



Single bout of vibration-induced hamstrings fatigue reduces quadriceps inhibition and coactivation of knee muscles after anterior cruciate ligament (ACL) reconstruction

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ABSTRACT

Persistent quadriceps strength deficits in individuals with anterior cruciate ligament reconstruction (ACLR) have been attributed to arthrogenic muscle inhibition (AMI). The purpose of the present study was to investigate the effect of vibration-induced hamstrings fatigue on AMI in patients with ACLR. Eight participants with unilateral ACLR (post-surgery time: M = 46.5, SD = 23.5 months; age: M = 21.4, SD = 1.4 years) and eight individuals with no previous history of knee injury (age: M = 22.5, SD = 2.5 years) were recruited. A fatigue protocol, consisting of 10 min of prolonged local hamstrings vibration, was applied to both the ACLR and control groups. The central activation ratio (CAR) of the quadriceps was measured with a superimposed burst of electrical stimulation, and hamstrings/quadriceps coactivation was assessed using electromyography (EMG) during isometric knee extension exercises, both before and after prolonged local vibration. For the ACLR group, the hamstrings strength, measured by a load cell on a purpose-built chair, was significantly ($P = 0.016$) reduced about 14.5%, indicating fatigue was actually induced in the hamstrings. At baseline, the ACLR group showed a trend ($P = 0.051$) toward a lower quadriceps CAR (M = 93.2%, SD = 6.2% versus M = 98.1%, SD = 1.1%) and significantly ($P = 0.001$) higher hamstrings/quadriceps coactivation (M = 15.1%, SD = 6.2% versus M = 7.5%, SD = 4.0%) during knee extension compared to the control group. The fatigue protocol significantly ($P = 0.001$) increased quadriceps CAR (from M = 93.2%, SD = 6.2% to M = 97.9%, SD = 2.8%) and significantly ($P = 0.006$) decreased hamstrings/quadriceps coactivation during knee extension (from M = 15.1%, SD = 6.2% to M = 9.5%, SD = 4.5%) in the ACLR group. In conclusion, vibration-induced hamstrings fatigue can alleviate AMI of the quadriceps in patients with ACLR. This finding has clinical implications in the management of recovery for ACLR patients with quadriceps strength deficits and dysfunction.

1. Introduction

There are about 250,000 cases of anterior cruciate ligament (ACL) tears each year in the United States (Lyman et al, 2009), making it one of the most commonly treated knee injuries with an annual cost of \$17.7 billion when treated with rehabilitation (Gottlob et al, 1999; Griffin et al., 2005). Serious ACL injuries require surgery to restore normal knee function. However, persistent muscle deficits in the quadriceps resulting from arthrogenic muscle inhibition (AMI) are still observed years after ACL reconstruction (ACLR) surgery (Snyder-Mackler et al, 1994). Changes in knee kinematics and kinetics due to AMI cause a higher risk of post-traumatic knee osteoarthritis for individuals with ACL injuries (Palmieri-Smith and Thomas, 2009). In addition, greater hamstrings/quadriceps coactivation during knee

extension in individuals with ACLR increases the compressive force at the knee joint, resulting in a higher risk for knee osteoarthritis (Tsai et al, 2012). On average, 50 percent of people with ACL injuries will develop knee osteoarthritis 10 to 20 years after diagnosis of ACL tear (Lohmander et al, 2007).

It is generally accepted that changes in the afferent discharge of joint receptors after knee injury are associated with AMI (Hopkins and Ingersoll, 2000). Abnormal afferent discharge may change the excitability of the reflex pathways within the spinal cord. Three spinal pathways have been suggested as potential mechanisms for AMI (Rice and McNair, 2010), including the group I nonreciprocal (Ib) inhibitory pathway, the gamma (γ)-loop pathway, and the flexion reflex pathway. The group I nonreciprocal (Ib) inhibitory pathway is supported by the relationship between joint afferent discharge and Ib interneuron

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activity in animal studies (Harrison and Jankowska, 1985; Lundberg et al, 1978) as well as human knee effusion model (Iles et al, 1990). The γ -loop pathway suggests that ACL injury results in the disruption of excitatory joint afferent output to the quadriceps γ -motoneuron pool, reducing γ -motoneuron discharge and consequently Ia afferent facilitation of the quadriceps α motoneuron pool (Johansson et al, 1991; Konishi et al, 2007, 2002b, 2003; Richardson et al, 2006). The flexion reflex pathway, producing overexcitation of the hamstrings and reciprocal inhibition of the quadriceps, is also suggested as one spinal reflexive mechanism for quadriceps AMI (Engelhardt et al, 2001; Pietrosimone et al, 2015; Rice et al, 2015; Snyder-Mackler et al, 1994; Young, 1993). Animal studies (You et al, 2003) suggest that wide dynamic range neurons may play an important role in mediating the flexion reflex. The activation threshold of wide dynamic range neurons is gradually reduced following joint injury in cats (Neugebauer and Schaible, 1990). Clinical studies have also shown that flexion reflex thresholds are lower in patients with knee osteoarthritis and knee pathology compared with age- and gender-matched controls (Courtney et al, 2009; Leroux et al, 1995). These three spinal pathways may not be mutually exclusive in controlling the magnitude of AMI (Rice and McNair, 2010). Other spinal pathways (e.g., recurrent inhibition) are also possible (Palmieri et al, 2004, 2005; Palmieri-Smith and Thomas, 2009).

In addition to spinal projections, joint afferents also have extensive supraspinal projections (Rice and McNair, 2010). Recent studies (Lepley et al, 2019; Needle et al, 2017; Neto et al, 2019; Pietrosimone et al, 2015; Ward et al, 2019) have examined changes in corticospinal excitability associated with ACL injury and reconstruction using transcranial magnetic stimulation (TMS) as well as functional magnetic resonance imaging (fMRI). These studies indicate that neuroplasticity of the motor cortex develops as a chronic adaptation of joint injury, which may also contribute to the clinical outcome such as persistent deficits of muscle strength (Needle et al, 2017).

Therefore, the objective of our research is to identify a rehabilitation strategy to alleviate AMI by modifying the sensory signals involved in the quadriceps inhibition. Muscle fatigue, the inability to maintain a desired force output (Basmajian and De Luca, 1985), has been shown to modify hamstring excitability and change the hamstring reflex response (Behrens et al, 2015; Melnyk and Gollhofer, 2007; Wojtys et al, 1996). In our previous study (Lowe and Dong, 2018), we demonstrated that hamstrings fatigue was an effective strategy to reduce quadriceps inhibition after ACLr by decreasing the over-excitability of the flexion reflex pathway. However, the conventional high-intensity whole-body exercises, such as the tempo squats that were used in our previous study, may not be appropriate for rehabilitation of patients with ACLr who are load-compromised.

A local muscle vibration technique, in which a participant receives vibration over the tendon or muscle belly from a portable vibrator (Souron et al, 2017b), may be an alternative to whole-body exercises to induce hamstrings fatigue for ACL rehabilitation. Fatigue is defined as a disabling symptom in which physical and cognitive function is limited by interactions between performance fatigability and perceived fatigability (Enoka and Duchateau, 2016; Kluger et al, 2013). Performance fatigability delineates the decline in an objective measure of performance over a discrete period, consisting of two domains: contractile function (peripheral) and muscle activation (central) (Enoka and Duchateau, 2016), and perceived fatigability indicates the changes in the sensations that regulate the integrity of the performer. Prolonged local vibration has been shown to induce muscle fatigue (Souron et al, 2017b) and result in a decrease of the endurance time during sustained submaximal voluntary contractions (Rothmuller and Cafarelli, 1995) and a faster force decline during sustained maximal voluntary contractions (Bongiovanni et al, 1990; Samuelson et al, 1989).

Vibration-induced muscle fatigue could arise from changes in performance fatigability: contractile function and/or muscle activation. Prolonged local muscle vibration using 20–30 min, 70–100 Hz

frequencies and 1–1.5 mm amplitudes did not change muscle properties such as electrically elicited twitch amplitude (Fry and Folland, 2014; Saito et al, 2016), contraction time and half contraction time (Ushiyama et al, 1985). In addition, maximal muscle response waves (M-wave) were not influenced by prolonged muscle vibration (Fry and Folland, 2014; Saito et al, 2016; Ushiyama et al, 1985), suggesting that neuromuscular propagation failure is not present. Therefore, vibration-induced muscle fatigue is not likely due to changes in contraction function (Souron et al, 2017b).

Vibration-induced muscle fatigue may be due to changes in neural drive happening at spinal and/or supraspinal levels (Souron et al, 2017b). Decreased spinal loop excitability has been suggested as a mechanism of force reductions (Herda et al, 2009; Jackson and Turner, 2003; Richardson et al, 2006; Ushiyama et al, 1985) due to reductions of the Hoffman reflex (H-reflex) after prolonged muscle (Fry and Folland, 2014; Heckman et al, 1984; Lapole et al, 2012; Ushiyama et al, 1985). Furthermore, a recent study (Souron et al, 2019) suggests that postsynaptic changes, rather than presynaptic mechanisms, are responsible for the depression of spinal loop excitability after local muscle vibration.

Therefore, in the present study we planned to answer the research question whether vibration-induced hamstrings fatigue would reduce the excitability of the hamstrings and consequently disinhibit the quadriceps, and further, decrease the hamstrings/quadriceps coactivation during knee extension for individuals with ACLr. Additionally, we would like to investigate whether individuals with ACLr would regain quadriceps strength during this period of quadriceps disinhibition.

2. Methods

2.1. Experimental design

The experimental design of this project was a pre-post study with two arms: ACLr and control groups. Two groups of participants, ACLr and control groups, were recruited for this study through convenience sampling using college student volunteers at our academic institution. IRB approval was given by our Institutional Review Board. Experimental procedures were explained to each participant and written informed consent was obtained prior to testing. Briefly, each participant performed a 5-min warm-up exercise on a cycle ergometer (Monark 828E Ergometer), pedaling at approximately 80–90 rpm with a low resistance of 2.5 kg. Then, quadriceps strength, hamstrings strength, quadriceps inhibition and hamstrings/quadriceps coactivation were assessed from a quadriceps MVIC (knee extension) and a hamstrings MVIC (knee flexion) before and after a prolonged local vibration of the hamstrings for both ACLr and control groups.

2.2. Participants

The sample size (N = 16) of this study was determined from the power analysis using a significance level of 0.05, a statistical power of 0.8, and an effect size (partial eta squared) of 0.231 for the central activation ratio of the quadriceps based on the results of our previous study (Lowe and Dong, 2018). Eight participants (age: M = 21.4, SD = 1.4 years; post-surgery time: M = 46.5, SD = 23.5 months; 3 males and 5 females, Table 1) who had undergone unilateral ACLr were recruited. Eight participants (age: M = 22.5, SD = 2.5 years; 2 females and 6 males, Table 1) with no previous history of knee injury were recruited as the control group. For participants in the ACLr group, four of them played highly competitive sports, one was well-trained and played sports frequently, two played sports sometimes, and one was non-sporting (Table 1). For participants in the control group, two of them played highly competitive sports, two were well-trained and played sports frequently, two played sports sometimes and two were non-sporting (Table 1). No significant differences in age, height, or weight were observed between the ACLr and control groups (Table 1).

Table 1
Demographic variables (Mean \pm Standard Deviation) of ACLr and control groups.

	ACLR (n = 8)	Control (n = 8)
Age (years)	21.4 \pm 1.4	22.5 \pm 2.5
Height (cm)	172.7 \pm 6.5	171.1 \pm 7.1
Mass (kg)	74.1 \pm 14.4	69.4 \pm 13.6
Post-surgery time (months)	46.5 \pm 23.5	
Graft type	patella tendon grafts (4) hamstrings tendon grafts (4)	
Type of injury	traumatic non-contact onset (3) non-traumatic sudden onset (3) traumatic contact onset (2)	
Activity level	highly competitive sporting (4) well-trained and frequently sporting (1) sporting sometimes (2) non-sporting (1)	highly competitive sporting (2) well-trained and frequently sporting (2) sporting sometimes (2) non-sporting (2)

Additional demographic information was available in Table 1.

2.3. Quadriceps strength and voluntary activation

The quadriceps inhibition of each participant was assessed through the central activation ratio (CAR) with a superimposed burst technique (Hart et al, 2010; Sedory et al, 2007; Snyder-Mackler et al, 1994). Participants were seated upright with knees and hips flexed at 90° (Fig. 1a) on a purpose-built chair (Lowe and Dong, 2018). Quadriceps strength was measured through a load cell (LCCA 200, Omega Engineering Inc., Stamford, Connecticut) mounted on the purpose-built chair (Fig. 1a). The load cell was connected to a Data Acquisition System (MP150; BIOPAC, Goleta, CA) with a sampling rate of 200 Hz. First, warm-up contractions in a series of submaximal isometric knee-extension contractions at 25%, 50% and 75% of their perceived maximal efforts were performed to minimize the risk of injury (Norte et al, 2015). Then, participants were asked to perform a maximum voluntary isometric contraction (MVIC) of knee extensors for at least 3 s, with verbal encouragement and visual feedback to motivate the participant. After a force plateau (F_{MVIC}) was reached (Fig. 1b), a superimposed burst (SIB) was delivered using a constant current electrical stimulator (DS7AH, Digitimer Ltd., UK). The trigger signals of DS7AH came from a train of 10 pulses at 100 Hz (Fig. 1a) provided by an analog output feature of an MP150 system (BIOPAC, Goleta, CA) using AcqKnowledge 4.4 (BIOPAC, Goleta, CA), a software package for the MP150 system. The MP150 system was able to output TTL trigger pulses through its analog channel. The TTL trigger pulses were delivered to DS7AH through a BNC cable and electrical stimuli from DS7AH were generated for the superimposed burst technique. One self-adhesive stimulating electrode (40x50 mm) was placed near the proximal rectus femoris

muscle and another stimulating electrode was placed over the vastus medialis (Norte et al, 2015; Pamukoff et al, 2017). The stimulus consisted of a train of 10 pulses; each pulse was 0.5 ms and was delivered at 100 Hz with 125 V with a predetermined individual-specific current intensity (Krishnan and Williams, 2009; 2011; Pamukoff et al, 2017). The electrical stimulus train caused a temporary increase in force output (F_{SIB} , Fig. 1b). F_{SIB} is defined as the additional force produced during the superimposed burst with the MVIC (Fig. 1b). The CAR was calculated as the ratio of F_{MVIC} over the sum of F_{MVIC} and F_{SIB} (Sedory et al, 2007). Quadriceps strength was defined as the peak force during the plateau of the MVIC of knee extension (F_{MVIC} , Fig. 1b). Three trials were collected, and averaged together, for each participant before and after the prolonged local vibration of the hamstrings.

2.4. Hamstrings strength and coactivation

To measure the hamstrings strength before and after the prolonged vibration, the participant was seated on the opposite side of the purpose-built chair with a Velcro strap connecting their lower leg to the load cell through a steel wire (Fig. 2a). Hamstrings strength was defined as the peak force during the plateau of the MVIC of knee flexion and was measured through a load cell mounted on the purpose-built chair (Fig. 2b).

Hamstrings/quadriceps coactivation was quantified through a wireless electromyography (EMG) system (BioNomadix, BN-EMG2, BIOPAC Systems, Goleta, CA) and was measured as the amount of hamstrings activation (normalized to maximum) during a quadriceps MVIC (Stevens-Lapsley et al., 2010). The BioNomadix amplifier has the following parameters (CMI: 1000 M Ω at 60 Hz; CMRR: 110 dB at 60 Hz; bandwidth: 5 Hz to 500 Hz; fixed gain: 2,000). Two surface

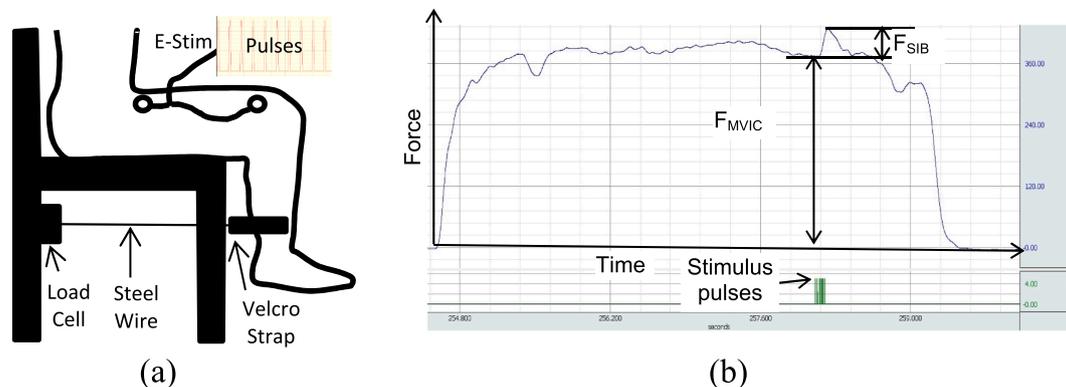


Fig. 1. Quantification of quadriceps inhibition by measuring the central activation ratio with a superimposed burst technique. (a) A custom-built chair to measure the quadriceps extension force through a load cell connecting to a steel wire and a Velcro strap; an electrical stimulator is used to provide a superimposed burst with a train of 10 pulses at 100 Hz, 0.5 ms pulse width and 125 V. (b) F_{MVIC} is the extension force of the quadriceps muscles during the MIVC; F_{SIB} is the force produced during the superimposed burst with the MVIC.

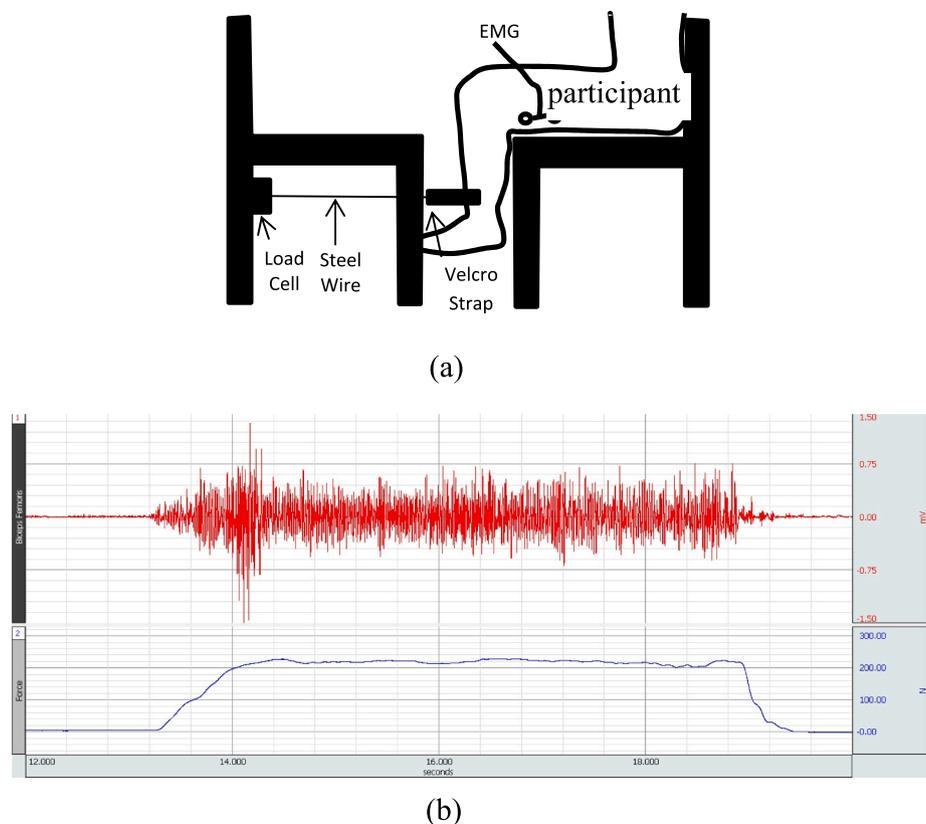


Fig. 2. (a) Hamstrings strength was measured using the purpose-built chair during the hamstrings MVIC; The participant was seated on another chair opposite to the purpose-built chair. (b) An example of load vs. time curve and raw EMG data of biceps femoris during the hamstrings MVIC.

electrodes (10 mm diameter, 20 mm inter-electrode distance; EL504, BIOPAC) were placed over the muscle belly of the biceps femoris according to the European Recommendations for Surface Electromyography (SENIAM) (Hermens, 1999; Hermens et al, 2000). The electrodes were placed at 50% of the distance between the ischial tuberosity and the lateral epicondyle of the tibia. The ground electrode was placed over the tibia, inferior to the patella. Before placing surface electrodes, skin preparation was conducted to ensure a low skin impedance resistance ($< 5 \text{ k}\Omega$) between the two surface electrodes through shaving hair, lightly abrading with a skin preparation paste, and cleaning with rubbing alcohol applied with a cotton ball (Konard (2005)). The skin impedance resistance was checked with a regular multimeter. The AcqKnowledge software (version 4.4) and BIOPAC MP150 system were used for data acquisition at the sampling rate of 2000 Hz. The raw EMG signals of the biceps femoris (Fig. 2b) were low-pass filtered (500 Hz), and high-pass filtered at 10 Hz. The root mean squared (RMS) values were derived from the raw EMG signals to smooth the whole data set with an epoch (i.e., time window) of 100 ms (Konard, 2005). The participant performed both a quadriceps MVIC (knee extension) and a hamstrings MVIC (knee flexion) on the purpose-built chair. Peak RMS EMG amplitude of the biceps femoris during the quadriceps MVIC was normalized to the peak RMS EMG amplitude of the biceps femoris during the hamstrings MVIC to calculate the hamstrings/quadriceps coactivation (Stevens-Lapsley et al., 2010). Hamstrings/quadriceps coactivation during knee extension was expressed as a percentage of this value (Eq. 1).

Hamstrings Coactivation

$$= \frac{\text{peak hamstring RMS EMG amplitude during a quadriceps MVIC}}{\text{peak hamstring RMS EMG amplitude during a hamstrings MVIC}}$$

Peak RMS EMG amplitude during each MVIC test was determined as the peak amplitude of the RMS EMG signal within the entire contraction. Three trials were collected from each participant before and after

prolonged local vibration of the hamstrings.

2.5. Vibration-induced hamstrings fatigue

10 min of local vibration (Dickerson et al, 2012), at 30 Hz with 6 mm amplitude, was applied directly to the hamstrings using the Thumper Versa Pro Massager (Thumper Massager Inc., Markham, Ontario, Canada). The participant was seated with the hips flexed and hamstrings placed directly on the vibration pad (Fig. 3). During the prolonged local vibration, the whole hamstrings were targeted, and therefore a relatively large amplitude of 6 mm was used in this study. Other studies (Souron et al, 2017b) investigating the effect of prolonged local vibration have used small vibration devices, which have covered only a part of the muscle, and small amplitudes ranging from 1 to 3 mm (Jackson and Turner, 2003; Konishi et al, 2002a; Kouzaki et al., 1985; Richardson et al, 2006).

2.6. Statistical analyses

A mixed-design analysis of variance (ANOVA) 2×2 (Group \times Time) was used to assess the differences between the ACLr and control groups for each repeated measure: hamstrings strength, quadriceps strength, quadriceps CAR and hamstrings/ quadriceps coactivation before and after prolonged local vibration of the hamstrings. The two independent variables were time (pre- or post-vibration, within-subjects factor) and group (AClr or control group, between-subjects factor). The α level was set a priori at $P < 0.05$. The partial eta-square (η^2) was calculated to define small ($\eta^2 = 0.01$), medium ($\eta^2 = 0.06$) and large ($\eta^2 = 0.14$) effects (Cohen, 1988, 1992; Lakens, 2013). All statistical analyses were performed using SPSS (Version 24, IBM Corp, Armonk, New York).

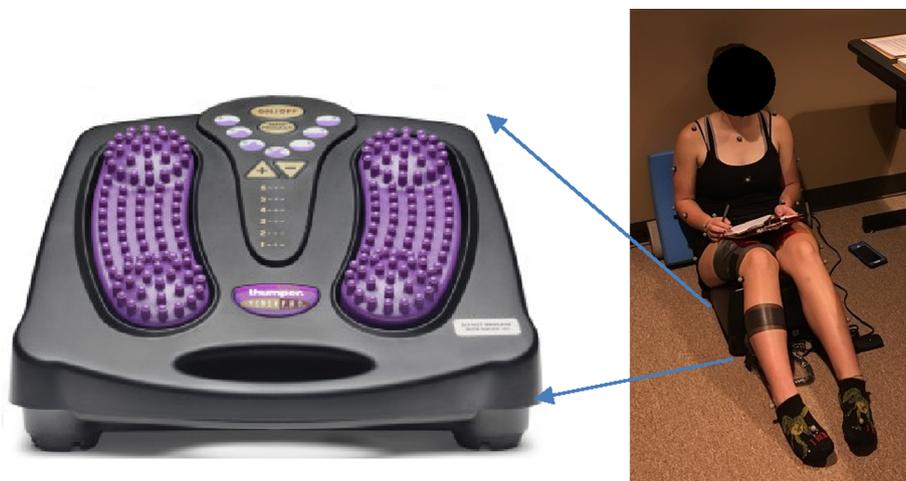


Fig. 3. A participant received 10 min of local vibration of the hamstrings using the Thumper Versa Pro Massager.

3. Results

Significant differences ($P = 0.016$, $F = 7.421$, $\eta^2 = 0.346$) were observed for hamstrings strength before and after prolonged vibration (Table 2, Table 3 and Fig. 4), indicating fatigue was indeed induced in the hamstrings after prolonged local vibration. For the ACLr group, the hamstrings strength was reduced about 14.5% from 147.7 ± 64.5 N to 126.0 ± 64.9 N after prolonged local vibration (Table 2). The main effect of group was not significant ($P = 0.412$, $F = 0.714$, $\eta^2 = 0.049$) for hamstrings strength (Table 3). No significant ($P = 0.677$, $F = 0.181$, $\eta^2 = 0.013$) interaction was found between time and group (Table 3).

No significant differences of quadriceps strength ($P = 0.160$, $F = 2.197$, $\eta^2 = 0.136$) were found before and after the vibration-induced hamstrings fatigue (Table 2, Table 3, and Fig. 5). There was no significant ($P = 0.137$, $F = 2.482$, $\eta^2 = 0.151$) main effect of group on quadriceps strength (Table 3). No significant interaction ($P = 0.688$, $F = 0.168$, $\eta^2 = 0.012$) between time and group was found for quadriceps strength (Table 3).

The CAR of the quadriceps was significantly different ($P = 0.001$, $F = 16.442$, $\eta^2 = 0.540$) before and after vibration-induced hamstrings fatigue (Table 2, Table 3 and Fig. 6). The main effect of group was marginally significant ($P = 0.051$, $F = 4.546$, $\eta^2 = 0.245$) for the quadriceps CAR (Table 3). No significant interaction ($P = 0.099$, $F = 3.121$, $\eta^2 = 0.182$) was present between group and time for the quadriceps CAR (Table 3). In the ACLr group, vibration-induced hamstrings fatigue significantly increased the quadriceps CAR (from $M = 93.2\%$, $SD = 6.2\%$ to $M = 97.9\%$, $SD = 2.8\%$, $P = 0.001$, Fig. 6). At baseline, there was a marginally significant ($P = 0.051$, Fig. 6) trend toward a lower quadriceps CAR in the ACLr group ($M = 93.2\%$, $SD = 6.2\%$) compared to the control group ($M = 98.1\%$, $SD = 1.1\%$).

There was a significant difference ($P = 0.016$, $F = 7.520$, $\eta^2 = 0.349$) in the degree of hamstrings activation during maximal knee

Table 2

Descriptive statistics (mean \pm standard deviation) of hamstrings strength, quadriceps strength, quadriceps CAR, and hamstrings/quadriceps coactivation before and after vibration-induced hamstring fatigue.

		ACLR	Control
Hamstrings strength (N)	Pre	147.7 \pm 64.5	168.5 \pm 44.3
	Post	126.0 \pm 64.9	152.9 \pm 55.0
Quadriceps strength (N)	Pre	154.0 \pm 48.0	222.4 \pm 114.7
	Post	173.5 \pm 35.5	233.5 \pm 107.6
CAR (%)	Pre	93.2 \pm 6.3	98.1 \pm 1.1
	Post	97.9 \pm 2.8	99.9 \pm 1.6
Coactivation (%)	Pre	15.1 \pm 6.2	7.5 \pm 3.9
	Post	9.5 \pm 4.6	6.5 \pm 2.9

extension (hamstrings/quadriceps coactivation) before and after vibration-induced hamstrings fatigue (Table 2, Table 3). The main effect of group was significant ($P = 0.016$, $F = 7.486$, $\eta^2 = 0.348$) for hamstrings coactivation (Table 2). No significant interaction ($P = 0.081$, $F = 3.543$, $\eta^2 = 0.202$) was found between time and group (Table 2). In the ACLr group, a significant difference ($P = 0.006$, Fig. 7) in hamstrings/quadriceps coactivation was observed before ($M = 15.1\%$, $SD = 6.2\%$) versus after ($M = 9.5\%$, $SD = 4.5\%$) the fatigue protocol, whereas no significant difference ($P = 0.553$) in coactivation was found in the control group pre- and post-fatigue. At baseline, a significant difference ($P = 0.011$, Fig. 7) of hamstrings/quadriceps coactivation was found between the ACLr group ($M = 15.1\%$, $SD = 6.2\%$) and the control group ($M = 7.5\%$, $SD = 4.0\%$); but no significant difference ($P = 0.131$) was observed after the vibration-induced hamstrings fatigue (Fig. 7).

4. Discussion

The purpose of this study was to identify a rehabilitation strategy to alleviate AMI by modifying the sensory signals involved in hamstrings overexcitation and quadriceps inhibition. A statistically non-significant ($P = 0.051$) trend was observed for lower quadriceps CAR and a significantly ($P = 0.011$) higher hamstrings activation during quadriceps MVIC was observed in the ACLr group when compared to control participants, suggesting that AMI existed in the ACLr group. Following prolonged vibration of the hamstrings, the quadriceps CAR significantly increased and hamstrings/quadriceps coactivation significantly decreased in the ACLr group, but not in the control group. It is also noted that no significant interactions were observed between time and group for the quadriceps CAR and the hamstrings/quadriceps coactivation. On the other hand, statistical significance is not so important here (du Prel et al, 2009; Lee, 2016), because despite small sample size, the effect sizes in this study are relatively large (> 0.182). This confirmed our hypothesis that prolonged vibration of hamstrings could reduce quadriceps AMI and may be used for optimizing quadriceps strength for individuals with ACLr.

Our results indicate a trend ($P = 0.051$) of lesser quadriceps CAR in individuals with ACLr than in control participants. Although this trend is not statistically significant, the effect size is relatively large ($\eta^2 = 0.245$). This is in agreement with prior studies that quantified quadriceps inhibition using the CAR method (Hart et al, 2011; Lowe and Dong, 2018; Pamukoff et al, 2017; Urbach et al, 2001). The voluntary activation of the quadriceps in individuals with ACLr has been found to remain less than that of control participants 18 months (Lowe and Dong, 2018), two years (Urbach et al, 2001), 47.5 months (Hart et al, 2011), and 50 months (Pamukoff et al, 2017) after the

Table 3

Summary statistics from a mixed-design analysis of variance (ANOVA) with repeated measures of hamstrings strength, quadriceps strength, quadriceps CAR, and hamstrings/quadriceps coactivation in which F-statistic (F), p-value (P), and partial eta squared (η^2) were included.

	Within-subjects (Time)			Between-subject (Group)			Interaction (Time \times Group)		
	F	P	η^2	F	P	η^2	F	P	η^2
Strength (H)	7.421	0.016	0.346	0.714	0.412	0.049	0.181	0.677	0.013
Strength (Q)	2.197	0.160	0.136	2.482	0.137	0.151	0.168	0.688	0.012
CAR	16.442	0.001	0.540	4.546	0.051	0.245	3.121	0.099	0.182
Coactivation	7.520	0.016	0.349	7.486	0.016	0.348	3.543	0.081	0.202

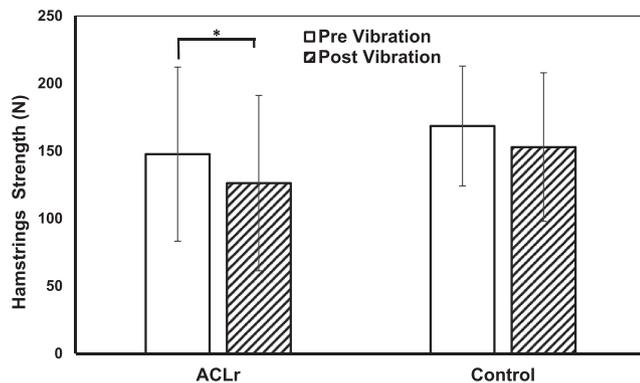


Fig. 4. Comparison of hamstrings strength (Mean \pm Standard Deviation) between the ACLr group (N = 8) and the control group (N = 8) before and after prolonged vibration of the hamstrings.

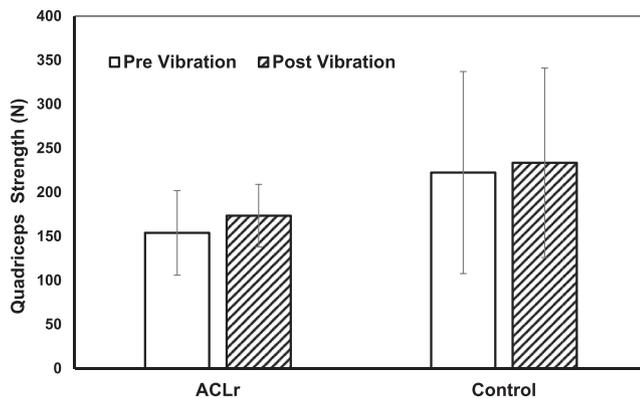


Fig. 5. Comparison of quadriceps strength (Mean \pm Standard Deviation) between the ACLr group (N = 8) and control group (N = 8) before and after prolonged vibration of the hamstrings.

reconstruction of ACL. Quadriceps inhibition following ACLr leads to muscle atrophy and prevents maximum muscle activation (Hurley et al, 1994). This inhibition interferes with attempts to strengthen the quadriceps muscle, and despite resistance training, quadriceps strength remains unchanged or declines over time (Keays et al, 2003). Persistent quadriceps deficits are clinically significant as it impairs dynamic knee stability, physical function, and quality of life, increases risk of re-injury to the knee joint (Stokes and Young, 1984) and contributes to the development and progression of osteoarthritis (Brandt et al, 2008; Mikesky et al, 2006; Slemenda et al, 1998).

In addition, we found that hamstrings/quadriceps coactivation during maximal knee extension was greater in individuals with ACLr than in control participants. This is consistent with previous reports of hamstrings/quadriceps coactivation in individuals with ACLr (Grabner and Weiker, 1993; Pamukoff et al, 2017; Tsai et al, 2012). Significantly higher hamstrings/quadriceps coactivation has been considered as a beneficial adaptation to increase the stability of the knee joint

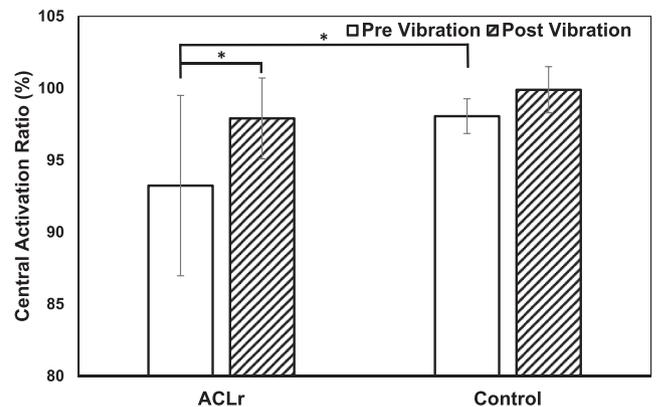


Fig. 6. Comparison of central activation ratio (CAR) of the quadriceps (Mean \pm Standard Deviation) between the ACLr (N = 8) group and control (N = 8) group before and after prolonged vibration of the hamstrings.

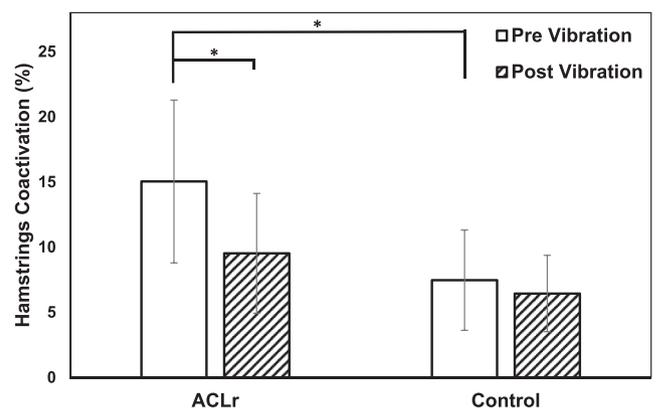


Fig. 7. Comparison of hamstrings/quadriceps coactivation (Mean \pm Standard Deviation) between the ACLr group (N = 8) and control group (N = 8) before and after prolonged vibration of the hamstrings.

(Grabner and Weiker, 1993). Therefore, it may be a protective response to limit anterior tibial translation and increase joint stability (Friemert et al, 2010; Grabner and Weiker, 1993; Pamukoff et al, 2017). In general, the coactivation of agonist and antagonist muscles appears to be a useful strategy when we learn novel tasks (Enoka, 2002) and could be beneficial during the early stage of ACLr rehabilitation. However, greater hamstrings/quadriceps coactivation during maximal knee extension contributes to lower knee extension torque for individuals with ACLr (Pamukoff et al, 2017). Moreover, greater hamstrings/quadriceps coactivation in individuals with ACLr produces higher compressive forces at the knee joint during a drop-land task, which increases risk for knee osteoarthritis (Tsai et al, 2012).

The increase of excitability in reflexive pathways within the spinal cord (Pamukoff et al, 2017; Rice and McNair, 2010) and/or changes in corticospinal excitability (Lepley et al, 2019; Needle et al, 2017; Neto et al, 2019; Pietrosimone et al, 2015; Ward et al, 2019) could be the

mechanisms of overexcitation of the hamstrings and reciprocal inhibition of the quadriceps in individuals with ACLr. In the present study, prolonged vibration of the hamstrings was designed to reduce spinal excitability. Prolonged vibration has been shown to decrease maximum voluntary contraction force (Bongiovanni et al, 1990; Kouzaki et al., 1985; Sammalı et al, 2018; Shinohara, 2005; Souron et al, 2017a). This is consistent with our observation that hamstrings strength in the ACLr group was significantly reduced after 10-min of vibration. The reduction in maximum voluntary force from prolonged vibration is possible due to changes in alpha motoneuron activity (Bongiovanni and Hagbarth, 1990; Bongiovanni et al, 1990), a decline in firing rates of high threshold motor units, and an attenuation of Ia afferent discharge supported by reductions in spinal loop excitability (Hayward et al, 1986; Heckman et al, 1984). However, a recent study (Souron et al, 2019) indicates that the depressed spinal excitability after prolonged local vibration depends on postsynaptic changes with potential decreased motoneuron excitability, rather than presynaptic mechanisms.

We showed that a single session of prolonged hamstrings vibration significantly reduced hamstrings/quadriceps coactivation during maximal knee extension and increased the quadriceps CAR for individuals with ACLr. Thus, it is likely that the reduction of hamstrings activation was the result of a decline of firing rates of high-threshold motor units through attenuation of Ia afferents to alpha motoneurons, although other mechanisms (Souron et al, 2019) are also possible. The well-known reciprocal-inhibition indicates that the activation of Ia afferents of muscle spindles in the agonist muscle prompts an excitation of the homonymous motor neurons but inhibits those of the antagonist muscle (Enoka, 2002). Because reciprocal-inhibition is a negative feedback mechanism, it is likely that a decrease of the excitability of Ia afferents in the hamstrings is associated with an increase in alpha motoneuron activity of the quadriceps. This may explain an increase of the quadriceps CAR observed in individuals with ACLr in the present study. A reduction in quadriceps inhibition, even temporarily, would allow individuals with ACLr to fully access all the quadriceps motor units to increase quadriceps strength (Hart et al, 2014). Vibration-induced hamstrings fatigue provides a window of time during which individuals with ACLr experience the disinhibition of the quadriceps motoneuron pool. During this time, participants can perform an open-chain exercise (e.g., leg extension) or a closed-chain exercise (e.g., leg press) to regain quadriceps strength due to the recruitment of motor units from an increase in the excitability of the motoneuron pool (Hart et al, 2014).

5. Limitations

There are several limitations to this study. One limitation is that the small sample size may leave this study statistically underpowered. Nevertheless, effect sizes were large for this study (Table 3). Future studies need to use larger sample sizes to examine the influences of sex and the choice of graft material for ACL reconstruction. Another limitation is that the average time after ACL reconstruction was about 46.5 months for participants in the ACLr group. It is possible that we may have recruited participants with less AMI and less coactivation than in patients with more acute injuries. In future studies, we may limit our participants to individuals within two years of ACL reconstruction surgery.

Third, the superimposed burst technique (Norte et al, 2015; Pamukoff et al, 2017) used in this study, in which electrically stimulation is delivered percutaneously to the muscles, may overestimate the central activation ratio of the quadriceps (Bampouras et al., 2006), compared with the interpolated twitch technique (Behm et al, 2001, 1996; Drechsler et al, 2006) in which an interpolated twitch stimulates the femoral nerve to fully activate the quadriceps (Park and Hopkins, 2011; Place et al, 2007). However, femoral nerve stimulation may cause major discomfort in some subjects, especially when applying a train of pulses (Bampouras et al., 2006).

Fourth, we did not quantify crosstalk between hamstrings and

quadriceps using the cross-correlation technique since only EMG signals of the hamstrings were collected in this study. However, cross-correlation analysis has been shown to be ineffective in identifying crosstalk and distinguishing between crosstalk and coactivation (Lowery et al., 1985; Serpell et al, 2015). We have taken care to minimize crosstalk by collecting EMG data according to SENIAM guidelines. In the future study, we may use a double differential signal amplifier which has been shown effective in minimizing cross talk (Koh and Grabiner, 1993).

Next, the SENIAM recommendations (Hermens, 1999; Hermens et al, 2000) for the placement of EMG electrodes in this study were developed about two decades ago and new guidelines are needed since significant new knowledge has been obtained since then (Merletti and Muceli, 2019). For example, the placement of EMG electrodes with an inter electrode distance of 20 mm may introduce substantial filtering due to the detection modality (Merletti and Muceli, 2019). Additionally, the placement of electrodes on the muscle belly may imply high likelihood of having them on the innervation zone (Barbero et al, 2012; Merletti and Farina, 2016; Merletti and Muceli, 2019).

Additionally, prolonged hamstrings vibration was applied to both ACLr and control groups. Future studies may include additional sham groups in which participants will be seated on the Thumper Versa Pro Massager and no local vibration will be introduced to the hamstrings.

Finally, only a single session of prolonged local vibration of the hamstrings was used in this study and a trend toward increases in quadriceps strength was observed, although it was only borderline significant. In the future, a small clinical trial of a prolonged training program should be performed to examine the effects of multiple training sessions of vibration-induced hamstrings fatigue on the improvement of quadriceps strength for individuals with ACLr compared it to conventional rehabilitation modalities. We expect that significant increases in quadriceps strength will be observed after the multiple training sessions.

6. Conclusion

Despite its limitations, this study found that following hamstrings fatigue, the ACLr group showed a temporary alleviation of problematic quadriceps muscle inhibition and high hamstrings/quadriceps coactivation during knee extension, supporting our hypothesis and providing critical support for a promising new rehabilitation strategy for restoring normal function at the knee joint following ACL reconstruction by overcoming quadriceps inhibition and weakness through a mechanism-based protocol.

Declaration of Competing Interest

Each author in this manuscript does not have and will not receive benefits in any form from a commercial party related directly or indirectly to the content in this manuscript. The authors declare that they have no competing financial interests

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