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Quadriceps cortical adaptations in individuals with an anterior cruciate ligament injury

Sarah H. Ward [a,*], Alan Pearce [b], Kim L. Bennell [a], Brian Peitrosimone [c], &, Adam L. Bryant [a]

[a] Centre for Health, Exercise and Sports Medicine, Department of Physiotherapy, Faculty of Medicine, Dentistry and Health Science, University of Melbourne, VIC, Australia
[b] Melbourne School of Health Science, Faculty of Medicine, Dentistry and Health Science, University of Melbourne, VIC, Australia
[c] Department of Exercise and Sport Science, University of North Carolina at Chapel Hill, NC, USA

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ABSTRACT

Background: Altered quadriceps corticomotor excitability has been demonstrated following anterior cruciate ligament (ACL) injury and reconstruction, however only the single joint vasti muscles have been assessed. There is no current data on rectus femoris corticomotor excitability following ACL injury, the biarticular quadriceps muscle also critical for force attenuation and locomotion. The purpose of this study was to examine rectus femoris corticomotor excitability, intracortical inhibition and cortical motor representation in individuals with and without an ACL injury.
Methods: A cross-sectional design was used to evaluate corticomotor excitability bilaterally in individuals with a physician confirmed ACL injury (12 males, six females; mean ± SD age: 29.6 ± 8.4 years; BMI: 24.8 ± 2.3 kg·m^2; 69.5 ± 42.5 days post-injury) compared to a healthy control group (12 males, six females; age: 29.2 ± 6.8 years; BMI: 24.6 ± 2.3 kg·m^2). Single-pulse transcranial magnetic stimulation (TMS) was used to assess corticomotor excitability and cortical motor representation, and paired-pulse TMS used to assess intracortical inhibition for rectus femoris while participants maintained a knee extension force at 10% of body weight.
Results: The cortical silent period (cSP) duration was longer in the injured limb of the ACL group compared to the uninjured limb ($P = 0.004$). No significant differences were found for corticomotor excitability, intracortical inhibition or cortical motor representation center position and size ($P > 0.05$).
Conclusions: There is preliminary evidence that the cSP is longer, but changes in rectus femoris corticomotor excitability and cortical motor representation are not present following ACL injury.

1. Introduction

Quadriceps muscle weakness is common in people who have sustained an anterior cruciate ligament (ACL) injury or undergone ACL reconstruction (ACLR) [1–3]. There is evidence that quadriceps weakness contributes to disability [4], and potentially influences the onset and progression of post-traumatic knee osteoarthritis in these individuals [5,6]. Understanding the causes of quadriceps muscle dysfunction is critical for developing interventions to effectively treat persistent muscle weakness following ACL injury [1,3]. There is evidence that persistent quadriceps muscle weakness is a consequence of alterations within the central nervous system (CNS), more specifically alterations in the excitability of the primary motor cortex of the brain and associated descending pathways [7–9] contribute to persistent quadriceps muscle weakness.

The excitability of the cortex and associated pathways can be measured with transcranial magnetic stimulation (TMS) by evaluating the motor threshold, or the amplitude of the muscle response evoked by the TMS [10]. The motor threshold is defined as the minimum stimulus intensity required to elicit a muscle response (motor evoked potential; MEP) of a predefined size. A higher motor threshold is considered indicative of reduced corticomotor excitability, requiring higher levels of stimulation or neural drive to create excitation and neuronal depolarization [11].

Previous studies have demonstrated alterations in quadriceps corticomotor excitability in individuals with ACL injury [7] and ACLR [2,12], and in individuals with chronic anterior knee pain [13]. Following ACLR, the active motor threshold of the primary motor cortex is higher in the involved versus uninvolved limb and uninjured healthy controls, indicating reduced corticomotor excitability in the involved limb [2,12]. However, there were no changes in the MEP amplitude following ACLR indicating that although a greater stimulus is required for excitation and depolarization, the amplitude of the motor response is similar within the target muscle of individuals with an ACLR and uninjured individuals [2,11]. The research suggests a role for the CNS in quadriceps neuromuscular dysfunction, as higher quadriceps active

* Corresponding author at: Centre for Health, Exercise and Sports Medicine, Department of Physiotherapy, Melbourne School of Health Sciences, Faculty of Medicine, Dentistry and Health Sciences, University of Melbourne, 161 Barry St., Carlton, Victoria 3053, Australia.
E-mail address: wardsh@student.unimelb.edu.au (S.H. Ward).

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motor threshold (AMT) was found in conjunction with reduced voluntary muscle activation and quadriceps strength deficits in individuals with an ACLR [2].

Transcranial magnetic stimulation (TMS) during an active muscle contraction produces an interruption in voluntary electromyography (EMG) known as the cortical silent period (cSP). The cSP is mediated by both spinal and cortical mechanisms, with the latter part of the cSP (>50 ms) mediated by inhibitory γ-aminobutyric acid receptor B ($GABA_B$) activity in the cortex [14]. The inhibitory system within the human brain can be more specifically assessed using paired-pulse TMS.

Paired-pulse TMS utilizes a conditioning stimulus and a test stimulus at varying inter-stimulus intervals (ISI). Subthreshold conditioning stimuli will preferentially excite the interneurons, which will suppress or facilitate the subsequent MEP generated from the test stimulus depending on the duration of the ISI. Subthreshold conditioning stimulus coupled with a supra-threshold stimulus using an ISI of one to six milliseconds produces short-interval intracortical inhibition (SICI), and is thought to represent γ-aminobutyric acid receptor A ($GABA_A$) activity [15,16]. Alternatively, long interval intracortical inhibition (LICI) is the result of two suprathreshold stimuli at an ISI of 50 to 200 ms and is thought to represent $GABA_B$ activity [15,16]. Intracortical inhibition has been assessed in this manner to examine changes in neuromuscular function associated with aging [17], and in clinical populations [18–20]. Physiological changes in the intracortical inhibitory circuits may be contributing to higher quadriceps AMT, and quadriceps neuromuscular dysfunction previously demonstrated in individuals with an ACL injury and ACLR [2,7,12]. Although SICI does not appear to differ between healthy individuals and those with knee osteoarthritis [18], intracortical inhibition has yet to be investigated in individuals with an ACL injury or ACLR.

Spatial reorganization within the CNS in terms of changes in size, shape and center of the cortical motor representation of the target muscle can occur following injury [21–23]. Although traditionally examined following neurological injury [24], cortical motor representation mapping has more recently been used in musculoskeletal injury research examining the effects of spatial reorganization on neuromuscular function. Alterations in cortical representation position and size have been found for forearm extensors in individuals with lateral elbow pain [22] and in the transversus abdominus in individuals with recurrent low back pain [23], but have yet to be investigated in relation to the quadriceps following ACL injury.

Identifying and understanding CNS adaptations contributing to quadriceps dysfunction would provide novel therapeutic targets within the motor cortex that may lead to improved quadriceps muscle function following ACL injury. Previous corticomotor excitability studies following ACL injury or reconstruction have focused primarily on evaluation of the single joint vasti muscles [2,4,7,12]. However, there is value in exploring changes in rectus femoris following ACL injury as it has been shown that all portions of the quadriceps work to enable knee extension and loading control [25]. Given that the rectus femoris spans two joints, it is possible that it is under differential cortical control compared to the single joint vasti and thus may not be affected to the same extent as the vasti following ACL injury.

Therefore, the aims of this study were: 1) to examine rectus femoris corticomotor excitability and intracortical inhibition in individuals with an ACL injury compared to healthy uninjured individuals, and 2) to determine the calculated center position and area of the rectus femoris cortical motor representation following ACL injury compared to healthy uninjured individuals. We hypothesized that there would be a significant reduction in rectus femoris active motor threshold (AMT), MEP amplitude and cortical motor representation area (size) (H_1), and that there would be a significant increase in intracortical inhibition (SICI, LICI and cSP) in those with an ACL injury compared to healthy uninjured individuals (H_2).

2. Methods

2.1. Study design

This was a cross-sectional laboratory study examining rectus femoris corticomotor excitability, intracortical inhibition and cortical motor representation in a group of individuals with ACL injury, as well as a group of healthy control participants. All main outcome measures were collected during a single data collection session. All participants gave written informed consent, and the study was approved by the Ethics Committee of the University of Melbourne (ID: 1340551).

2.2. Participants

All ACL injured participants were recruited from two orthopedic surgeons within the Melbourne metropolitan area. We included individuals between the ages of 18 to 50 years old, within eight months of an initial isolated ACL injury and no meniscal trauma requiring meniscectomy. Those with multi-ligament trauma, chondral defects (grades III to IV), and previous ACL injury and/or surgery on either limb were excluded. In addition to the ACL group, a control group of healthy, recreationally active men and women with no history of lower limb musculoskeletal injury in the past year that limited function for more than one week, or required surgical intervention were recruited from the university community. Each participant completed a 15-item questionnaire to assess for any contraindications to non-invasive brain stimulation [26]. No participant in either group reported any neurological or medical condition that would contraindicate TMS. Leg dominance was self-reported and determined by the foot preferred for kicking a ball [27].

2.3. Instrumentation

Quadriceps contraction intensity during TMS was measured via a force transducer (Sensortronics 60001 Scale Components, Australia), attached to the distal shin one centimeter proximal to the malleoli using a soft Velcro cuff. All participants were securely seated for testing in a supportive chair, to keep the hip joint at 90° and knee joint at 60° of flexion.

A Bi-Stim^2 magnetic stimulator (Magstim Co, UK) producing a monophasic pulse shape, with a figure-of-eight 70 mm coil (Magstim Co, UK) held tangential to the skull was used to examine corticomotor excitability, intracortical inhibition and the cortical motor representation. A custom designed form-fitting cap (EasyCap, Germany), with stimulus sites marked at one centimeter spacing in latitude and longitude, was fitted to the participant's head with the vertex aligned with the center of the cap co-ordinates [28]. The placement of the cap was continuously monitored during testing to ensure consistency of the site of stimulation.

A Trigno wireless electromyography (EMG) sensor (Delsys, USA) was affixed to the skin with double-sided tape over the rectus femoris muscle belly halfway between the anterior superior iliac spine and patella in the direction of muscle fiber orientation [29]. The rectus femoris muscle was identified via palpation during manually resisted knee extension in a seated position. Prior to attaching the EMG sensor the skin site was prepared by shaving, debriding, and cleaning with alcohol wipes [30]. EMG signals were sampled at 2000 Hz for 500 ms, and EMG amplification was set at a gain of 1000 (PowerLab 4/35 ADInstruments, USA) with a 10 Hz highpass filter. The common mode rejection ratio of the EMG amplifier was 100 dB with an input impedance of one megaohm.

2.4. Knee function

The Knee Injury and Osteoarthritis Outcome Score (KOOS) was used to assess self-reported knee function, and is a valid measure of function following knee injury [31]. A Visual Analogue Scale (VAS), a

unidimensional measure of pain intensity, was used to measure pain levels. A horizontal line of 100 mm was used in this study [32].

2.5. Corticomotor excitability and intracortical inhibition

Corticomotor excitability was examined in terms of AMT, and MEP amplitude at 120% AMT [2,12,33]. Sites near the estimated center of the rectus femoris area (one to three centimeters lateral to the vertex) were explored to determine the site at which the largest MEP could be obtained [11]. The site with the largest MEP amplitude was defined as the 'optimal site' where AMT was established for both left and right rectus femoris. For this study AMT was defined as the minimum stimulus intensity required to elicit a MEP of >200 μV in three out of five stimulations while the participant maintained a slight contraction in the rectus femoris (10% of body weight) [10]. A body weight adjusted force target was used rather than percentage of maximum voluntary isometric contraction (MVIC), as it was not feasible to get an accurate assessment of MVIC in individuals with an ACL injury because of limitations associated with joint effusion and muscle inhibition [34]. A target torque line and a depiction of the participant's quadriceps torque in real-time were displayed on a computer screen using a custom LabVIEW program to provide visual feedback regarding contraction intensity. MEP amplitudes were analyzed offline (LabChart 8, USA) via examination of the peak-to-peak values, averaged and expressed in mV.

The TMS intensity for the cSP was set at 120% of AMT. Four TMS were delivered at five second intervals over the optimal stimulation site while the participant maintained a contraction of the rectus femoris at 10% of body weight. The duration of the cSP was determined by averaging the four trials for each participant. Each trial was visually inspected, and the duration measured from the onset of the MEP to the return of uninterrupted EMG activity [35]. In the instances where EMG returned gradually the criteria for the end of the cSP was when the EMG activity reached and exceeded the pre-TMS baseline level [11]. Prior to assessing intracortical inhibition, one set of eight unconditioned stimuli were delivered at 110% AMT, while the participant maintained a quadriceps contraction at 10% of body weight, for the purposes of normalizing SICI and LICI [17,18]. SICI was measured using a subthreshold conditioning stimulus set at 80% of AMT, and a second suprathreshold test stimulus set at 110% AMT, with a two millisecond inter-stimulus interval [15,16,36]. LICI was measured with two suprathreshold pulses at 110% AMT with a 100 ms inter-stimulus interval [15,16,36]. SICI and LICI were quantified as a percentage of the unconditioned stimuli delivered at 110% AMT [16].

2.6. Cortical motor representation mapping

The stimulus intensity used to determine the cortical motor representation area, or cortical map, was set at 120% of AMT for each individual. The protocol consisted of delivering TMS while participants contracted the quadriceps to maintain a knee extension force at 10% of body weight. Four stimuli were delivered at each site a minimum of five seconds apart with 30 s rest between the sites, starting at the identified optimal site and then moving in an anterior direction, then in a posterior direction until an observable MEP could no longer be elicited. A similar pattern was repeated for lateral and medial sites until all map borders had been determined.

The cortical motor representation maps were generated via custom LabVIEW software incorporating the Advanced Signal Processing Toolkit (National Instruments, USA), using a previously published protocol replicating prior work by Borghetti et al. (2008) [37]. The mean MEP amplitude, and the *x* and *y* coordinate location of the coil at each stimulus site were saved to a text file, and then spline interpolated in two dimensions to create a topographic map of the intensity of the MEP with a position resolution of one millimeter for each axis [37]. From the results of this interpolation two outcome measures were derived: 1) center of gravity (CoG), which is the amplitude weighted indication of map position [38] expressed for both the *x*-axis (mediolateral) and *y*-axis (anteroposterior) for each individual; and 2) area, which represents the surface area on the map which exceeds a threshold of 66% of the peak MEP value [39]. All map-derived outcome measures were expressed in millimeters from the vertex and inter-aural line.

2.7. Statistical analysis

We determined that a minimum of 14 participants would be needed to detect statistical significance ($\beta = 80\%$, $\alpha = 0.05$) for strong standardized mean differences ($d = 1.07$) between limbs and groups using previously published AMT means [2]. We determined the percentage of dominant limbs that were injured in the ACL participants, and randomly assigned which of the control participants would contribute a dominant limb as an injured match.

Before conducting the primary analyses, normality of all data was analyzed using the Shapiro–Wilk test. For normally distributed data independent sample *t*-tests were used to compare participant demographics, KOOS self-reported knee function and pain. The Mann–Whitney *U* test was used for comparisons between group demographics for data that was not normally distributed. All TMS derived outcome measures were normally distributed. The primary analyses were a series of mixed 2 × 2 (limb × group) analysis of variance (ANOVA) with limb being a repeated measure, examining differences in quadriceps corticomotor excitability, intracortical inhibition, and motor map center position and area between the ACL and control groups.

In the event of a significant limb by group interaction, separate corrected paired *t*-tests were used to compare means between limbs within each group and corrected independent sample *t*-test was used to compare limb means between the ACL and control groups. The alpha level for all *t*-tests was set at $P < 0.017$ (0.05/3). Statistical analyses were performed using Statistical Package for Social Sciences (SPSS) Version 21.0 (IBM Corporation, Chicago IL) and the level of significance was set a priori at $P < 0.05$.

3. Results

3.1. Participant characteristics

Eighteen (n = 18) individuals with ACL injury, and 18 uninjured healthy individuals participated in the study. Participant demographics are provided in Table 1. Individuals with ACL injury had significantly lower self-reported knee function (KOOS-Pain, KOOS-ADL, KOOS-Symptoms and KOOS-QoL) and significantly higher self-reported pain compared to uninjured controls, but no other significant differences were found between groups (Table 1).

3.2. Corticomotor excitability and intracortical inhibition

There was a significant limb by group interaction ($F_{1,32} = 4.487$, $P = 0.043$) for the cSP. The cSP duration was longer in the injured limb compared to the uninjured limb in the ACL group ($P = 0.004$). There were no differences in cSP duration between injured

Table 1
Participant demographics given as the mean (SD) or the number.

	ACL group	Control group	P-value
Age (years)	29.6 ± 8.4	29.2 ± 6.8	0.868
Height (m)	1.74 ± 0.07	1.79 ± 0.07	0.076
Mass (kg)	76.0 ± 10.4	79.0 ± 8.4	0.357
Body Mass Index (kg·m^2)	24.8 ± 2.3	24.6 ± 2.3	0.763
KOOS-Pain	73 ± 19*	99 ± 3	<0.001
KOOS-ADL	78 ± 17*	99 ± 1	<0.001
KOOS-Symptoms	68 ± 19*	99 ± 2	<0.001
KOOS-QoL	38 ± 22*	100 ± 0	<0.001
VAS (cm)	1.4 ± 1.7*	0 ± 0.0	0.005
ACL limb (R/L)	12/6	N/A	N/A
Dominant limb (R/L)	17/1	17/1	N/A
Days post-injury	69.5 ± 42.5	N/A	N/A
Male/female	12/6	12/6	N/A

ACL anterior cruciate ligament; ADL — activities of daily living; KOOS — knee osteoarthritis outcome score; QoL — quality of life; VAS — visual analogue scale.
* Different to healthy control group. Alpha level P < 0.05.

and matched limbs when comparing the ACL group to the control group ($P = 0.281$), and no difference between limbs in the control group ($P = 0.829$). There was no significant interactions or main effects for AMT, MEP amplitude, SICI or LICI measures ($P > 0.05$) (Table 2).

3.3. Cortical motor representation

The mean *x*- and *y*-CoG, and map area for each limb are shown in Table 2. There was no significant interactions or main effects for the *x*-axis or *y*-axis CoG position, or for the area of the cortical motor representation ($P > 0.05$) (Table 2).

3.4. Post hoc analysis

To help interpret the results, we determined the association between corticomotor excitability, intracortical inhibition and cortical motor representation and time since injury in the ACL group [40]. We conducted separate Pearson Product Moment correlations with the significance set at $P < 0.05$. The time since injury ranged from 11 to 143 days in this study (mean ± SD in Table 1). There were no significant associations between time since injury, and measures of corticomotor excitability (AMT $r = 0.095$ $P > 0.05$; MEP $r = 0.313$ $P > 0.05$), intracortical inhibition (SICI $r = 0.530$ $P > 0.05$; LICI $r = 0.001$ $P > 0.05$) or the cortical motor representation position (APCoG $r = 0.344$ $P > 0.05$; MLCoG $r = 0.083$ $P > 0.05$) and area ($r = 0.265$ $P > 0.05$).

4. Discussion

The aim of the present study was to examine rectus femoris corticomotor excitability and cortical motor representation in individuals with an isolated ACL injury, compared to healthy uninjured individuals. To our knowledge this is the first study to examine these TMS-related measures in rectus femoris. We found the duration of the cSP to be longer in the injured limb only of the ACL group, compared to the uninjured limb of the ACL group and matched limbs of the control group. Contrary to our primary hypothesis (H_1) we did not find any alterations in rectus femoris corticomotor excitability or the center position of the cortical motor representation between the injured and uninjured limbs of the ACL group, and matched limbs of the control group. Again in contrast to our hypothesis (H_2), there were no differences in SICI or LICI in those with an ACL injury compared to healthy uninjured individuals.

The cSP is a gross measure of corticomotor excitability, and thought to originate primarily in the motor cortex via activation of cortical GABAergic inhibitory interneurons, with the initial 50 ms mediated by spinal interneurons [14,35]. Although alterations in the cSP duration have been demonstrated in movement disorders [20,41,42] the cSP has not been widely investigated following musculoskeletal injury, and there is mixed evidence regarding the effect of injury on cSP duration. A previous study involving individuals with an ACL injury found that there were no side-to-side differences in quadriceps cSP following ACL injury, assessed from the distal rectus femoris [7]. However, a recent knee joint effusion study found a significant reduction in quadriceps cSP duration following experimental effusion [43]. Contrary to previous findings, the current study found a significantly longer cSP duration in the injured limb compared to both the uninjured limb and to those of the matched controls. It is probable that differences in experimental effusion studies and the pathological effects of ACL injury may contribute to the observed difference in results from the current study. A prolonged cSP is suggestive of an increase in GABA mediated inhibition, however we found no associated increase in intracortical inhibition or reduced corticomotor excitability following ACL injury in the current study.

The cSP duration is a gross measure of corticomotor excitability, while SICI and LICI provide more specific probes of intracortical circuits [14–16,36]. It is possible that changes at the spinal reflex excitability level underlie changes in cSP duration, while cortical excitability remains unchanged following ACL injury. It is possible that the prolonged cSP duration may be contributing to quadriceps dysfunction in these individuals, however the clinical significance of a 20 ms difference remains unknown. Additionally, although every precaution was taken to minimize errors, it is possible that measurement error occurred. Although the cSP is thought to originate primarily in the motor cortex, other non-primary motor areas in the brain can influence cSP duration [14]. The TMS set-up used in the current study only allowed for assessment of the primary motor cortex response to an ACL injury, so it is possible that alterations in non-primary motor areas following ACL injury may also play a role.

Altered corticomotor excitability has previously been reported in individuals who were on average 22 months post ACL injury [7]. Heroux and Tremblay [7] reported that AMT was elevated overall following ACL injury, with an asymmetry between limbs in those with an ACL injury (higher in the injured limb). Differences in TMS coil and the use of active rather than resting motor threshold in the current study may contribute to observed differences in results between the present study and those of Heroux and Tremblay [7]. The participants in the present study were on average 69.5 ± 42.7 days post-injury, thus it is possible that it requires a longer time post-injury for cortical changes to manifest. Post hoc analysis of our data showed no association between time since injury and corticomotor excitability, intracortical inhibition or cortical representation. A recent longitudinal study by Lepley et al. [2] demonstrated no alteration to quadriceps corticomotor excitability following ACL injury (average 37.1 ± 15.3 days post-injury); however, there were significant reductions in quadriceps spinal reflex excitability in the ACL group compared to healthy uninjured controls. These data from Lepley et al. [2] further support the view that corticomotor excitability is not altered following ACL injury.

The inability to fully and voluntarily contract a muscle is known as arthrogenic muscle inhibition or reflex inhibition [44]. The concept of reflex inhibition of the quadriceps has been consistently mentioned as a contributing factor to strength deficits in the muscle group following ACL injury or reconstruction [1,9,45]. Joint damage, pain and swelling associated with injury and surgery are thought to alter the ascending signal from the knee joint to the CNS, resulting in inhibitory descending signals to the quadriceps α-motor neuron pool and thus, a reduction in the ability to voluntarily activate the muscle. Simulated acute injury

Table 2
Quadriceps corticomotor excitability, intracortical inhibition and cortical motor representation measures between limbs given as the mean (SD).

	ACL group		Control group	
	Injured limb	Uninjured limb	Matched injured limb	Matched uninjured limb
AMT (%)	51.8 ± 9.9	50.1 ± 9.2	53.3 ± 8.9	53.4 ± 7.9
MEP (mV)	0.56 ± 0.23	0.58 ± 0.23	0.63 ± 0.44	0.60 ± 0.51
x-CoG (cm)	1.6 ± 0.37	1.6 ± 0.46	1.6 ± 0.34	1.7 ± 0.56
y-CoG (cm)	0.27 ± 0.66	0.43 ± 0.33	0.39 ± 0.48	0.52 ± 0.34
Area (cm^2)	0.77 ± 0.51	0.92 ± 0.57	0.79 ± 0.67	0.76 ± 0.75
cSP (ms)	110 ± 30*	99 ± 27	97 ± 31	96 ± 30
SICI (%)	59.3 ± 19	59.6 ± 22	58 ± 23	64 ± 19
LICI (%)	58.6 ± 21.5	54.4 ± 22	54.9 ± 13	52.8 ± 15

ACL — anterior cruciate ligament; AMT — active motor threshold; MEP — motor evoked potential; CoG — center of gravity (center position); cSP — cortical silent period; SICI — short interval intracortical inhibition; LICI — long interval intracortical inhibition.
* Different to uninjured limb, and healthy control limbs. Alpha level $P < 0.05$.

models using knee joint effusion have demonstrated immediate alterations to the quadriceps spinal reflex excitability [44,46], but no changes in corticomotor excitability acutely following effusion [47]. Although we had no measure of spinal reflex excitability in the present study, previous studies have demonstrated decreased Hoffman reflexes (H-reflex) in the quadriceps following ACL injury [2,7]. Quadriceps spinal reflex excitability differs compared to uninjured controls in the initial weeks post ACL injury and remains lower immediately following ACLR (<2 weeks). In the same cohort of individuals with ACL injury, corticomotor excitability was not different between groups prior to surgery or two weeks following ACLR, yet corticomotor excitability decreased in the ACL reconstructed individuals six months after reconstruction compared to the healthy controls [2]. These results from rectus femoris and the vasti studies would suggest that quadriceps corticomotor excitability is not altered following ACL injury, and is not contributing to quadriceps dysfunction following injury.

Alterations in afferent input to the CNS have been found to be capable of inducing cortical motor representation reorganization [48]. Repetitive aberrant afferent input to the CNS from altered motor patterns appears to be key to maladaptive cortical reorganization following injury [22]. In this manner spatial reorganization within the primary motor cortex has been demonstrated in chronic musculoskeletal conditions [22,23]. Alternatively the loss of afferent input such as that following amputation [24,49] and immobilization [21] can also induce significant alterations in terms of size, shape and position of the cortical motor representations. Spatial reorganization in the cortical motor representation has been associated with neuromuscular dysfunction in recurrent low back pain [23], and in lateral elbow pain conditions [22]. A posterior and lateral shift in the cortical motor representation center position for the deep transversus abdominus muscles has been reported in patients with recurrent low back pain, and is associated with delayed onset of transversus abdominus contraction compared to healthy individuals [23]. Although there is a lack of studies assessing spatial reorganization in the lower limb from which to draw comparisons, it is conceivable that there are similar changes occurring in terms of quadriceps cortical motor representation center and size following ACL injury.

Previous studies have argued that ACL injury can be viewed as a deafferentation injury [8,50]. Temporary deafferentation of the lower limb using a removable ischemic block results in a rapid increase in excitability of the cortical motor representation of muscles proximal to the block [51]. This increase in MEP amplitude is thought to come about from removal of GABA mediated inhibition within the cortex. However, following ACL injury there appears to be no alterations in GABA mediated intracortical inhibition or corticomotor excitability that may be required to generate reorganization within the cortical motor representation. Although there was a significant difference in self-reported pain between those with an ACL injury and healthy controls, the ACL group reported less pain than expected thus the ACL group in this study would be considered relatively high functioning. It is possible that corticospinal excitability may be less affected in individuals who report less pain following ACL injury. Nociceptor-mediated pain, such as that seen following ACL injury or in osteoarthritis, may not be sufficient enough to induce the changes seen in neuropathic driven pain conditions such as chronic low back pain [23,52]. Thus it is possible that ACL injury does not evoke a sufficient neurological insult to drive corticospinal or intracortical changes in relation to the quadriceps, particularly in the absence of high or prolonged pain.

4.1. Limitations

A homogenous group of individuals with isolated ACL injury were recruited for the current study therefore it is possible that they had less neural reorganization than the general ACL injury population. Furthermore, this study focused on assessing excitability of the rectus femoris, which may not be affected to the same extent as the vasti following ACL injury and ACLR [2,7,12]. No measures of quadriceps strength or voluntary activation were collected and as such it is unclear if the participants demonstrated comparable neuromuscular function to a general group of ACL injured individuals. The sample size in the current study was powered to detect large differences between groups and as such was underpowered to detect smaller differences as statistically significant. However, previous analogous studies with similar outcome measures have used comparable sample sizes (n = 20 Lepley et al. [2], and n = 17 Kittelson et al. [18]).

4.2. Conclusion

Understanding the underlying mechanisms of ongoing quadriceps dysfunction following ACL injury is clinically important. The results of the current study indicate that changes in rectus femoris corticomotor excitability and spatial reorganization may not present in individuals with an ACL injury. The longer cSP duration in the involved limb of the ACL group may indicate changes in GABA mediated inhibition. However, the clinical meaningfulness of the prolonged cSP is unknown, particularly in the absence of differences in intracortical inhibition between those with an ACL injury and healthy controls. Therefore, interventions targeting the cortical level may not be the best way to improve quadriceps strength and function immediately following ACL injury.

Conflict of interest

The authors declare that they have no conflicts of interest.

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