The Bilateral Limb Deficit (BLD) Phenomenon During Leg Press: An Investigation Into Central And Peripheral Factors

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Abstract

Background: The bilateral limb deficit (BLD) phenomenon is the difference in maximal or near maximal force generating capacity of muscles when they are contracted alone or in combination with the contralateral muscles. It has been suggested that the BLD may be due to interhemispheric inhibition, however the origin of the deficit is yet to be determined. The aim of this study was to investigate central and peripheral factors responsible for the BLD during leg press using surface electromyography (EMG) and electroencephalography (EEG).

Methods: Fourteen adults (age = 23.7 ± 4.7 years old) completed bilateral (BL), unilateral left (UL) and unilateral right (UR) isometric leg press exercises. Bilateral limb ratio (BLR) was calculated similar to previous studies and surface EMG from three muscles of the quadriceps femoris (vastus lateralis, vastus medialis and rectus femoris) were used to compare signal amplitude in each condition. Movement related cortical potentials (MRCPs) over the left and right motor cortex areas (C3 and C4, respectively) were used to assess brain activity asymmetries reflecting central factors.

Results: The BLD was present in ten of the fourteen participants (mean BLR=81.4%). Mean RMS activity demonstrated differences in amplitudes between the quadriceps muscles, however no significant differences were noted between bilateral and unilateral conditions. No significant differences in MRCPs were observed between brain activity of the C3 and C4 electrodes in any of the conditions.

Conclusion: This study noted the presence of BLD however the results did not provide evidence of significant limitations in either the EMG and EEG data.

Background

Evidence suggests that lower forces are produced with bilateral limb contraction when compared to the summed force produced when the same homologous muscles are contracted unilaterally (Ruiz-Cárdenas et al. 2018). This phenomenon, termed as bilateral limb deficit (BLD), has been exhibited in both upper and lower limbs, however the magnitude of the deficit is typically larger in lower limbs (Magnus & Farthing 2008). BLD occurs similarly in males and females (Kuruganti et al. 2005; Kuruganti & Seaman 2006), but it has been shown to be sensitive to limb dominance and training interventions (Cornwell et al., 2012; Howard & Enoka, 1991; Kuruganti et al., 2005; Yuko Taniguchi, 1998). It has been demonstrated that specificity training can reduce BLD, for example, training under unilateral and bilateral conditions can increase unilateral and bilateral strength, respectively (Kuruganti et al., 2005; Rube & Secher, 1991; Yuko Taniguchi, 1998).

Despite the established force deficit, the source of BLD is still poorly understood. Understanding the cause of the deficit is important to understand neuromuscular function and how it can be impacted by tasks which use both limbs simultaneously. Investigating the source of this inhibition will help to understand the effect of the deficit and its functional implications including muscle imbalance and coordination.

Two primary theories that have been proposed, and they are referred to as the postural stability theory and the neural inhibition theory. The postural stability theory postulates that that postural stability requirements of the exercise studied may be the cause of the deficit (Herbert & Gandevia, 1996; Magnus & Farthing, 2008). This was further supported by evidence demonstrating that multi-jointed lower body exercises, particularly those involving large muscles and high force generation, require more postural stability and exhibit a greater deficit (Ning Lan, 2002). It has been suggested that those exercises involving multiple muscle groups and higher ground reaction forces may exhibit larger bilateral deficits due to the increased difficulty in maintaing postural stability under the bilateral condition (Magnus & Farthing, 2008). However, no differences in activation of postural-related core muscles has been found, and still does not explain why we see BLD even in upper limb tasks (Magnus & Farthing, 2008).

The neural inhibition theory, conversely, has received more attention. Surface electromyography (EMG) obtain though RMS calculations to measure the extent of the neural commands sent to the muscle. Although some work has had mixed results regarding the relationship between force and muscle activity (Cresswell & Overdal, 2002; Häkkinen et al., 1997; Howard & Enoka, 1991; Kuruganti et al., 2011; Kuruganti & Seaman, 2006), a there is evidence suggesting neural mechanism are behind BLD. Early research (Ohtsuki, 1983) suggested that the deficit could be related to inhibitory spinal reflexes, which occur when the neural control for one limb is affected when the opposite limb is simultaneously activated. It is possible that afferent sensory information from one limb may inhibit the control of the motor neurons acting on the contralateral limb (Khodiguian et al. 2003). Furthermore, a study looking at BLD in plantar flexor muscles also suggested reduced motor neuron excitability during bilateral contraction may also contribute to BLD (Kawakami et al., 1998).

Despite this evidence, making conclusions about where these changes happen in the neural circuitry is limited, as EMG only provides a final snapshot of the overall neural commands sent to the muscle. Voluntary movement of the limbs is attained through the corticospinal tract, made of upper motor neurons (UMN), originating mostly from the primary motor cortex, which in turn synapse with interneurons and lower motor neurons (LMN) that lead to the neuromuscular junctions responsible for the contraction and relaxation of skeletal muscle. To disentangle whether this neurological change causing BLD occurs in the central (UMN) or in the peripheral (interneurons and LMN), experiments have used measures of brain activity such as electroencephalography (EEG) to investigate the potential central neurological origin for BLD.

EEG can be an effective method of measuring brain activity during human movement (Spring et al. 2016). During maximal voluntary contractions, the preparatory brain activity that occurs prior to the onset of movement can be analyzed to investigate event-related potentials, more specifically, movement-related cortical potentials (MRCPs). MRCPs are composed of two distinct components. The first component is termed the Bereitschaftspotential (or Readiness Potential, RP), which is classified as a slow negative shift that occurs between onset of movement and is related to the MRCP peak amplitude (Shibasaki & Hallett 2006; Spring et al. 2016). The second component is called the Negative Slope (NS’) which occurs between 500 ms before the onset of movement and movement onset. The Motor Potential (MP) falls within the NS’ and occurs at the onset of movement and corresponds to the peak amplitude of the MRCP. MRCPs have been investigated in the motor cortex area (C3 and C4) during unilateral and bilateral handgrip contractions (Oda & Moritani, 1995, 1996). It was concluded that a bilateral deficit in both force production and EMG was associated with a reduction in MRCPs, indicating that the bilateral handgrip contraction produced less force and EMG activity than the unilateral handgrip contraction because of a mechanism of interhemispheric inhibition. Interhemispheric inhibition is thought to occur when the activity in one hemisphere of the brain affects the activity in the opposite hemisphere while both are concurrently activated, thereby decreasing neural drive to the muscles (Oda & Moritani, 1995; Y. Taniguchi et al., 2001; Van Dieen et al., 2003). However, it remains that few studies that have examined brain activity simultaneously with EMG and force to study BLD, and this effect has not been shown during lower limb movements.

The purpose of the current study was to investigate the underlying cause of the BLD phenomenon in active, young adults in the lower limbs. Force output was recorded in parallel with surface EMG and EEG data during unilateral and bilateral leg press exercises using an isokinetic dynamometer. It was hypothesized that (1) the bilateral force output will be less than the sum of the unilateral force output during the leg press, (2) the unilateral muscle activity will support the discrepancies in force output, and (3) there will be differences in neuronal activity between the bilateral and unilateral leg press suggesting that the bilateral deficit is caused, at least in part, by the central nervous system.

Methods

Fourteen healthy men (n = 5) and women (n = 9) participated in the present study. Participant characteristics are summarized in Table 1. A questionnaire was distributed prior to beginning the study and it was observed that all participants were right-leg dominant (determined by asking which leg they would kick a soccer ball with) and were considered active (i.e., they engaged in resistance training at least three times per week on a regular basis) but were not varsity athletes. All participants were provided a detailed overview of the study and written informed consent was obtained from each participant prior to testing. This study was approved by the University of New Brunswick Research Ethics Board and has been assigned the file number REB#2019 – 159.

Table 1
Participant Characteristics (mean and standard deviation)

Characteristic	Male (n = 5)	Female (n = 9)	Total (n = 14)
Age [years]	27.2 ± 6.8	21.8 ± 1.3	23.7 ± 4.7
Height [m]	1.79 ± 0.06	1.66 ± 0.06	1.71 ± 0.09
Weight [Kg]	82.8 ± 9.3	69.7 ± 8.2	74.4 ± 10.5
Body Mass Index (BMI) [kg/m^2]	25.7 ± 1.9	25.3 ± 3.1	25.5 ± 2.7
Thigh Girth [cm]	61.5 ± 3.2	62.7 ± 6.3	62.3 ± 5.3
Right Anterior Thigh Skinfold [mm]	12.0 ± 3.2	15.1 ± 4.0	14.0 ± 3.9
Right Anterior Patella Skinfold [mm]	9.9 ± 3.9	14.6 ± 2.0	12.9 ± 3.6

Instrumentation

Torque data for the unilateral and bilateral leg press was collected using an isokinetic dynamometer (Cybex Humac Norm, CSMI Inc., USA) with an attached closed kinetic chain adapter. The sampling frequency of the dynamometer was 100 Hz. A 32-channel wireless surface EMG system (Trentadue, OT Bioeletrronica, Italy) was used to record muscle activity during all maximal voluntary contractions (MVCs). The EMG system had a Common Mode Rejection Ration (CMMR) of over 96 dB and a signal bandwidth of 10/500 Hz. The signals were sampled at a frequency of 2000 Hz, and an A/D converter resolution of 24 Bit, with a gain of 256. A dry, wireless EEG system (Cognionics Quick-30 Dry Electrode, Cognionics Inc., San Diego, CA, USA) was used to acquire brain activity during the leg press at a sampling frequency of 1000 Hz. To create a time-stamp for the MRCPs, a microcontroller (Arduino MEGA 2560, Arduino LCC, Italy) was used to send a trigger impulse to the EEG system when the participant reached 5 percent of their maximum torque production.

Isometric Strength Testing

Participants were seated in an upright position on the Cybex. The dynamometer was positioned at a self-selected back-angle (approximately 90°) and a horizontal translation (35–40°) to ensure comfort, and the closed kinetic chain adapter was set so that participant’s knees were at a 90° angle, measured using a goniometer. Hip angle varied as participant’s were able to adjust the back angle for comfort, but the angle was typically kept at approximately 90° (85–100°). To ensure no contribution of force transmitting from the upper body, participants crossed their arms over their chest during the contractions. Participants were then instructed to perform three bilaterally maximum voluntary contractions (MVCs), unilaterally three MVCs with their left leg, and three unilaterally MVCs with their right leg, where the order of testing was randomized. Participants were asked to hold the contraction for 5 seconds to provide sufficient time to reach maximal force production. A two-minute rest period was given after each MVC to minimize fatigue.

During all trials, experimenters provided verbal encouragement (such as “push as hard as you can”) to elicit motivation for maximal force production.

Surface Electromyography

Skinfold measurements were taken on the right leg of all participants in the supine position for anterior thigh (mid-point between the patella and the inguinal fold) and patella (2 cm above the proximal edge of the patella). Thigh girth for the right leg of each participant was also measured. Criteria for skinfold measurements was similar to that of Kuiken et al., (2003) to ensure that all participants had less than 0.4 mm of adipose tissue which could interfere with the myoelectric signal. Bipolar surface electrodes (Duotrode silver-silver chloride electrodes (Myo-tronics Inc.); interelectrode spacing of 21.0 ± 1.0 mm) were placed bilaterally (left and right) on palpated muscle bellies of the rectus femoris (RF), vastus medialis (VM), and vastus lateralis (VL) adhering to Seniam guidelines (The Seniam Project, 1999). To reduce impedance caused by skin, the area was shaved and cleaned with alcohol wipes prior to electrode placement. For the RF, electrodes were placed parallel to the muscle fibers at half the distance between the anterior superior iliac spine (ASIS) and the superior part of the patella. Electrodes were placed over the VL at two-thirds the distance between the ASIS and the lateral aspect of the patella. Electrodes were then placed over the VM at an oblique angle (55°) at 80% of the distance between the ASIS and the joint space in front of the anterior border of the medial ligament. The reference electrode was placed over the right patella. All data was filtered using commercial software (OTBioLab Software, Bioelettronica, Italy).

Electroencephalography

A dry EEG headset (Cognionics Quick-30) was used to acquire continuous brain wave activity during each set of 3 trials for the leg press. The sampling rate of the EEG was 1000 Hz and conductive gel was used to keep impedances around 100 kOhm for the electrodes. The system was positioned on each participant’s head based on the standard 10/20 channel system with the left earlobe as the reference point as shown in Fig. 1.

Data Analysis

Torque

The trial with the highest peak force was chosen for further analysis. The corresponding trial was used for further processing for the EMG data. The bilateral limb ratio (BLR) was calculated similar to previous studies as follows (Ohtsuki, 1983).

$$BLR_{torque}\ (\%) = \frac{Bilateral\ Peak\ Force}{Total\ Unilateral\ Peak\ Force}\ x\ 100 \qquad \text{(Equation 1)}$$

Surface Electromyography

Surface EMG signals that corresponded to the trial with the maximum peak torque were used for processing. For these trials, a bandpass filter of 20-400Hz was applied in the OTBioLab software and the files were then exported into an Excel spreadsheet. For further processing, the data were converted to a MATLAB file and a notch 60 Hz filter was applied to the data. The amplitude of the EMG signal was estimated using the root mean square calculation (RMS). A 1.0 second window of EMG data, centered at the peak force was used for all calculations similar to previous studies (Kuruganti et al. 2008, Kuruganti et al., 2011).

Electroencephalography

The EEG data were processed using a custom MATLAB script (MathWorks, Natick, MA, USA) using EEGLAB (Delorme & Makeig, 2004) functions. Data were first filtered with a band-pass filter of 0.1-100Hz to eliminate low frequency noise/DC offset. All blinking and other ocular artifacts were removed from the data using an independent component analysis approach (Delorme & Makeig, 2004). Epochs time-locked to the onset of movement were extracted from the data from − 1500 ms to 200 ms in order to analyze the MRCP. Similar to the EMG data, a notch 60 Hz filter was applied. The electrodes used to analyze the MRCP were over the left and right precentral cortex (C3 and C4, respectively), as they reside over the primary motor cortex (Oda & Moritani, 1995, 1996). The grand average of all EEG trials was calculated and then used to obtain the MRCP according to (Shibasaki & Hallett, 2006) at 3 phases: readiness potential (RP; -1000 ~ -600 ms), negative slope (NS’; -600 ~ -200 ms) and the motor potential (MP; -200 ~ -50 ms).

Normality of the dataset was assessed using a Shapiro-Wilks test prior to any statistical analyses. A two-way repeated measures analysis of variance was used to examine the effect of contraction type (bilateral, unilateral) and muscle type (VM, RF, VL) on the RMS values. A pairwise t-test using a Bonferroni correction was used when an ANOVA resulted in a p-value less than the alpha value, which was set at 0.05. All of the statistical tests were performed using RStudio 1.0. 136 (RStudio, Boston, MA).

Results

Unilateral and Bilateral Torque

The mean torque data for the unilateral and bilateral conditions are shown in Table 2. The mean BLR across all participants was 94.8 ± 22.0% which was less than, but not statistically significantly different ($p > 0.05$) than 100%. Out of 14 participants, 10 showed a bilateral limb deficit. An analysis was performed on both the participants that demonstrated a BLD response (n = 10) and the participants that demonstrated a facilitation (n = 4). A t-test showed that those participants that exhibited a deficit had a mean BLR = 81.4% which was significantly lower than 100% ($p < 0.01$). The participants that demonstrated a facilitation had a BLR of 117.1% which was significantly higher than 100% ($p = 0.0155$) indicating a bilateral facilitation.

Table 2
Mean ± SD unilateral and bilateral torque (Nm) and BLR (%) during isometric leg press. Values are mean ± SD.

	Unilateral Left	**Unilateral Right**	**Bilateral**	**BLR (%)**
Torque (Nm) (n = 16)	127.6 ± 45.2	129.1 ± 45.2	232.0 ± 61.8	94.8 ± 22.0

Unilateral and Bilateral EMG

Figure 2 provides sample EMG data from one subject. Muscle activity from the rectus femoris (RF), vastus medialis (VM), and vastus lateralis (VL) during unilateral and bilateral isometric leg press is shown. Table 3 presents the amplitude data for each muscle (RF, VM, VL) for bilateral and unilateral conditions. The one-way repeated measures ANOVA did not reveal any significant differences due to condition (bilateral versus unilateral). The subset of individuals who presented a BLD were also examined and there were no significant differences detected due to condition in those individuals either. There were significant differences detected between muscles ($p < 0.001$) with the VM having higher amplitude than either the VL or RF.

Table 3
Mean ± SD unilateral and bilateral EMG RMS values (mV) during isometric leg press. * indicates statistically significant differences ($p < 0.05$) due to condition (unilateral versus bilateral).

	EMG RMS (mV) All Participants (n = 9)			
Muscle	**Unilateral Left**	**Bilateral Left**	**Unilateral Right**	**Bilateral Right**
VM	0.471 ± 0.31	0.446 ± 0.26	0.392 ± 0.29	0.551 ± 0.52
VL	0.142 ± 0.13	0.13 ± 0.11	0.137 ± 0.1	0.213 ± 0.16
RF	0.299 ± 0.29	0.261 ± 0.27	0.148 ± 0.08	0.169 ± 0.13

Unilateral and Bilateral EEG

Figure 4 illustrates the average integrated amplitudes during the three components of the MRCP (RP, NS’, and MP) during the three conditions. The C3 and C4 electrodes represent electrical activity at the left (C3) and right (C4) precentral cortex. There were no significant differences found between the electrodes for the RP, NS’, or MP for any condition ($p > 0.05$). When comparing within each electrode, there was a significant difference found in C4 (the precentral cortex of the right hemisphere) between the unilateral right and bilateral conditions; the average NS’ was significantly greater in the bilateral condition than the unilateral right condition (0.00257 ± 0.00475mV*s and − 0.00168 ± 0.00361mV*s for the bilateral and unilateral right conditions, respectively; $p < 0.05$). The average MP was also greater in the bilateral condition compared to the unilateral right condition (0.00106 ± 0.00238mV*s and − 0.000351 ± 0.00187mV*s for the bilateral and unilateral right conditions, respectively; $p < 0.05$).

Discussion

This study presents BLD leg press similar to other studies (Janzen et al., 2006, Magnus & Farthing, 2008, MacDonald, Losier, Chester & Kuruganti., 2014), but with varying results. While the mean BLR detected in the present study was similar but slightly higher (~ 81%) than what was discovered in previous research (MacDonald et al., 2014). This could due, in part, to the fact that MacDonald et al. studied varsity swimmers that incorporate potential unilateral and bilateral training into their programs, ultimately reducing the deficit. Overall, the torque data presented in this work was also higher than that of MacDonald et al. (2014).

It has been previously reported that the BLD is more evident in dynamic exercises (e.g. isokinetic knee extension) than isometric contractions (Jakobi and Chilibeck, 2001, Kuruganti et al. 2005, Kuruganti et al., 2006). Similar to Janzen et al. (2006), we found that the BLD is present in complex exercises such as the leg press which combines hip and knee extension. In addition, the nervous system may be more involved during multi-articulate contractions such as the leg press, that involve movements at multiples joints (Chilibeck et al., 1998). The postural stability theory suggests that exercises involving multiple muscle groups and higher ground reaction forces, such as the leg press, might exhibit larger bilateral deficits because it is more difficult to maintain postural stability under the bilateral condition (Magnus and Farthing 2008). There is comparable evidence to suggest that single-jointed movements, such as knee extension, may result in a smaller bilateral deficit compared to multi-jointed movements, such as a lateralis pull-down and leg press (Janzen et al. 2006). This is because multi-jointed movements tend to involve larger muscles and greater force production, thus requiring greater postural stability (Simoneau-Buessinger et al., 2015). It was determined that muscle activation of the trunk was significantly greater in the leg press, a multi-joint movement, compared to the knee extension and handgrip exercises, which are single-jointed movements.

The surface EMG data in this study did not show any differences between the bilateral and unilateral conditions for any of the quadriceps muscle. While 14 individuals participated in this research, EMG from only nine participants was used for analysis due to a hardware issue further reducing the sample size. The EMG was also examined from those that exhibited a BLD (10/14 participants) and no significant trend was observed with respect to the deficit.

Similar to previous studies, this study found that the muscles of the quadriceps femoris are not homogenously activated during the leg press (Ema et al., 2016). They studied knee extension and leg press at differing intensities and found inter-muscle and inter-exercise differences in the activation of the quadriceps femoris from the involvement of the hip extension torque and that the RF activation is low in multi-joint exercise. However, Alkner et al. (2000) did not find significant differences in the EMG amplitude of the VL, VM, RF and Biceps Femoris (BF) between isometric knee extension and leg press. While the sample in this study was small, the results suggest that there are differences in the relative contributions of each muscle to the overall activation. One limitation of the present study was the lack of measured antagonist muscle activity. In addition, this work used traditional bipolar surface EMG over the three muscles. Using multichannel, high density EMG electrodes over the entire quadriceps muscle may reveal greater insight regarding muscle activation during the leg press and also provide greater support to the postural stability theory of the BLD.

Previous studies that have investigated the role of surface EMG and the development of the BLD have been inconclusive and in many cases EMG data have not paralleled force or torque data under the same conditions. Some researchers have reported that the amplitude of the EMG signal is lower under bilateral conditions compared to unilateral conditions (Kawakami et al.1998 ; Koh et al. 1993 ; Oda and Moritani 1994 ; Ohtsuki 1981, 1983 ; Rube and Secher 1990 ; Steger and Denoth 1996 ; Van Soest et al. 1985 ; Vandervoort et al. 1984). Several authors (Henry & Smith, 2013; Oda & Moritani, 1994; Ohtsuki, 1981) have observed a greater force reduction in the dominant limb when investigating BLD, however, these results were primarily based on upper limbs. Other studies have also found that bilateral EMG amplitudes are lower than the unilateral (Cresswell & Overdal, 2002; Oda & Moritani, 1995, 1996; Rejc et al., 2009; Vandervoort et al., 1984). While some researchers have found that EMG amplitudes are lower during bilateral conditions compared to unilateral conditions (MacDonald et al., 2014, and Murphy 2008; Cresswell and Ovendal 2002; Kawakami et al. 1998; Koh et al. 1993; Oda and Moritani 1994; Ohtsuki 1981, 1983; Rube and Secher 1990; Steger and Denoth 1996; Van Soest et al. 1985; Vandervoort et al. 1984) others have shown no deficit in the EMG data (Howard and Enoka 1991; Owings and Grabiner 1998; Schantz et al. 1989). In addition, this study only found differences in bilateral and unilateral EMG on the left side suggesting other factors contribute to the deficit. It has been suggested by researchers that the deficit may be caused by significant decreases in motor unit activation of the quadriceps muscles during the bilateral contraction compared to the unilateral (Vandervoort et al., 1984), decreased cortical activity (Oda & Moritani, 1995), and a reduction in neural drive in conjunction with interhemispheric inhibition (Cresswell & Overdal, 2002; Rejc et al., 2009).

While some studies have proposed that BLD is due to neural inhibition during bilateral compared to unilateral tasks (Vandervoort et al., 1984), few studies have used EEG to explore brain activity during these types of contractions (Oda and Moritani, 1995). In this study we examined strength, surface EMG measures, and brain activity during bilateral and unilateral contractions. Previously, Oda and Moritani (1995) concluded that there was a greater MRCP deficit of the non-dominant right hemisphere compared to the dominant left hemisphere. It was also suggested that the bilateral deficits in the integrated amplitudes for both the negative slope (NS’) and motor potential (MP) could be due to the decreased neural activation of the primary motor cortex. Similarly to their findings, our results illustrated no differences between hemispheres during each condition, but there was a decrease in brain activity in the (non-dominant) right hemisphere during the unilateral right condition compared to the bilateral condition. Given that the right hemisphere controls the left side of the body, it is plausible that this hemisphere would display a decrease in neural activity when the left leg is not involved in the MVC.

This study was limited to one movement and it would be interesting to determine if there are neural differences in other types of contractions which have demonstrated the BLD such as elbow flexion. Given that the lower-extremity primary motor cortex is located in close proximity to the medial longitudinal fissure may introduce barriers in measuring interhemispheric interactions in lower extremities (Palmer et al., 2017). One such challenge may be because the electrical fields created by the activation in the adjacent parts of the fissure may be polar opposites, thus canceling out the signal when measuring the overall potential using EEG.

Conclusions

This study found the presence of the BLD during isometric leg press. There was no evidence of reduced muscle activity in bilateral compared to unilateral contractions. There were also no significant differences found between cortical hemispheres bilateral and unilateral contractions, indicating that the deficit was not induced because of interhemispheric inhibition during isometric leg press. This study examined contractions from healthy, university aged men and women. It is well established that muscle strength declines due to age and is often accompanied by alterations in muscle and neural activity. A higher sample size as well as a larger age range may provide greater information regarding muscle and neural adaptation due to the deficit. Furthermore, it has been shown that the BLR can be reduced with targeted training. Including EEG measurement may provide greater insight regarding the response of the deficit to training.

Abbreviations

ANOVA	Analysis of variance
ASIS	Anterior superior iliac spine
BLD	Bilateral limb deficit
BLR	Bilateral limb ratio
BP	Bereitschaftspotential
EEG	Electroencephalography
EMG	Electromyography
MRCP	Movement related cortical potential
MP	Motor potential
MVC	Maximal voluntary contraction
NS	Negative slope
RF	Rectus femoris
RMS	Root mean square
VL	Vastus lateralis
VM	Vastus medialis

Declarations

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Conflicts of interest/Competing interests (include appropriate disclosures): N/A

Ethics approval (include appropriate approvals or waivers): We confirm that we have read the Journal’s position on issues involved in ethical publication and affirm that this report is consistent with those guidelines. This project was approved by the University of New Brunswick Research Ethics Board (REB) and is filed with the university (REB#2019-159).

Consent to participate (include appropriate statements): Written informed consent was obtained from all participants prior to engaging in the experiment.

Consent for publication (include appropriate statements): Informed consent was obtained from all participants ensuring that they understood that while their individual identifiable data would not be made public, aggregate and coded mean data would be made available for publication.

Availability of data and material (data transparency): The datasets generated and/or analysed during the current study are not publicly available due privacy issues but are available from the corresponding author on reasonable request.

Code availability (software application or custom code): The software and custom code used are not available for public use.

Authors' contributions: UK conceived and designed research. EW, OO and JT conducted experiments. EW, OO and JT analyzed data. EW wrote the manuscript. All authors read and approved the manuscript.

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Figures

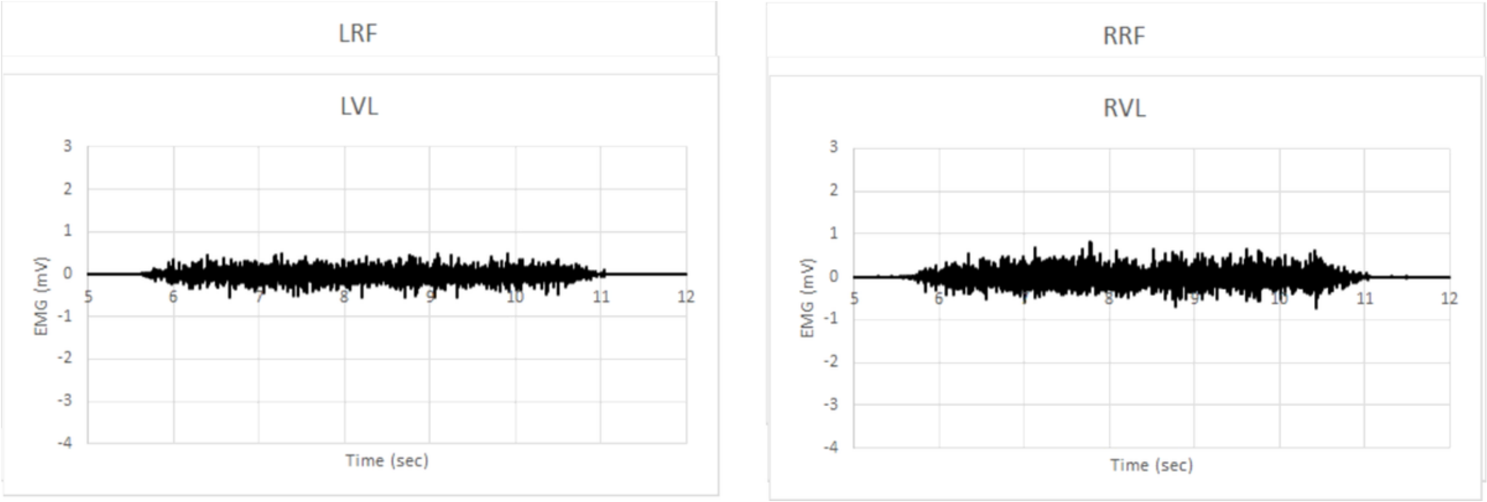

Figure 1

Experimental set up


[redacted]

Figure 2

Sample Data. EMG data from one subject during an MVC in a bilateral leg press. First column EMG data from the left limb (RF, VM, VL). Second column EMG data from the right limb (RF, VM, VL).

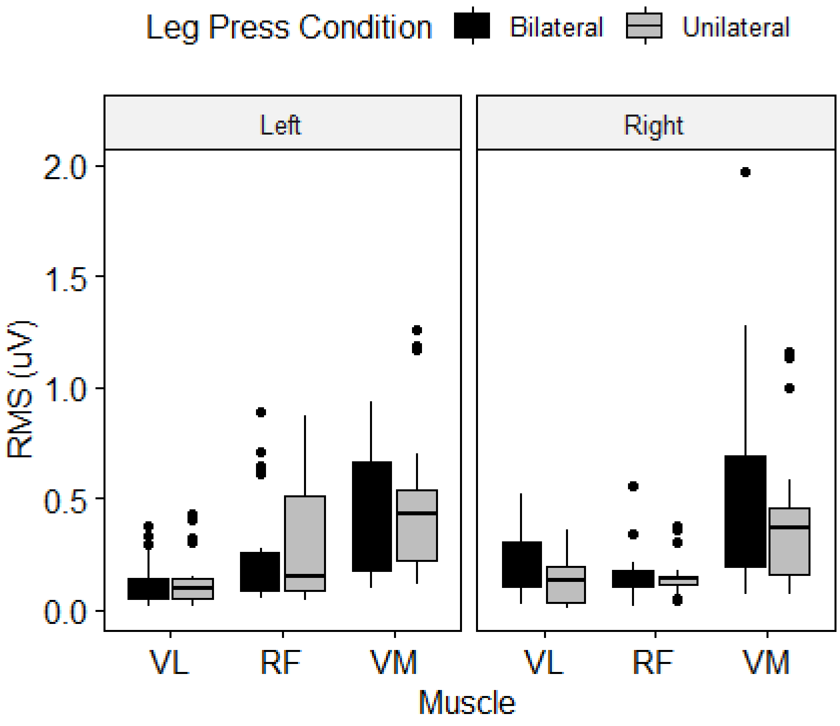

Figure 3

Mean RMS values of the left and right sided muscles between the unilateral and bilateral conditions

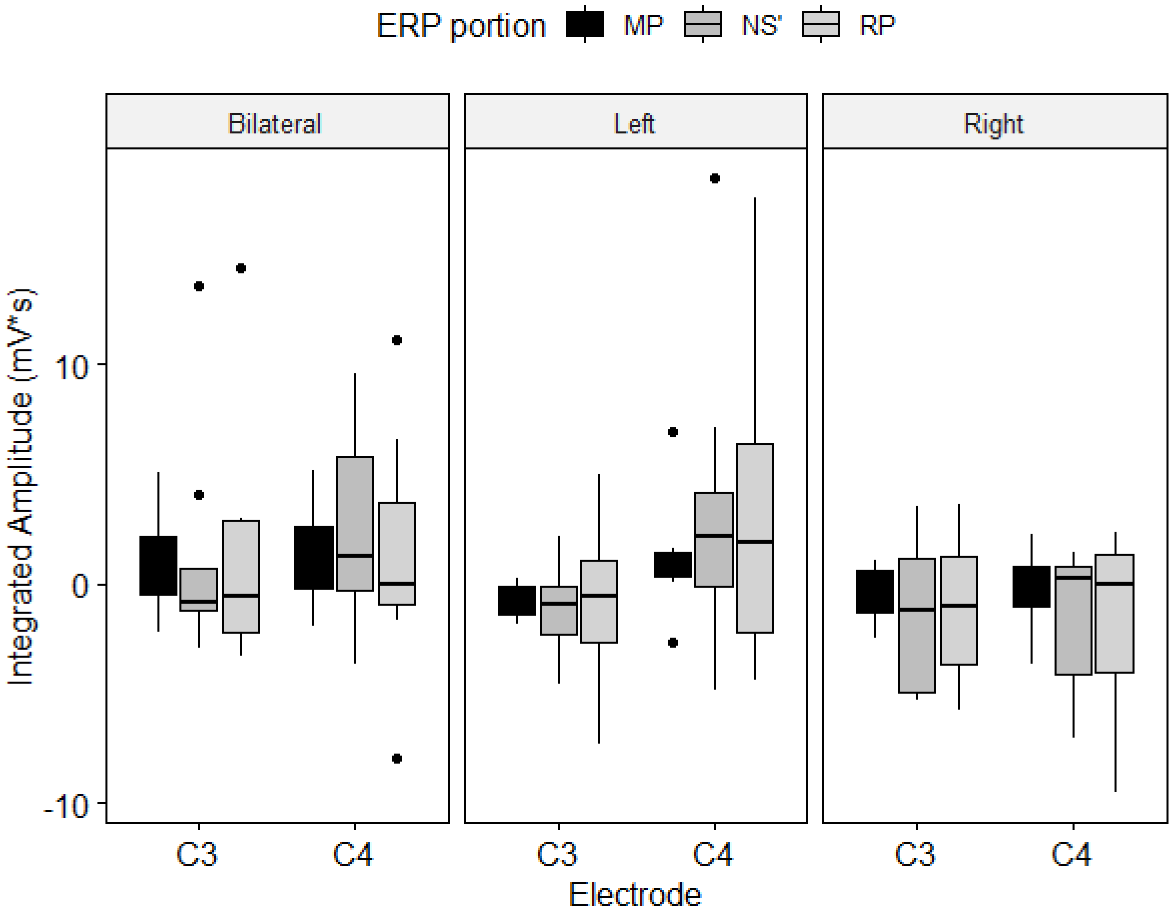

Figure 4

Mean integrated amplitudes (mV*s) of the RP, NS’, and MP at the C3 and C4 electrodes during each condition