 2003; Nicassio, Wallston, Callahan, Herbert, & Pincus, 1985). This survey was modified to change language regarding arthritis to wording indicating knee injury and served as an exploratory subjective measure, to help identify and assess perceptions of helplessness specific to knee injuries. To our knowledge, this is the first time that the LHS and ACL-HI scales have been used to longitudinally evaluate helplessness in an ACLR cohort; therefore, reliability of these scales for this population has not yet been established. Higher scores on both the aforementioned scales are indicative of greater amounts of helplessness. LH was obtained at all three test sessions.

2.8. Knee function

In order to capture a measure of knee function, patients performed a single limb hop for distance (SLHD) task commonly used as a component for clearance to unrestricted functional activities. Sagittal plane knee kinematics and kinetics were collected simultaneously during the SLHD clinical task. A 12-camera motion capture system (Vicon, Oxford Metrics, London, England) sampling at 240 Hz and synchronized with 2 force plates (Bertec Corp., Columbus, Ohio) sampling at 1200 Hz was utilized. Data were collected until at least 3 successful trials were captured for each limb. A trial was considered successful when the participants jumped as far as possible and landed and balanced for at least 1 s on the force platform. Hop distance was measured in meters for each trial and averaged across the three trials. A static trial (McLean, Lipfert, & van den Bogert, 2004) of each subject aligned with the laboratory coordinate system was recorded and a kinematic model including eight skeletal segments and 27 degrees of freedom was created using Visual3D software (C-Motion; Rockville, MD, USA) (Burland et al., 2019b). Ground reaction force data was sampled and synchronized with the kinematic data and filtered using a fourth-order, zero-lag, low-pass Butterworth filter at 12 Hz cut-off frequency (McLean et al., 2007). Filtered kinematic and ground reaction force data was submitted to a standard inverse dynamics approach within Visual3D. Kinetic outputs were normalized to body height and mass and represented as internal moments and time normalized across stance (100%). Knee biomechanics were evaluated at the final RTP test session following clearance to resume functional/sport related activities by treating physician.

2.9. Self-reported function

For clinical relevance, several other commonly utilized self-reported outcome measures were captured longitudinally in this cohort. These scales included the International Knee Documentation Committee (IKDC) form (Collins, Misra, Felson, Crossley, & Roos, 2011), the Knee Injury and Osteoarthritis Outcome Score (KOOS) subscales (Roos, Roos, Lohmander, Ekdahl, & Beynnon, 1998), the ACL return to sport after injury scale (ACL-RSI) (Webster, Feller, & Lambros, 2008) and the Tampa Scale of Kinesiophobia (TSK) (George, Lentz, Zeppieri, Lee, & Chmielewski, 2012; Swinkels-Meewisse, Swinkels, Verbeek, Vlaeyen, & Oostendorp, 2003). These scales are commonly used to measure knee disability, pain, symptoms, quality of life, readiness to return to functional activities, and fear of reinjury, respectively.

3. Results

Due to the nature of the case-series study design, the data are presented individually and descriptively to qualitatively highlight overall trends between outcome measures across the pre-surgery, 3-month and return to activity time points. We caution the reader to inferences made and emphasize that although we are presenting overall trends, it is important to note that we are unable to determine whether these changes are statistically different in this cohort. Percent change scores (Equation (1)) are presented in Tables 2–4 and were used to describe changes between pre-surgery and 3-months, 3-month and RTP, and pre-surgery and RTP time-points. Individual raw outcome scores and average group trends are also presented in Figs. 1–3. Finally, exploratory Pearson and Spearman's rho correlation analyses were performed to determine preliminary associations between helplessness and neural excitability measures and knee function outcomes (Figs. 4–7). Additionally, analyses between helplessness and other measures of perceived function (IKDC, KOOS, ACL-RSI and TSK) were performed for clinical applicability. Correlation analyses were performed using the Statistical Package for the Social Sciences (SPSS) software version 24.0 (IBM Corp., Armonk, NY, USA) and α-level was set a priori at $P \leq 0.05$.

$$\text{Percent change} = \left(\frac{(3\ \text{months post} - \text{ACLR} - \text{pre} - \text{ACLR})}{\text{pre} - \text{ACLR}}\right) * 100 \tag{1}$$

Individual values for neural excitability of the ACLR limb of all patients are presented in Fig. 1. For spinal-reflexive excitability, the overall trend was that this parameter of neural excitability decreased in the ACLR limb by 27% from pre-surgery to RTP. Intermediate timepoints illustrate that from pre-surgery to 3-months post-ACLR spinal-reflexive excitability increased by 34% and then decreased by 46% from the 3-months to the RTP timepoint. Overall there was an approximately 9% percent decrease in AMT values from pre-surgery to RTP. Intermediate timepoints highlight that AMTs increased from pre-surgery to 3-months post-ACLR by 4% and decreased by 13% from 3-months to RTP. MEPs also demonstrated a 7% increase from pre-surgery values to the time of RTP. Intermediate timepoints illustrate that from pre-surgery to 3-months post ACLR corticospinal excitability (MEPs) increased by 141% and then decreased by 55% from 3-months to the RTP timepoint.

Overall quadriceps strength decreased in the ACLR limb by 10% from pre-surgery to RTP. Intermediate timepoints illustrate that from pre-surgery to 3-months post-ACLR that strength decreased by 43% and then increased by 57% from the 3-months to the RTP timepoint. Quadriceps activation (Fig. 2) overall decreased by 11% from pre-surgery to RTP. During the intermediate time points activation decreased by 12% from pre-surgery to 3-months post-ACLR and increased by 2% from 3-months to the time of RTP. Although this study contains a small cohort of patients and the trends presented are preliminary, the individual variations within both neural excitability measures and quadriceps strength/activation are consistent with previous work (Lepley et al., 2015b, 2018a) where similar alterations in these measures are observed across recovery after ACLR.

LH overall decreased by 5% between pre-surgery and the time of RTP (Fig. 3). During the intermediate time points there was a 7% reduction in helplessness from pre-surgery to 3-months and 3% increase from 3-months to RTP. Similarly, LH measured using the ACL-HI scale decreased by 16% from pre-surgery to time of RTP. Intermediate time points illustrate that between pre-surgery and 3 months there was a 3% reduction in LH and a 14% reduction between 3-months post ACLR and RTP.

Following the preliminary correlation analyses, there were several significant associations between measures of neural excitability, quadriceps function and LH. LHS scores at 3-months post-ACLR were associated with quadriceps strength ($r = -.707$, $p = 0.050$, Fig. 4a) and activation at the time of RTP ($r = -0.818$, $p = 0.013$, Fig. 4b) where individuals with less helplessness exhibited better strength and activation. Changes in spinal-reflexive excitability from pre-surgery to RTP ($r = -0.750$, $p = 0.032$, Fig. 5a) indicated that those who exhibited greater increases in spinal-reflexive excitability across recovery reported less LH at RTP. Similarly, we observed that individuals who demonstrated greater perceived helplessness across recovery (pre-surgery to 3-months) also exhibited lesser corticospinal excitability (higher AMTs) ($r = 0.899$, $p = 0.015$, Fig. 5b).

There were also preliminary associations between several measures of knee function and LH variables. Reduced helplessness between pre-surgery and the time of clearance to RTP were associated with improvements in hop performance ($r = -0.719$, $p = 0.045$, Fig. 6a). Reduced helplessness between pre-surgery and

Table 2
Percent change scores for corticospinal and spinal-reflexive excitability.

% Change Score										
Outcome		AMT			MEP			H:M		
Patient	Limb	Pre to 3	3 to RTP	Pre to RTP	Pre to 3	3 to RTP	Pre to RTP	Pre to 3	3 to RTP	Pre to RTP
1	ACL	27.27	−30.00	−10.91	386.38	−74.48	24.14	8.96	−80.75	−79.03
	Uninjured	42.86	−11.43	26.53	30.96	−60.33	−48.05	480.85	−96.95	−82.27
2	ACL	53.33	0.00	53.33	1014.60	−64.77	292.67	197.26	80.87	437.65
	Uninjured	4.88	−6.98	−2.44	26.84	10.23	39.81	1412.97	−51.17	638.71
3	ACL	−9.23	*	*	1752.50	*	*	−42.94	−48.21	−70.45
	Uninjured	−14.93	−12.28	−25.37	497.44	−74.63	51.55	12.79	−80.84	−78.39
4	ACL	−10.64	2.38	−8.51	114.42	78.78	283.34	62.58	−35.38	5.06
	Uninjured	4.76	2.27	7.14	−12.52	2390.64	2078.81	−28.30	382.54	245.98
5	ACL	−15.52	*	*	17.31	*	*	23.91	−60.53	−51.09
	Uninjured	−17.39	*	*	−46.54	*	*	29.61	−8.19	18.99
6	ACL	22.58	−2.63	19.35	1156.53	−72.12	250.30	25.61	−70.91	−63.46
	Uninjured	0.00	29.17	29.17	458.80	−54.35	155.10	−51.97	−76.77	−88.84
7	ACL	−15.09	−8.89	−22.64	−61.34	−21.70	−69.73	217.70	−25.63	136.27
	Uninjured	4.00	−28.85	−26.00	18.84	−60.22	−52.73	131.03	−46.47	23.66
8	ACL	9.68	2.94	12.90	200.99	−42.27	73.75	34.56	−20.89	6.45
	Uninjured	4.00	−28.85	−26.00	18.84	−60.22	−52.73	143.25	74.79	325.17
Average	ACL	3.51	−12.62	−9.55	141.10	−55.69	6.83	33.85	−46.17	−27.94
	Uninjured	3.13	−17.68	−15.10	57.67	64.85	159.93	63.92	−26.38	20.67

Abbreviations: AMT, active motor threshold; MEP, motor evoked potential; H:M, Hoffmann reflex to muscle response ratio; Pre-3, percent change score between pre-surgery and 3-month timepoint; Pre-RTP, percent change score between pre-surgery and return to play timepoint; 3-RTP, percent change score between 3-month time point and return to play; RTP, return to play timepoint. *Patient 3 and 5 data for corticospinal testing is not available due to equipment malfunction.

Table 3
Percent change scores for quadriceps strength and activation.

% Change Score							
Outcome		Quadriceps MVIC			Quadriceps Activation		
Patient	Limb	Pre to 3	3 to RTP	Pre to RTP	Pre to 3	3 to RTP	Pre to RTP
1	ACL	−74.89	55.37	−60.98	−44.30	0.23	−44.17
	Uninjured	4.41	−16.56	−12.88	−5.26	−5.11	−10.10
2	ACL	−31.98	41.05	−4.06	3.87	−2.22	1.56
	Uninjured	36.04	−2.55	32.56	−0.23	0.79	0.55
3	ACL	−53.53	214.04	45.95	−11.90	41.22	24.42
	Uninjured	−15.41	96.19	65.96	−3.93	15.40	10.86
4	ACL	−63.12	46.69	−45.89	−34.53	9.79	−28.12
	Uninjured	−13.50	3.17	−10.76	1.43	−14.54	−13.31
5	ACL	−39.95	44.23	−13.39	−10.71	−14.36	−23.53
	Uninjured	−13.08	7.09	−6.92	−0.99	−13.92	−14.77
6	ACL	−26.21	19.89	−11.53	1.39	−2.75	−1.39
	Uninjured	−9.01	2.22	−6.99	−1.42	2.59	1.14
7	ACL	−22.60	40.55	8.78	−1.58	−3.57	−5.10
	Uninjured	10.18	1.90	12.28	3.74	−0.59	3.14
8	ACL	−24.86	55.04	16.50	−0.80	−1.37	−2.16
	Uninjured	4.43	2.39	6.93	−0.93	0.13	−0.80
Average	ACL	−42.88	57.15	−10.23	−12.24	1.85	−10.62
	Uninjured	1.54	8.62	10.29	−0.94	−1.32	−2.24

Abbreviations: MVIC, maximum voluntary isometric contraction; Pre-3, percent change score between pre-surgery and 3-month timepoint; Pre-RTP, percent change score between pre-surgery and return to play timepoint; 3-RTP, percent change score between 3-month time point and return to play; RTP, return to play timepoint.

3 months was also associated with greater peak knee extension moments during the SLHD ($r = -0.778$, $p = 0.023$, Fig. 6b). Similarly, raw LHS self-reported helplessness scores at 3 months were associated with SLHD limb symmetry ($r = -0.719$, $p = 0.045$, Fig. 6c) indicating that individuals with less helplessness exhibited better symmetry. Helplessness change scores measured using the ACL-HI between pre-surgery and 3 months were associated with peak knee moments during the SLHD ($r = -0.762$, $p = 0.028$, Fig. 7a). Further, helplessness change scores from pre to RTP were also associated with greater peak knee flexion angle during the SLHD ($r = 0.738$, $p = 0.037$, Fig. 7b. Lastly, raw helplessness scores on the ACL-HI were associated with SLHD average hop distance ($r = -0.762$, $p = 0.028$, Fig. 7c).

Several clinically relevant associations between measures of perceived helplessness and knee function, readiness to return to sport and fear of reinjury were also observed across recovery. Specifically, pre-surgery LHS scores were strongly associated with pre-surgery TSK ($r = 0.744$, $p = 0.034$) and pre-surgery ACL-HI scores were associated with perceived knee pain ($r = -0.772$, $p = 0.025$) and overall quality of life ($r = -0.816$, $p = 0.013$). Three-month LHS scores were associated with 3-month KOOS symptoms ($r = 0.889$, $p = 0.003$) and TSK scores (0.870 $p = 0.005$). Additionally, 3-month TSK ($r = 0.832$, $p = 0.010$) and ACL-RSI ($r = -0.792$, $p = 0.019$) scores were associated with LHS scores at the time of RTP. Six-month ACL-HI scores were also associated with readiness to return to play at the RTP timepoint ($r = -0.752$, $p = 0.031$).

Table 4
Percent change scores for learned helplessness.

% Change Score						
Outcome	Learned Helplessness Scale (LHS)			ACL Helplessness Index (ACL-HI)		
Patient	Pre to 3	3 to RTP	Pre to RTP	Pre to 3	3 to RTP	Pre to RTP
1	27.59	−13.51	10.34	7.41	−6.90	0.00
2	10.00	−9.09	0.00	6.67	−18.75	−13.33
3	−20.00	16.67	−6.67	−20.00	16.67	−6.67
4	0.00	−2.56	−2.56	7.69	0.00	7.69
5	2.78	−2.70	0.00	2.70	−15.79	−13.51
6	0.00	20.69	20.69	2.86	−25.00	−22.86
7	−16.00	0.00	−16.00	−11.43	−29.03	−37.14
8	−38.78	16.67	−28.57	−15.38	−18.18	−30.77
Average	−7.00	2.51	−4.67	−3.09	−13.55	−16.22

Abbreviation: Pre-RTP, percent change score between pre-surgery and return to play timepoint; 3-RTP, percent change score between 3-month time point and return to play; RTP, return to play timepoint.

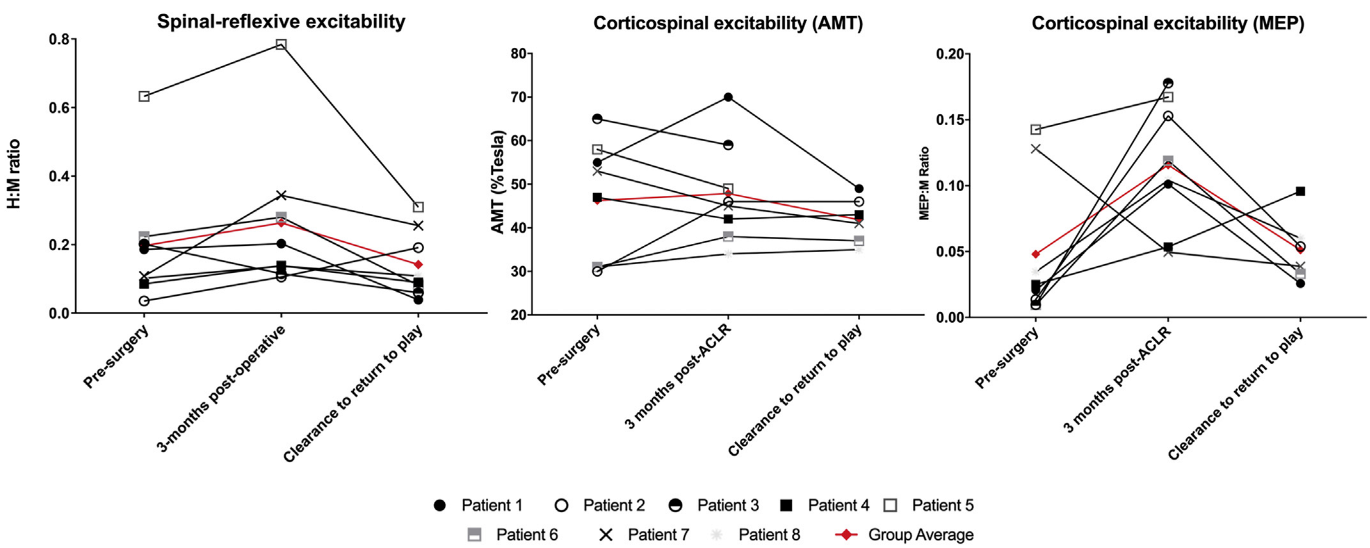

Fig. 1. Neural excitability measures of the involved ACLR limb for all patients and overall group trend. Abbreviations: AMT, active motor threshold; H: M, Hoffmann reflex to muscle response ratio; MEP:M ratio, motor evoked potential to muscle response ratio.

4. Conclusions

The purpose of this case series was to gain preliminary insight into the relationships between spinal-reflexive and corticospinal excitability, quadriceps function and self-reported LH prior to and across recovery after ACLR. Secondly, to improve the clinical applicability of LH, we sought to evaluate the relationship between longitudinal measures of neural excitability and helplessness and more common clinical assessments such as knee mechanics and patient reported function. In our cohort of patients, we observed the greatest increase in LH between the 3-month and RTP timepoint; however, there were global improvements in self-reported LH across recovery, indicating that as recovery time passes, helplessness diminishes after ACLR. We also found that patients exhibited bilateral deficits in spinal-reflexive excitability prior to undergoing ACLR, as well as reductions in the ability to excite descending motor neurons (reduced AMTs) at 3-months post-ACLR and reduced motor output (MEP) at the time of clearance to resume functional activities. Together, these findings indicate a systemic inability to generate appropriate neural signaling to the quadriceps at various timepoints throughout recovery. We also observed that both quadriceps strength and activation were highly impacted during the acute phases of recovery (pre-surgery to 3 months) and never reached or surpassed pre-surgery values (Table 3).

A novel aspect of this study was the observation of perceived LH across recovery in an ACLR cohort. Previous work has hypothesized (Burland et al., 2019) that LH responses post-ACLR may be influenced by the differing neural changes ongoing throughout recovery and thus could impact recovery by resulting in maladaptive motor and behavioral responses (Salomons et al., 2012; Burland et al., 2019; Maier & Seligman, 2016). Although our findings indicate that helplessness decreased over the course of recovery, it is interesting to note that prior to undergoing ACLR, helplessness was generally high in many of the patients at a time when spinal-reflexive excitability was also reduced (Figs. 1 and 3). There was a vast amount of variability in perceived helplessness amongst our patients prior to ACLR. This is in line with previous work (Everhart, Best, & Flanigan, 2013; Shapiro, Brewer, Cornelius, & Van Raalte, 2017) that indicates that psychological responses differ amongst individuals after ACLR and can influence long term function. Further, helplessness scores on the ACL-HI (Fig. 3) were greater 3-months post-ACLR, a time when previous research has suggested that brain neuroplasticity is occurring (Burland et al., 2019; Grooms et al., 2017; Lepley et al., 2015b; Needle et al., 2017). During this time frame our patients also demonstrated reductions in motor threshold (higher AMTs) and facilitations in motor output (higher

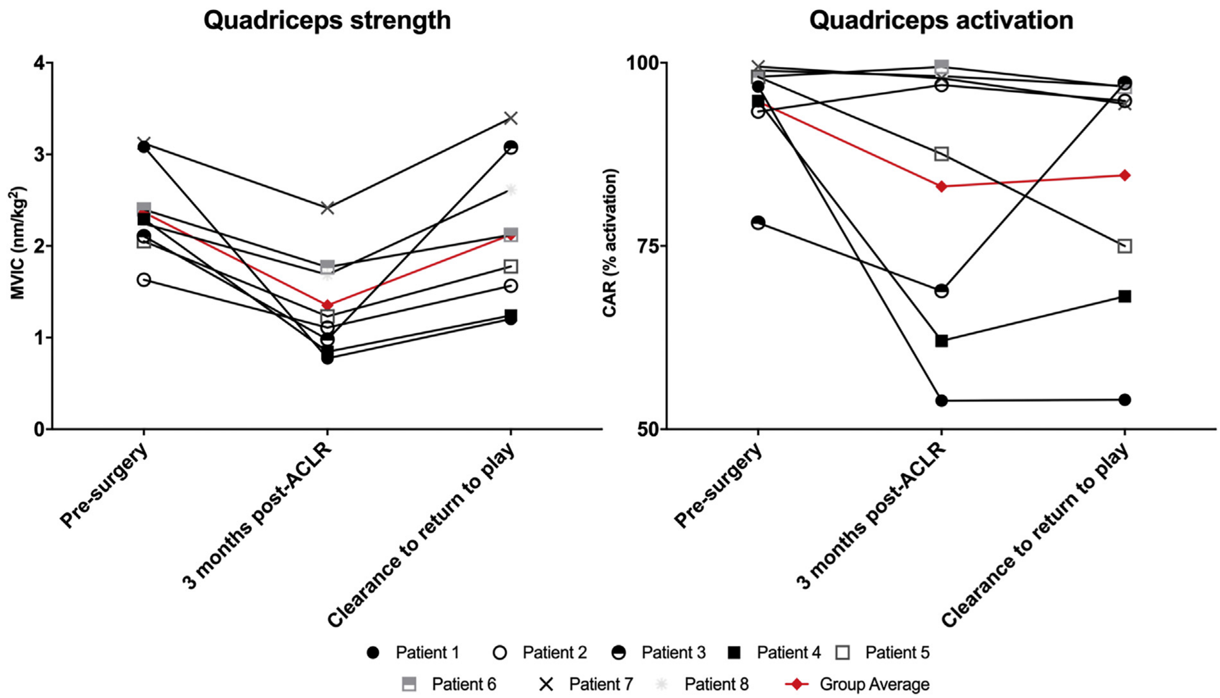

Fig. 2. Quadriceps strength and quadriceps activation measures of the involved ACLR limb for all patients and overall group trend. Abbreviations: CAR, central activation ratio; MVIC, maximal voluntary isometric contraction.

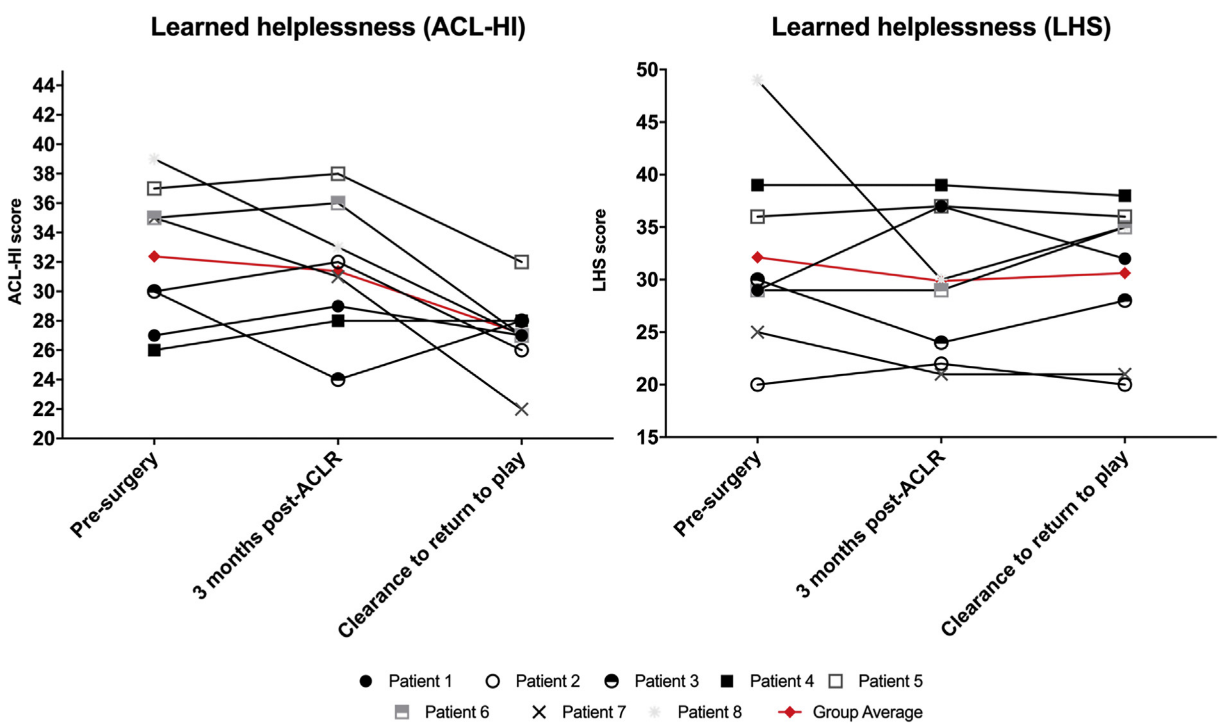

Fig. 3. Self-reported learned helplessness of the involved ACLR limb for all ACLR patients and overall group trend. Higher scores are indicative of greater helplessness. Abbreviations: ACL-HI, anterior cruciate ligament helplessness index; LH, learned helplessness.

MEPs). Together, these findings highlight the potential for neural alterations to coincide with perceived helplessness after ACLR.

As neural excitability is inherently variable across recovery after ACLR, it is likely that changes in neurocognitive function, including LH, would be greatest during the time brain neuroplasticity is occurring (Burland et al., 2019; Grooms et al., 2017). Acute spinal-reflexive alterations can initiate changes within the corticospinal pathways and may further exacerbate functional deficits (Needle et al., 2017) (i.e. quadriceps weakness, activation) promoting an environment of uncontrollability. This feeling of uncontrollability is a classic characteristic of LH where the lack of control over the outcome of a certain task promotes negative motor and behavioral

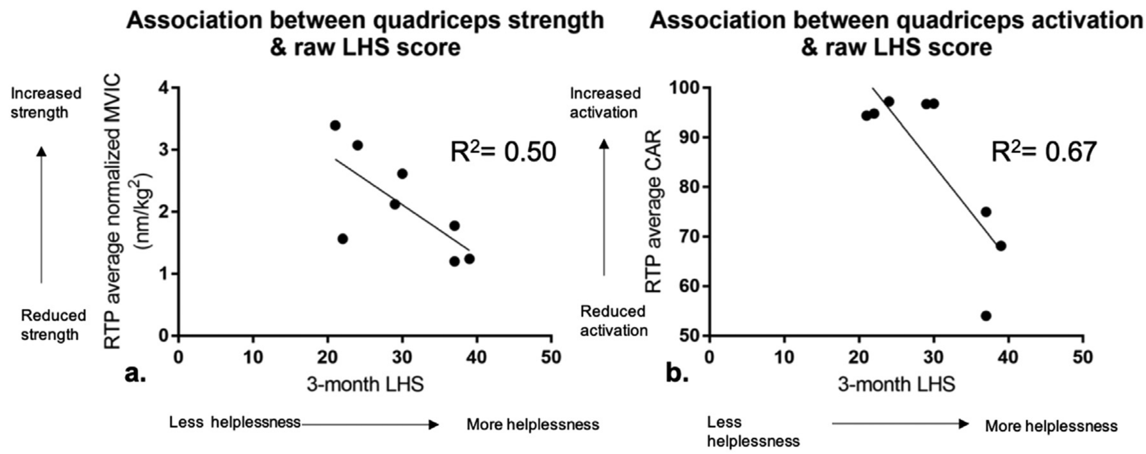

Fig. 4. a-b. Correlation analyses between quadriceps function and LH.

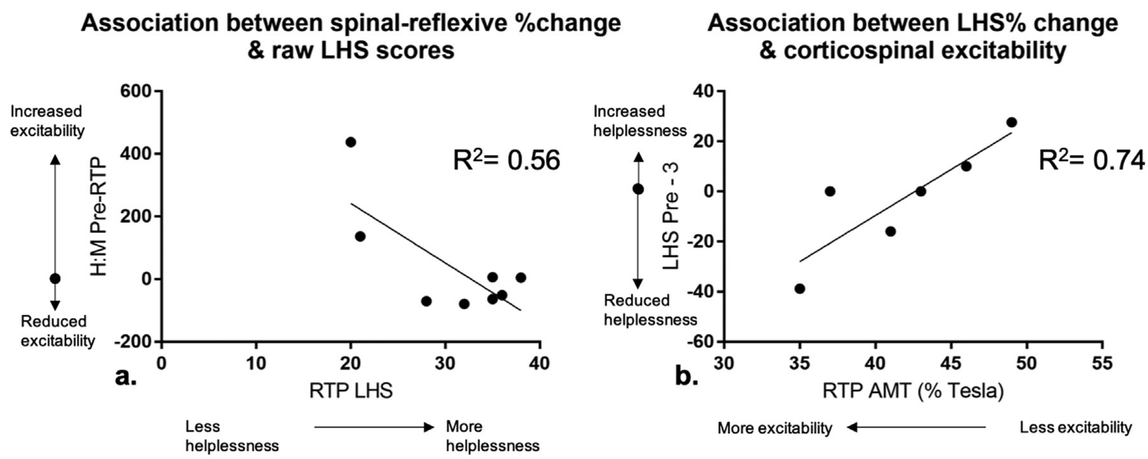

Fig. 5. a-b. Correlation analyses between neural excitability and LH.

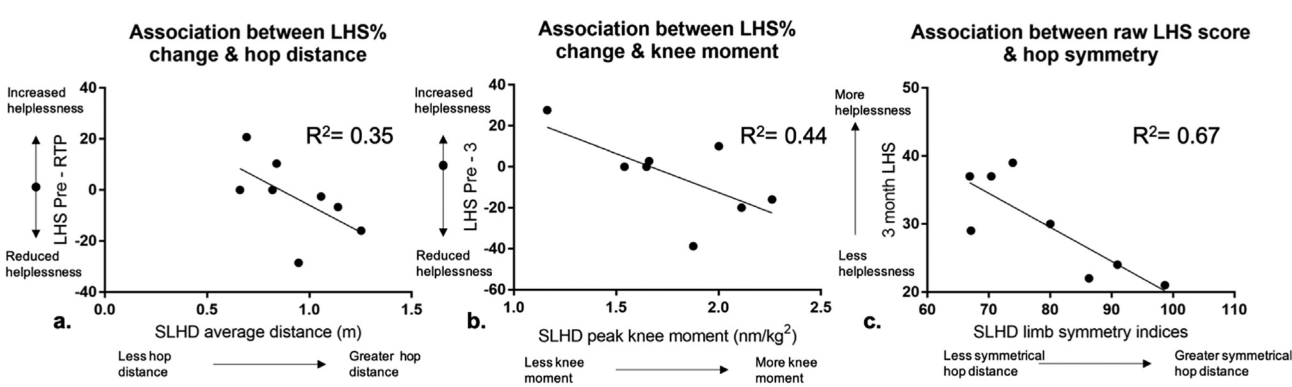

Fig. 6. a-c. Correlation analyses between the Learned Helplessness Score and Knee Function Outcomes.

adaptations (Diener & Dweck, 1980; Maier & Seligman, 1976; Salomons et al., 2012; Taub et al., 2006). Because LH is considered a neurocognitive construct, patients who sustain an ACL injury may be at a disadvantage as the recovery process encompasses neural alterations and periods of uncontrollability, both of which may promote feelings of helplessness. Based on the findings of our study, we postulate that it is likely that during the earlier phases of recovery, LH may be more prominent due to the early ongoing neural compensations that occur as a consequence of the loss of mechanoreceptors and peripheral changes, in addition to an overwhelming feeling that certain aspects of recovery are not within the individual's control. These findings are distinctly different from classic fear avoidance paradigms commonly experienced after ACLR where fear may be related to associating a certain movement with pain during activity or fear of related injury once the patient resumes functional tasks, but does not necessarily originate after a

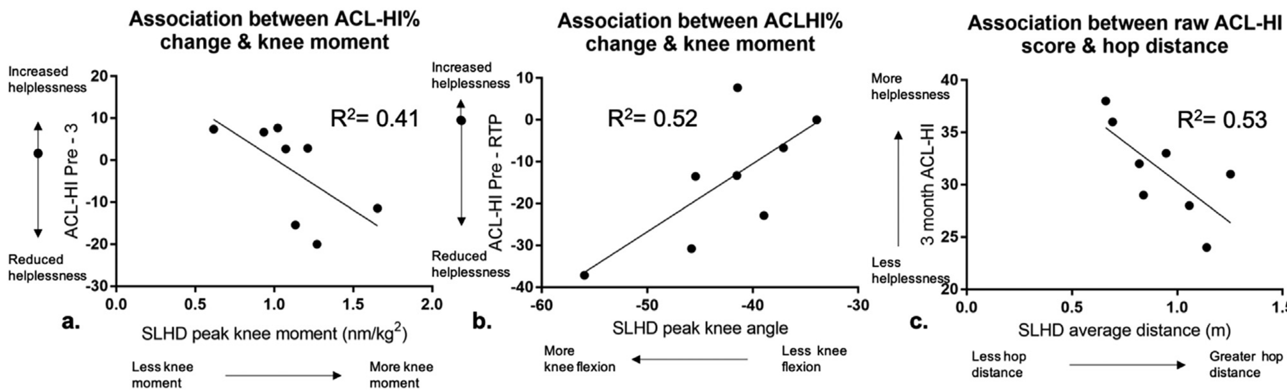

Fig. 7. a-c. Correlation analyses between the ACL Helplessness Index and Knee Function Outcomes.

neural injury or because of feelings of uncontrollability (Ardern, Taylor, Feller, & Webster, 2012; Chmielewski et al., 2008). We descriptively observed lower levels of spinal-reflexive excitability prior to surgery compared with 3-months post-ACLR which is consistent with previous work evaluating alterations in peripheral pathways (Lepley et al., 2015b). There were also large changes in corticospinal excitability measures, specifically MEPs, occurring around the 3-month time point. These peripheral and central changes in excitability may promote a ripe environment for the development of LH.

Results from our preliminary correlation analyses support the potential relationship between neural excitability and LH. Specifically, individuals who reported greater helplessness at 3-months post-ACLR exhibited larger reductions in quadriceps strength and activation at the time of RTP (Fig. 4). Similarly, overall change in spinal-reflexive excitability from pre-surgery to RTP was associated with greater perceived helplessness at the time of RTP (Fig. 5a). When patients have difficulty initiating appropriate motor control strategies (due to neural inhibition) to perform certain tasks early on in recovery after ACLR, it is plausible that they may also experience greater feelings of uncontrollability and helplessness. These helpless feelings may cause individuals to adopt maladaptive motor patterns or negative behaviors that further increase dysfunction. Although trends in LH showed a decrease over time after ACLR, which contrasts our previous hypothesis (Burland et al., 2019), greater increases in LH from pre-surgery to 3-months were associated with depressed corticospinal excitability at the time of RTP (higher AMTs). Thus, it seems that greater perceived helplessness during the acute phases of recovery is more highly associated with larger neural alterations in both the peripheral and central pathways. This is an area where targeted interventions to reduce helplessness may prove beneficial.

A clinically relevant finding of this study was the relationship between LH and clinical function, providing us with preliminary evidence of how helplessness, developing in the presence of neural impairments, may negatively impact important functional outcomes after ACLR. Previous research has identified a relationship between self-reported LH and knee flexion angle during a single limb forward hop task, however this hop task is often not used as a measure of clinical function or progression to return to sport (Burland et al., 2019). Notably, we observed that both reductions in change scores across time and lower raw helplessness scores (LHS, Fig. 6) after ACLR were associated with greater hop distance, higher knee moments and better hop distance symmetry during the SLHD task. Similar findings were observed when using the knee specific ACL-HI measure, where reduced helplessness was significantly associated with higher peak knee moments, peak knee angles and greater hop distance (Fig. 7). Together, these findings illustrate that individuals who generally have higher helplessness attributes throughout recovery tend to perform worse on clinically meaningful tasks, indicating that reducing feelings of helplessness may help to improve physical function. Although this study is the first longitudinal study to evaluate LH in a cohort of ACLR patients, these findings are consistent with other measures of self-reported function that evaluate psychosocial constructs of knee function (not encompassing neural insult and uncontrollability), where patients who report less disability often perform better physically on functional tasks (Lepley et al., 2018b; Logerstedt et al., 2012; Trigsted, Cook, Pickett, Cadmus-Bertram, Dunn, Bell; Paterno, Flynn, Thomas, & Schmitt, 2018; Pietrosimone et al., 2013; Pietrosimone et al., 2016).

Further supporting the relationship between helplessness and clinically important outcomes, we also observed strong associations between helplessness outcome scores and perceived fear of reinjury, knee pain/symptoms, quality of life and readiness to return to sport. These findings highlight that individuals with greater helplessness at varying time points across recovery also experience greater psychological deficits and worse perceived knee function (pain and symptoms). These are areas where clinicians could feasibly intervene over the course of recovery to help improve outcomes after ACLR. It is interesting that the helplessness scales were associated with measures of persistent knee symptoms and pain. If patients perceive that their knee pain and symptoms are not within their control, it may promote greater feelings of helplessness. Notably, recent work (Lepley et al., 2019) observed that patients who reported greater perceived knee symptoms and pain also exhibited increased frontal lobe brain activation, an area of the brain responsible for motor planning and attention. They speculated that this increase in perceived disability and increased activation of these cortical areas may lead to decreased excitability within the motor cortex. As LH has been preliminarily associated with changes in neural excitability in this cohort of patients, future work should evaluate whether this relationship exists in a larger cohort and whether perceived helplessness is associated with changes in similar brain activation patterns after ACLR.

This case series highlights the interrelationships between neural excitability, quadriceps function and LH that vary across the course of recovery after ACL injury and reconstruction. While these findings provide us with preliminary insight into the relationships, we caution the reader to the inferences made and emphasize that future research within a larger cohort is required to fully expand on the direct relationship between these outcome measures after ACLR and to determine whether changes observed within this population are statistically different. Our data indicate that neural excitability is variable across recovery and corroborates previous data (Lepley et al., 2015b) where changes in spinal-reflexive excitability precede chronic, persistent alterations in corticospinal excitability. Together these alterations in neural excitability also promote an environment suitable for the development of psychological behavioral manifestations consistent with LH that have the potential to further prolong dysfunction. A unique finding of this study is that LH is in some way related to both measures of physical function (hop tasks, quadriceps strength) and neural outcomes. This may provide clinicians with a feasible clinical tool that has the potential to identify a variety of impairments arising after ACLR. Naturally, due to the small cohort size, there are individual variations in neural and helplessness responses observed across the three test sessions. This highlights the notion that despite undergoing the same injury and surgery, some patients vary in their responses to certain stimuli throughout recovery and these differing responses can ultimately influence both physical, neural and psychological wellness. Future work is necessary to statistically evaluate these trends and relationships between neural excitability and helplessness in an ACLR cohort. Further, due to the novel aspect of helplessness outcome measures in an ACLR population, future work should look to establish minimal clinical differences for the LH scales in a larger cohort to improve clinical utility. Lastly, although there were no appreciable descriptive differences in responses between sex, age or graft type among the patients in our cohort, these factors should be considered when designing future research studies.

Ethical statement

The Institutional Review Board at the University of Connecticut approved this study and all subjects gave informed consent.

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Declaration of competing interest

None declared.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2019.09.009.

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