AN EXAMINATION OF THE EFFECTS OF BILATERAL AND UNILATERAL VERY SHORT-TERM DCER TRAINING ON STRENGTH AND NEUROMUSCULAR RESPONSES WITHIN THE LOWER LIMB BILATERAL DEFICIT

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Digital Object Identifier: https://doi.org/10.13023/etd.2019.405

Recommended Citation

Byrd, Mark Travis, "AN EXAMINATION OF THE EFFECTS OF BILATERAL AND UNILATERAL VERY SHORT-TERM DCER TRAINING ON STRENGTH AND NEUROMUSCULAR RESPONSES WITHIN THE LOWER LIMB BILATERAL DEFICIT" (2019). Theses and Dissertations--Kinesiology and Health Promotion. 63.

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AN EXAMINATION OF THE EFFECTS OF BILATERAL AND UNILATERAL
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NEUROMUSCULAR RESPONSES WITHIN THE LOWER LIMB BILATERAL
DEFICIT

DISSertation

A dissertation submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in the College of Education at the University of Kentucky

By
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Lexington, KY

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2019

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ABSTRACT OF DISSERTATION

AN EXAMINATION OF THE EFFECTS OF BILATERAL AND UNILATERAL VERY SHORT-TERM DCER TRAINING ON STRENGTH AND NEUROMUSCULAR RESPONSES WITHIN THE LOWER LIMB BILATERAL DEFICIT

The very short-term resistance training (VST) model, utilizing only 2-3 training sessions, has been used to examine early phase skeletal muscle, neural, and performance adaptations. The VST model has previously been used to examine these early phase adaptations in bilateral and unilateral, isometric, isokinetic, and dynamic muscle actions in the limbs of the upper- and lower-body. The bilateral deficit (BLD) is a phenomenon in which the sum of the forces produced unilaterally is greater than the force produced bilaterally during maximal contraction of the limbs. The appearance of a bilateral deficit has been related to various factors; including training status and mode of training (bilateral versus reciprocal muscle actions). No previous study, however, has examined the effects of VST on the BLD. The VST model has potential implications for examining acute changes in strength and neuromuscular responses of the trained muscles. These adaptations, however, may be specific to unilateral or bilateral training. Therefore, the purposes of this study were to: 1) examine one repetition maximum (1RM) strength and neuromuscular responses (EMG AMP, EMG MPF, MMG AMP, MMG MPF) during the measurement of bilateral and unilateral leg extension exercise before and after dynamic constant external resistance (DCER) VST; 2) examine the magnitude of the BLD; 3) examine the effect of bilateral versus unilateral training on the BLD; and 4) use the neuromuscular responses measured bilaterally and unilaterally to infer about the motor unit activation strategies that may underlie the BLD and changes in 1RM strength.

Twenty-four (14 males, 10 females) subjects (mean ± SD age: 23.0 ± 3.2 yr; height: 174.7 ± 8.5 cm; body mass: 75.4 ± 14.1 kg) with no resistance training experience within the last three months were randomly assigned to either the bilateral (BL) training group or the unilateral (UL) training group. The subjects completed a total of seven visits, consisting of a familiarization, pre-test visit, three training visits, and one post-test visit. The pre-test visit was used to record the subject’s electromyographic (EMG) and mechanomyographic (MMG) responses from the right and left vastus lateralis (VL) during bilateral and unilateral seated maximum isometric voluntary contractions (MVIC) and 1RM. Visits four through six were the training sessions, with each subject preforming 5 sets of 6 repetitions utilizing 65% of the 1RM for resistance where the BL group trained both limbs (right and left) at the same time and the UL group trained both limbs separately. Visit seven was the post-test and the same testing procedures as the pre-test visit were followed. Statistical analyses consisted of four-way and three-way mixed model ANOVAs, with follow up three-, two- and one-way repeated measures and/or
mixed model ANOVAs, Bonferroni corrected paired, and independent samples t-tests when appropriate. An alpha level of $P \leq 0.05$ was considered statistically significant for all ANOVAs. The BL group demonstrated a significant increase ($p = 0.006$; 6.8%) in BL$^{1RM}$ pre- to post-test, but no change in unilateral summed (US$^{1RM} = $ right + left limb; $p = 0.726$) $1RM$ strength. The UL group demonstrated an 8.7% increase in BL strength collapsed across testing mode (BL$^{1RM}$ and US$^{1RM}$) ($p = 0.0001$) and UL strength ($p = 0.0001$) collapsed across limb (UL left + UL right/2) from pre- to post-test. The BL group had a significant ($p = 0.001$) increase in the BI (indicating a decrease in the BLD) from pre- to post-test, but there was no significant change for the UL group. The BL group demonstrated a significant ($p = 0.029$) decrease in the EMG mean power frequency (MPF) measurement pre- to post-test, however the UL group showed no change. The unilateral movement, collapsed across limbs (unilateral left and unilateral right) also showed a significant ($p = 0.022$) decrease in the MMG MPF measurement pre- to post-test, whereas the BL movement showed no change. These findings indicated that BL and UL DCER training increased strength after 3 training sessions. The bilateral DCER training resulted in bilateral, but not unilateral strength increases and unilateral DCER training resulting in both bilateral and unilateral strength increases. However, bilateral training was the only mode of training that significantly decreased the BLD.

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10-11-19
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ABBREVIATIONS

DCER – dynamic constant external resistance
RM – repetition maximum
EMG – electromyography
MMG – mechanomyography
AMP – amplitude
MPF – mean power frequency
VST – very short-term
VL – vastus lateralis
BLD – bilateral deficit
BI – bilateral index
MVIC – maximum isometric voluntary contraction
BL$_{1RM}$ – bilateral 1 repetition maximum
UL$_{1RM}$ – unilateral left 1 repetition maximum
UR$_{1RM}$ – unilateral right 1 repetition maximum
US$_{1RM}$ – unilateral left and right summed 1 repetition maximum
FAM$_{VISIT}$ – familiarization
ICC – intra-class correlation
SEM – standard error of the measurement
MD – minimum difference
BD$_{ABS}$ – absolute bilateral deficit
BL – bilateral
UL - unilateral
CHAPTER ONE: INTRODUCTION

Dynamic constant external resistance (DCER) exercise is a common form of resistance training used in injury rehabilitation as well as general fitness and sports performance development to increase strength in sedentary, active, and highly trained individuals (Housh et al. 1996). Typically, studies have examined training protocols consisting of 18 to 36 training sessions within a 6 to 12 week period (Paulsen et al. 2003, Kraemer et al. 1995). For previously untrained individuals, 6-week DCER training programs typically result in 10% to 26% increases in upper- and lower-body strength (Paulsen et al. 2003). For example, in untrained males, a 6-week DCER training program, performed at the 7 repetition maximum (RM) for 1 or 3 sets, 3 times per week, resulted in average increases in pre- to post-training 1RM strength of 18.6% for the squat, 18.7% for leg extension, 15.5% for leg curl, 9.7% for bench press, 23% for shoulder press, and 13.5% for lat pull-down (Paulsen et al. 2003). Thus, upper- and lower-body 6-week, DCER training protocols utilizing only one set, 3 times per week, have been shown to result in significant upper and lower body strength increases (10% to 26%) in previously untrained subjects.

Skeletal muscle and performance adaptations to resistance training exercise programs are well documented (Grgic et al. 2018), and reflect both neuromuscular adaptations and skeletal muscle hypertrophy (Aagaard et al. 2002, Staron et al. 1994). During the first few weeks of training, significant increases in strength are typically attributed to neuromuscular adaptations (Aagaard et al. 2002, Staron et al. 1994, Moritani & Devries 1979), with the effects of skeletal muscle hypertrophy on strength becoming more dominant after 8 to 12 weeks of resistance training (Jones & Rutherford 1987).
Possible early phase neuromuscular adaptations include increases in the conduction velocity of the action potential, motor unit recruitment, and/or changes within the motor unit-firing rate as well as a decreased co-activation of the antagonist muscle group (Cramer et al. 2007, Coburn et al. 2006, Traylor et al. 2014). The early phase (1 to 6 weeks) neuromuscular adaptation to resistance training are reflected by an increased movement velocity and a shift in the force-velocity curve, resulting in increased rate of force development (Osteras et al. 2002).

Electromyography (EMG) and mechanomyography (MMG) have been used to further understand the possible neuromuscular responses and early phase resistance training adaptations. The amplitude (AMP) of the EMG signal reflects global motor unit activation and the mean power frequency (MPF) reflects the conduction velocity of the action potential along the sarcolemma (Basmanjian 1985, DeLuca 1997, Traylor et al. 2014). The use of MMG provides the mechanical counterpart to the motor unit electrical activity measured by EMG (Beck et al. 2005, Traylor et al. 2014). The MMG AMP reflects motor unit recruitment and the MMG frequency domain provides qualitative information regarding the global firing rate of the unfused activate motor units (Orizio 1993, Beck et al. 2005, Beck et al. 2007). It has been suggested (Beck et al. 2005, Orizio et al. 2003), that the fatigue-induced recruitment of additional motor units can increase the MMG amplitude and MPF responses, while reductions in firing rate can decrease these responses. Thus, the simultaneous examination of the EMG and MMG signals can be used to identify changes in motor unit activation strategies as a result of resistance training, such as increases in motor unit recruitment (EMG and MMG AMP), firing rate (MMG MPF), and action potential conduction velocity (EMG MPF).
The very short-term resistance training (VST) model utilizes 2-3 training sessions to determine the minimal number of sessions necessary to observe the early phase neuromuscular and performance adaptations. Previous VST studies have examined forearm flexor isokinetic and isometric performance (Beck et al. 2007, Traylor et al. 2012, Traylor et al. 2013, & Traylor et al. 2014), forearm extensor isokinetic performance (Beck et al. 2007), and leg extensor isokinetic performance (Prevost et al. 1999, Coburn et al. 2006, Brown & Whitehurst 2003, Cramer et al. 2007). In addition, the VST model has recently been applied to both lower (Costa et al. 2013, Costa et al. 2016) and upper body (Byrd & Bergstrom 2018) DCER exercise. Very short-term training has resulted in 1.3% to 40% increases in isokinetic peak torque at various training velocities (Brown & Whitehurst 2003, Coburn et al. 2006). Recently, significant increases (3.5%) in absolute strength have been reported for upper body, multi-joint DCER exercises (Byrd & Bergstrom 2018). Thus, the VST model has been shown to effectively initiate early phase increases in strength and performance parameters for upper and lower body, isokinetic, isometric, and DCER modes of exercise.

Previous VST strength increases in the leg extensors have been accompanied by changes in the EMG and MMG signals. For example, increases in leg extension strength were accompanied by increases EMG MPF (action potential conduction velocity), but no changes in EMG AMP (muscle activation) in females (Coburn et al. 2006). In males, increases in leg extensor muscular strength after VST were associated with increases in EMG MPF and MMG MPF (firing rate), but no changes in EMG AMP or MMG AMP (motor unit recruitment) from the VL (vastus lateralis) (Cramer et al. 2007). There were, however, increases in MMG AMP (motor unit recruitment) reported for the forearm
flexors after VST in males, but not in females (Traylor et al. 2014). Thus, the early phase increases in strength and performance parameters after VST are associated with changes in motor unit activation strategies reflected by the EMG and MMG signals.

In an environment of increasing health care costs and limited medical coverage for injury rehabilitation through physical therapy, the demand for cost-effective alternatives is rising (Fries et al. 1993, Landry et al. 2008). Lower limb injuries are one of the most common types of workplace (14%) and sport injuries (54.2%), often requiring surgery or long-term therapy programs (Davis et al. 2003, Junge et al. 2009). The VST model has been shown to improve muscle function within a limited time frame and could be a cost-effective and time-efficient alternative for those who have limited medical coverage. These early phase muscle function improvements have been primarily attributed to neural adaptations, such as an increased central nervous system (CNS) efferent neuron activity (Aagaard et al. 2002, Staron et al. 1994, Moritani & DeVries 1979). These neural adaptations are important for returning to normal function or improving the ability to perform activities of daily living. After a lower limb injury and immobilization, however, training is often limited to the non-immobilized limb during the initial phase of rehabilitation and/or performed using unilateral exercises for the injured and non-injured limbs. Unilateral training may affect strength and neural adaptations differently than bilateral training, and may affect the magnitude of the bilateral deficit (BLD) (Weir et al. 1997).

The BLD, first described by Henry & Smith (1961), is the phenomenon in which the sum of the forces produced unilaterally (right and left separately) is greater than the force produced bilaterally (right and left together) during maximal contractions of the
limbs. In the lower limbs, this phenomenon has been shown to occur in males and females, young and old, and across athletic and non-athletic populations (Botton et al. 2013, Brown et al. 1994, Costa et al. 2015, Cresswell & Ovedal 2002, Dickin & Too 2006, Kuruganti & Seaman 2006, Owings & Grabiner 1998). When examining athletic performance, a lower limb BLD has been shown to be associated with slower times in overall sprint (60m and 100m) performance (Bracic et al. 2010). The BLD is commonly examined using the bilateral index (BI) calculation presented by Howard & Enoka (1991):

\[
BI(\%) = \left( 100 \times \frac{\text{bilateral}}{\text{right unilateral} + \text{left unilateral}} \right) - 100.
\]

In this equation ‘bilateral’ is the sum of the forces of the individual limbs during a bilateral movement. A negative bilateral index would indicate a BLD, whereas a positive bilateral index would indicate bilateral facilitation. Bilateral facilitation is when the sum of forces produced by the individual limbs bilaterally is greater than the sum of the forces produced unilaterally, during maximal contractions of the same movement. The BLD typically falls between -3 to -25% (Archontides & Fazey 1993, Botton et al. 2013, Brown et al. 1994, Costa et al. 2015, Cresswell & Ovedal 2002, Dickin & Too 2006, Kuruganti & Seaman 2006, Owings & Grabiner 1998, Howard & Enoka 1991), however, there is also evidence of no BLD (Botton et al. 2015, Howard & Enoka 1991) and bilateral facilitation (Hakkinen et al. 1996b, Hakkinen et al. 1997, Howard & Enoka 1991).

The BLD has been suggested to be independent of strength (Owings & Grabiner 1998) and result from neural mechanisms such as neural inhibition, reduced
activation/neural drive (Botton et al. 2013, Brown et al. 1994 Cresswell & Ovedal 2002, Dickin & Too 2006), or even as a result of fiber type characteristics (Brown et al. 1994). The true underlying mechanism(s), however, is largely unknown. When examining EMG activity during bilateral and unilateral contractions within the lower limbs, bilateral contractions have resulted in lower EMG AMP of both legs (Cresswell & Ovedal 2002), than unilateral contractions (Botton et al. 2015, Vandervoort et al. 1984). Researchers have also reported no differences in EMG AMP between unilateral and bilateral movements, indicating the central nervous system is capable of maximal activation of bilateral muscle groups (Hakkinen et al. 1996b). Thus, there are limited and conflicting data regarding the EMG responses during the assessment of the BLD. In addition, no previous studies have used the simultaneous examination of EMG and MMG signals during the assessment of the BLD before and after DCER VST. Therefore, the purposes of this study were to: 1) examine 1RM strength and neuromuscular responses (EMG AMP, EMG MPF, MMG AMP, MMG MPF) during the measurement of bilateral and unilateral leg extension exercise before and after DCER VST; 2) examine the magnitude of the BLD; 3) examine the effect of bilateral versus unilateral training on the bilateral BLD; and 4) use the neuromuscular responses measured bilaterally and unilaterally to infer about the motor unit activation strategies that may underlie the BLD and changes in 1RM strength. Based on previous studies (Kuruganti et al. 2005, Jazen et al. 2006, Beursken et al. 2015, Botton et al. 2015, Byrd & Bergstrom 2018, Cramer et al. 2007, Coburn et al. 2006), we hypothesized there would be: 1) an increase in 1RM strength and increases in the frequency domain of both the EMG and MMG signals as a result of VST DCER training, indicating increases in the motor unit firing rate and action potential.
conduction velocity of the active muscle; 2) bilateral training would result in greater increases in bilateral than unilateral strength and unilateral training would result in greater increases in unilateral than bilateral strength; and 3) unilateral training would result in an increase in the BLD, but bilateral training will result in a decrease or no change in the BLD.
CHAPTER TWO: REVIEW OF LITERATURE

Effects of Very Short-Term Training on Strength

Prevost et al. 1999

The purpose of this study was to examine the effects of 2 days of velocity specific training on isokinetic leg extension peak torque production at three different speeds. Eighteen male subjects (19-35 years) were randomly placed into two training groups; slow (SVT) velocity training (0.52 rad\,s^{-1}) and fast (FVT) velocity training (4.71 rad\,s^{-1}). Using an isokinetic dynamometer, the subjects knee extension peak torque (left leg only) was determine at three different velocities (4.71, 2.62, & 0.52 rad\,s^{-1}). This testing was performed on two separate visits (3 days apart), to determine if peak torque remained unchanged in the absence of training, which allowed the subjects to serve as their own controls. Three days after the second testing session, the subjects performed their first training session, consisting of each group performing 3 sets of 10 maximal contractions using the isokinetic dynamometer at their pre-determined velocities (0.52 & 4.71 rad\,s^{-1}), with a second training visit occurring two days later. Two days after the second training session, the subject’s knee extension peak torque (left leg only) was determined at three different velocities (4.71, 2.62, & 0.52 rad\,s^{-1}) on the isokinetic dynamometer. Neither group showed a significant change in peak torque between the first two testing sessions for any of the three test velocities (4.71, 2.62, & 0.52 rad\,s^{-1}). Following the third testing session, the SVT group showed no change in torque at any speed, but the FVT showed a significant (p<0.05) 22.1 \pm 10\% increase in mean peak torque at 4.71 rad\,s^{-1}. These results lead the researchers to suggest that neural adaptations have a major role in torque
production improvements that are specific to a single fast training velocity, as skeletal muscle hypertrophy would have also caused an increase at the slower velocities.

**Coburn et al. 2006**

Researchers examined the effects of 3 days of velocity-specific isokinetic training on peak torque (PT). Thirty females subjects (19-29 years) were randomly assigned to three groups, SVT (30° s⁻¹), FVT (270° s⁻¹), or control (CON). During the first testing session (pre-test), all subjects performed 3 maximal, concentric, isokinetic leg extensions (with the nondominant leg) on a dynamometer, at 30 and 270° s⁻¹ to determine PT (highest of the 3 muscle actions). The two training groups (SVT & FVT) then participated in 3 training sessions separated by 48-72 hours. The training sessions consisted of 4 sets of 10 maximal, concentric, isokinetic leg extension muscle actions of the nondominant leg. Following the 3 training session, all three groups (SVT, FVT, & CON) were tested again (post-test), utilizing the procedures as the pretest visit. The results showed the SVT group showed an increase in PT at 30° s⁻¹ (24.4%) and 270° s⁻¹ (11.5%), where as training at the FVT group increased PT only at 270° s⁻¹ (40.2%). The researchers suggested neural adaptations such as the training-induced reduction in coactivation of the antagonist hamstring muscles, or increased coordination of stabilizing muscles, could increase the net leg extension torque production.

**Brown & Whitehurst 2003**

The purpose of this study was to determine the effects of short-term isokinetic training on rate of velocity development (RVD) and force. Sixty subjects (30 males, 30 females) with dominant right legs were divided into 3 groups, slow (1.04 rad s⁻¹), fast (4.18 rad s⁻¹) or control, with 10 males and 10 females in each group. Each subject
participated in the first testing session (pre-test), performing 5 maximal concentric reciprocal knee extension and flexion repetitions in a fixed order of velocities at 1.04 and 4.18 rad s\(^{-1}\) with 1-minute rest between bouts. The 2 training groups (slow and fast) participated in 2 training sessions, separated by 48-72 hours, consisting of 3 sets of 8 maximal intensity repetitions at the respective training velocities. Following the completion of the second training visit, all subjects were tested again (post-test), following the same procedures as the first testing visit. The results showed a significant (p<0.05) decrease in RVD between the pre- and post-test for the slow group at the slow velocity (13.6%) and for the fast group at the fast velocity (4.6%). There were no significant differences for force between pre- and post-test. Both RVD and force showed a main effect for velocity and gender, therefore gender was removed as a variable. This indicated limb acceleration may be increased in the absence of force improvements and that these increases are velocity-specific. The authors suggested these performance increases may be explained as a neural adaptation and these increases are similarly expressed across genders.

*Cramer et al. 2007*

This study examined the effects of 3 days of isokinetic resistance training combined with 8 days of creatine monohydrate supplementation on PT, mean power output (MP) and acceleration time (ACC). Twenty-five males (21.17 ± 2.79 years) were randomly assigned to either creatine (CRE; n=13) or the placebo (PLA; n=12) group. The CRE group consumed a total of 14 servings of creatine (10.5 g per serving) over the course of 8 days. Before the start of creatine consumption (pre-test), both groups performed 3 maximal voluntary concentric isokinetic leg extension muscle actions for the
right leg at 30, 150 and 270° s⁻¹ on a dynamometer. 48 hours after the pre-test visit, subjects begin the training sessions, consisting of 3 sets of 10 maximal voluntary concentric isokinetic leg extensions at 150° s⁻¹, with each of the 3 training session being 48 hours apart. After the completion of the final training session (48 hours), subject performed the same procedures as the pre-test visit once again (post-test). Researcher indicated both groups (CRE & PLA) significantly (p<0.05) increased PT (13% & 6%) and decreased ACC (42% & 34%) from pre- to post-test across all velocities (30, 150 & 270° s⁻¹), however, the differences between groups were not significant. The authors suggested that neural adaptations, rather than muscle hypertrophy is the primary explanation for the increased performance adaptations after short-term resistance training.

*Beck et al. 2007*

The researchers of this study examined the effects of 2 days of isokinetic training of the forearm flexors and extensors on strength. Seventeen male (21.9 ± 2.8) subjects were divided into either the training group (TRN; n=8) or control group (CTL; n=9). The subjects first participated in a pre-test visit, consisting of 2 MVICs (115° for 6 second durations), followed by 3 maximal concentric reciprocal forearm flexion and extension muscle actions at 3 randomly ordered velocities (60, 180 & 300° s⁻¹). The highest torque output from each of the 3 velocities was used as the PT value. The TRN group then attended 2 separate training visits, with at least 48 hours between each visit, where they performed 6 sets of 10 maximal concentric isokinetic muscle actions of the forearm flexors and extensors, in a reciprocal manner, at a velocity of 180° s⁻¹. All subjects then completed a post-test visit, following the same testing procedures as the pre-test visit, one week after the completion of the initial pre-test visit. The results of the study indicated no
significant pre- to post-test changes in concentric isokinetic forearm flexion and extension PT, suggesting that 2 days of isokinetic training may not be sufficient to elicit significant increases in strength.

*Traylor et al. 2012*

The purpose of this study was to examine the effects of 3 concentric isokinetic training sessions on the forearm flexors on PT in females at 4 velocities (maximal voluntary isometric contraction (MVIC), 60, 180 & 300°·s⁻¹). Ten females (21.2 ± 0.8 years) visited the lab a total of 7 times with 48 to 72 hours between each visit, including two pre-test visit. With the utilization of a dynamometer, the pre-test visits consisted of 2 MVIC’s (at 115° for 6 second durations), and 3 maximum concentric isokinetic muscle actions each (non-dominant arm) at 3 randomly ordered velocities (60, 180, & 300°·s⁻¹), with the highest PT value at each velocity being selected. Following the two pre-test visits, subjects then participated in 3 separate training visits, performing 5 sets of 10 maximal concentric isokinetic muscle actions (non-dominate arm) of the forearm flexors at a velocity of 60°·s⁻¹. After the completion of all training visits a post-test was completed following the same procedures as the previous two pre-test visits. The study resulted in significant (p<0.05) decreases in PT at each velocity. The researchers suggested that three isokinetic training sessions for the forearm flexors were not sufficient to induce significant neural adaptations for positive performance increases in females and the effects of short-term training were specific to the muscle groups involved.

*Traylor et al. 2013*
The purpose of this study was to examine the effects of 3 concentric isokinetic training sessions on the forearm flexors on PT in males at 4 velocities (MVIC, 60, 180 & 300° s⁻¹). Ten males (21.8 ± 1.2 years) visited the lab a total of 7 times with 48 to 72 hours between each visit, including two pre-test visit. With the utilization of a dynamometer, the pre-test visits consisted of 2 MVIC’s (at 115° for 6 second durations), and 3 maximum concentric isokinetic muscle actions each (non-dominant arm) at 3 randomly ordered velocities (60, 180, & 300° s⁻¹), with the highest PT value at each velocity being selected. Following the two pre-test visits, subjects then participated in 3 separate training visits, performing 5 sets of 10 maximal concentric isokinetic muscle actions (non-dominate arm) of the forearm flexors at a velocity of 60° s⁻¹. After the completion of all training visits a post-test was completed following the same procedures as the previous two pre-test visits. The results showed a significant main effect for time and velocity, with the marginal means of the post-test being significantly greater that both pre-test visits. There were an increased PT at MVIC (11%), 60 (13%), 180 (15%) and 300° s⁻¹ (17%). These increased were suggested to possibly be due to gender of the subject, training velocity, and number of repetitions with possible mechanisms from neural adaptations, or even increased muscle activation and/or decreased antagonist muscle coactivation.

*Traylor et al. 2014*

This study examined the effects of sex on PT, average power (AP) following very short-term training of the forearm flexors. Nine males (22.3 ± 2.1 years) and nine females (21.7 ± 1.1 years) completed 2 pre-test visits, 3 training visits and 1 post-test visit with 48 to 72 hours between each visit. The 2 pre-test visit consisted of 3 maximal
concentric forearm flexion muscle actions (non-dominant arm) at randomly ordered velocities of 60 and 180°·s⁻¹, utilizing a dynamometer. PT was determined for the highest value of the 3 muscle actions. The 3 training visits consisted of 5 sets of 10 maximal concentric isokinetic muscle actions (non-dominant arm) of the forearm flexors at a velocity of 60°·s⁻¹. The post-test visit followed the same testing procedures at the two pre-test visits. The study indicated the presents of a gender difference in which PT and AP both significantly increased for the males from pre-test 1 to post-test, but not the females. AP of the forearm flexors increased by 8.4 to 20.2% at both velocities (60 & 180°·s⁻¹). The authors indicated that up to 50% of the training-induced increases in forearm flexion PT occur within the first 3 training sessions for males, but not females. The researchers suggested the difference in PT and AP responses between males and females may be due to activities of daily living (ADL) and its affect on antagonist co-activation and/or morphological changes to the muscle fibers.

Costa et al. 2016

The purpose of this study was to examine the effects of three days of unilateral dynamic constant external resistance (DCER) training and detraining on the strength of the trained and untrained legs. Nineteen male subjects (21.6 ± 3.4) were randomly assigned to a DCER training group (n = 10) or a control group (n = 9). There were a total of 8 visits, including a familiarization session, pre-training assessment, 3 training visits (for the DCER training group), and 3 post-training assessments (at 48 hours, 1-week, 2-week). During the pre-training assessment, a one-repetition maximum (1RM) was determined, using a leg extension machine for both the dominant and non-dominant lower limb. The DCER training consisted of the training group performing 4 sets of 10
repetitions on a leg extension machine, using only the dominant limb. The results showed the DCER training group had a strength increase in both the trained and untrained limb and the strength remained elevated during the 1-week and 2-week post-training assessment, with no changes observed within the control group. The authors suggest neural adaptations play a major role in the strength improvements observed in this study.

*Byrd and Bergstrom 2018*

The purpose of this study was to examine the effect of an upper body dynamic constant external resistance (DCER) exercise (barbell bench press [BP]), using the very short-term training (VST) model on strength and barbell velocity. Ten (5 females, 5 males) subjects (21.4 ± 2.8 years) completed 2 pre-test visits, 3 training visits and one post-test visit with 48 to 72 hours between each visit. During the 2 pre-test visits, the subject’s one repetition maximum (1RM) was determined for the BP. Subjects then performed 3 repetitions on the barbell bench press throw (BT) utilizing 35% of the subject’s BP 1RM as resistance. Both mean and peak velocity measures were recorded from each subject’s 1RM and the highest mean and peak velocity recording of the 3 BT repetitions was used. The 3 training visits then consisted of performing 5 sets of 6 repetitions, using 65% of the subject’s 1RM as resistance. The post-test followed the same testing procedures the previous 2 pre-test visits. Overall, there were significant increases of 3.5% in 1RM, 2.4% in BT\textsubscript{MV}, and 3.5% in BT\textsubscript{PV} from pre-test 2 to post-test, with a non-significant increases of 26% in BP\textsubscript{MV} and 20% in BP\textsubscript{PV} from pre-test 2 to post-test. These findings showed the VST model, utilizing an upper body DCER exercise improved strength and barbell velocity in untrained subjects.
Summary

The very-short term resistance training (VST) model consists of two to three training sessions. The VST model has been used to examine forearm flexor performance (Beck et al. 2007, Traylor et al. 2012, Traylor et al. 2013, & Traylor et al. 2014), forearm extensor performance (Beck et al. 2007), leg extensor performance (Prevost et al. 1999, Coburn et al. 2006, Brown et al. 2003, Cramer et al. 2007, & Costa et al. 2016), leg flexor performance (Brown et al. 2003), and upper body barbell bench press performance (Byrd & Bergstrom 2018). Isokinetic exercise, using a wide range of velocities, has been the primary mode of training examined within the VST model (Prevost et al. 1999, Coburn et al. 2006, Brown et al. 2003, Cramer et al. 2007, Beck et al. 2007, Traylor et al. 2012, Traylor et al. 2013, & Traylor et al. 2014). More recently, the VST model has been applied to dynamic constant external resistance (DCER) exercise (Costa et al. 2016, Byrd & Bergstrom 2018). Utilization of the VST model has shown isokinetic peak torque increases ranging from 6 to 40%, depending on training velocity; increased rate of velocity development (Brown et al. 2003), decreased acceleration time (Cramer et al. 2007), along with increases in multi-joint exercise absolute strength measures (Byrd & Bergstrom 2018). Thus, the VST model has been shown to improve performance within a limited time frame.
Neuromuscular Responses within VST using EMG and MMG

Electromyography Sub-Section

The physiological signal observed through electromyography (EMG) has been described as “...the electrical manifestation of the neuromuscular activation associated with a contracting muscle” (Basmanjian 1985, pg. 53). During a muscle contraction, the depolarization propagates along the muscle fiber membrane (sarcolemma), accompanied by a movement of ions (sodium, potassium, etc...) in and out of the muscle cell, generating an electromagnetic field (Basmanjian 1985). This voltage signal is measured through the use of EMG. The EMG signal provides a time domain (amplitude) and a frequency domain. The amplitude (AMP) of the EMG signal reflects the global motor unit activation and the mean power frequency (MPF) is reflecting the conduction velocity of the action potential along the sarcolemma (Basmanjian 1985, DeLuca 1997, Traylor et al. 2014). Researchers have suggested the EMG signal can be affected by the anatomical and physiological properties of the active muscle; the control scheme of the peripheral nervous system; electrode location; as well as the characteristics of the instrumentation used to detect and observe it (Basmanjian 1985, DeLuca 1997).

Mechanomyography Sub-Section

During a muscle contraction, the movement of the muscle creates vibrations/oscillations within the muscle fibers, creating a measurable, mechanical signal that can be detectable at the surface of the active muscle (Orizio 1993, Beck et al. 2005, Beck et al. 2007). The measurement of this signal is known as mechanomyography (MMG). This mechanical signal reflects global motor unit activation and provides both a time (amplitude) and frequency domain (Orizio 1993, Beck et al. 2005, Beck et al. 2007).
The MMG amplitude reflects motor unit recruitment and the MMG frequency domain provide qualitative information regarding the global firing rate of the unfused activated motor units (Orizio 1993, Beck et al. 2005, Beck et al. 2007). Researchers have suggested the MMG signal can be influenced by muscle stiffness; intramuscular fluid pressure; tissue thickness between the muscle and MMG sensor; muscle temperature; and muscle length.

**Coburn et al. 2006**

Researchers examined the effects of 3 days of velocity-specific isokinetic training on electromyographic (EMG) signal. Thirty females subjects (19-29 years) were randomly assigned to three groups, SVT (30°·s⁻¹), FVT (270°·s⁻¹), or control (CON). During the first testing session (pre-test), all subjects performed 3 maximal, concentric, isokinetic leg extensions (with the non-dominant leg) on a dynamometer, at 30 and 270°·s⁻¹, with EMG signals being recorded from the vastus lateralis, rectus femoris and vastus medialis. The two training groups (SVT & FVT) then participated in 3 training sessions separated by 48-72 hours. The training sessions consisted of 4 sets of 10 maximal, concentric, isokinetic leg extension muscle actions of the non-dominant leg. Following the 3 training session, all three groups (SVT, FVT, & CON) were tested again (post-test), utilizing the procedures as the pretest visit. The results showed a pre- to post-test increase in EMG mean power frequency (MPF) from the vastus medialis (23.7%) at a velocity of 270°·s⁻¹ for the FVT group. From the lack of consistent EMG amplitude or MPF results, the researchers suggest increased activation of the active muscle were not the cause of the observed increased strength values (FVT group increased PT at 270°·s⁻¹ (40.2%), however, it is possible that neural adaptations not reflected by EMG may have had
contributions, such as coactivation of the antagonist muscles (biceps femoris, semitendinosus, semimembranosus). Another possibility suggested by the authors are morphological changes with in the active muscle could have also contributed to the performance increases.

**Beck et al. 2007**

The researchers of this study examined the effects of 2 days of isokinetic training on electromyographic amplitude in the agonist and antagonist muscle of the forearm flexors and extensors. Seventeen male (21.9 ± 2.8) subjects were divided into either the training group (TRN; n=8) or control group (CTL; n=9). The subjects first participated in a pre-test visit, consisting of 2 MVICs (115° for 6 second durations), followed by 3 maximal concentric reciprocal forearm flexion and extension muscle actions at 3 randomly ordered velocities (60, 180 & 300°s⁻¹). Surface EMG signals were detected from the biceps brachii and triceps brachii muscles. The TRN group then attended 2 separate training visits, with at least 48 hours between each visit, where they performed 6 sets of 10 maximal concentric isokinetic muscle actions of the forearm flexors and extensors, in a reciprocal manner, at a velocity of 180°s⁻¹. All subjects then completed a post-test visit, following the same testing procedures as the pre-test visit, one week after the completion of the initial pre-test visit. The results indicated no significant pre- to post-test changes in EMG amplitude for the agonist and antagonist muscles, suggesting that 2 days of isokinetic training may not be sufficient to elicit significant neural adaptations in the forearm flexors and extensors.

**Cramer et al. 2007**
This study examined the effects of 3 days of isokinetic resistance training combined with 8 days of creatine monohydrate supplementation on surface electromyography (EMG) and mechanomyography (MMG) of the vastus lateralis. Twenty-five males (21.17 ± 2.79 years) were randomly assigned to either creatine (CRE; n=13) or the placebo (PLA; n=12) group. The CRE group consumed a total of 14 servings of creatine (10.5 g per serving) over the course of 8 days. Before the start of creatine consumption (pre-test), both groups performed 3 maximal voluntary concentric isokinetic leg extension muscle actions for the right leg at 30, 150 and 270° s⁻¹ on a dynamometer. 48 hours after the pre-test visit, subjects begin the training sessions, consisting of 3 sets of 10 maximal voluntary concentric isokinetic leg extensions at 150° s⁻¹, with each of the 3 training session being 48 hours apart. After the completion of the final training session (48 hours), subject performed the same procedures as the pre-test visit once again (post-test). Researcher indicated EMG median frequency increase for all velocities (30, 150 and 270° s⁻¹) and MMG median frequency increased at 30° s⁻¹ from pre- to post-test for both groups (CRE & PLA). Based on results of the EMG and MMG signals, the researchers suggest that training induced increases in the motor unit firing rate (per the increases in the frequency domain measurements) may have been responsible for the observed improvements.

Costa et al. 2013

The purpose of this study was to investigate and compare the effects of 3 days of dynamic constant external resistance (DCER) and isokinetic (ISOK) training and subsequent detraining on electromechanical delay (EMD). Thirth-one male (22.2 ± 4.2) subjects were randomly assigned to a DCER training group (n = 11), ISOK training
group (n = 10) or a control group (n = 10). There were a total of 8 visits, including a
familiarization session, pre-training assessment, 3 training visits (for the 2 training
groups), and 3 post-training assessments (at 48 hours, 1 week, 2 week). For the three
training visits, the ISOK group performed isokinetic leg extensions and the DCER group
performed leg extensions for 3 sets of 10 repetitions. Electromyography data were
collected from the rectus femoris muscle. Electromechanical delay was assessed during
the 4 assessment visits (1 pre-training, 3 post-training) by 5 single 200 μs-duration
square-wave supramaximal transcutaneous electrical stimuli (each separated by 5
seconds). The results showed no significant interactions. The researchers suggested
increases in strength observed after short-term resistance training may not be attributed to
stiffness changes in the series-elastic component.

Traylor et al. 2014

This study examined the effects of sex on electromyographic (EMG) and
mechanomyographic time (amplitude) and frequency (MPF) domain following very
short-term training of the forearm flexors (biceps brachii). Nine males (22.3 ± 2.1 years)
and nine females (21.7 ± 1.1 years) completed 2 pre-test visits, 3 training visits and 1
post-test visit with 48 to 72 hours between each visit. The 2 pre-test visit consisted of 3
maximal concentric forearm flexion muscle actions (non-dominant arm) at randomly
ordered velocities of 60 and 180°·s⁻¹, utilizing a dynamometer. The 3 training visits
consisted of 5 sets of 10 maximal concentric isokinetic muscle actions (non-dominant
arm) of the forearm flexors at a velocity of 60°·s⁻¹. The post-test visit followed the same
testing procedures at the two pre-test visits. The results indicated an increase within the
time (amplitude) domain of the MMG signal at both velocities (60 & 180°·s⁻¹), pre- to
post-test for the males only. The authors suggested these results might be due to decreased antagonist co-activation, adaptations in the forearm flexor muscles other than the biceps brachii, and/or morphological changes to the muscle fibers.

**Summary**

Electromyography (EMG) has been used to further understand the possible neuromuscular responses of skeletal muscle, with the amplitude (AMP) of the EMG signal reflecting global motor unit activation and the mean power frequency (MPF) reflecting the conduction velocity of the action potential along the sarcolemma (Beck et al. 2005, Traylor et al. 2012). EMG MPF has been shown to increase in the knee extensor muscles, in both males and females after VST (Coburn et al. 2006, Cramer et al. 2007). The use of mechanomyography (MMG) provides the mechanical counterpart to the motor unit electrical activity measured by EMG (Beck et al. 2005, Traylor et al. 2012). The MMG amplitude reflects motor unit recruitment and the MMG frequency domain provide qualitative information regarding the global firing rate of the unfused activate motor units (Beck et al. 2005, Beck et al. 2007). The results of studies utilizing MMG to assess motor control strategies have shown increases in the AMP (reflect motor unit recruitment) and MPF (reflects motor unit firing rate) only within male populations during both upper and lower body measures (Cramer et al. 2007, Traylor et al. 2014). Within the leg extensors, researchers have shown an increase in MMG MPF after VST (Cramer et al. 2007), whereas other researchers have shown an increase in MMG AMP within the forearm flexors for male, but not female subjects, leading researchers to suggest the presence of a gender difference with the neuromuscular responses as a result of VST (Traylor et al. 2014).
Bilateral Deficit within the Lower Limbs during Dynamic Con contractions

Botton et al. 2013

The aim of this study was to compare the magnitude of bilateral deficit (BLD) between isometric and concentric actions of the knee extensors. Eleven males (20.6 ± 1 years) completed 1 familiarization and 2 testing visits, with 48 hours between visits. The testing sessions were performed on a dynamometer and composed of 5 isokinetic concentric actions of the knee extensors at 60°s⁻¹ and 3 maximal isometric voluntary contraction (MVIC) at a 60° angle of knee flexion. The testing sessions were arranged in a randomized order with either a unilateral (right and left limb separately) or bilateral (right and left limb together) condition. The greatest peak torque production of each condition was used for analyses. The results showed the presence of a BLD in both isometric (-9.7 ± 6.7%) and concentric (-9.6 ± 6.8%) muscle actions, with no significant difference between them. The researchers suggested the observed BLD was possibly due to neural inhibition that occurs during the bilateral condition which inhibits maximal torque production and demonstrates that isometric and concentric muscle actions exhibit similar BLD for the knee extensors.

Brown et al. 1994

The purpose of this study was to investigate the effects of velocity on the bilateral deficit and estimate the relative contribution of muscle fiber type to the bilateral deficit in untrained women. Twelve subjects (34.9 ± 2.4 years) performed 3 reciprocal knee extension and flexion repetitions on a dynamometer, at isokinetic speeds of 60, 120, 180, 240 and 360°s⁻¹ in a fix order, for both the unilateral and bilateral condition. Each test were administered in a random order and separated by 48 hours. The results showed a
decrease in the bilateral deficit with increasing velocity, with greater torque outputs coming from the bilateral movement the unilateral movements combined. The researchers suggested that slow-twitch fibers might be primarily responsible for the observed bilateral deficit.

*Costa et al. 2015*

This study investigated the effect of unilateral and bilateral resistance exercise on maximal voluntary strength and total volume of load lifted (TVLL). Twelve males (24 ± 3.7 years) determined their leg extension one repetition maximum (1RM) for both bilateral and unilateral contractions. Subjects then performed 3 sets of leg extensions until failure, utilizing 50% of the subject’s predetermined 1RM, with 2 minutes rest between each set. For the unilateral portion, subjects began with their dominant limb and upon failure; subjects’ immediately started with their non-dominant leg and continued performing repetitions until failure, preceded by a 2-minute rest period. The results showed a significant difference in the bilateral (120 ± 11.9 kg) and unilateral (135 ± 20.2 kg) 1RM strength. The TVLL was similar between both bilateral and unilateral sessions; however, more repetitions were performed in the bilateral (48) sessions than the unilateral (40) session.

*Cresswell & Ovedal 2002*

This study examined whether or not a bilateral strength deficit occurs during bilateral velocity controlled dynamic knee extensions. Twenty-eight (15-males, 13-females) subjects (24 ± 3 years) performed maximal unilateral and bilateral isokinetic leg extensions at a velocity of 60°·s⁻¹ through a 90° range of motion of the knee joint for 3 trials for each of the 3 conditions (unilateral-right, unilateral-left, bilateral). The results
showed a significant bilateral deficit of 17% in torque production, however there were no
significant difference between the left and right limb. The researchers suggest that altered
neural mechanisms are to some extent, responsible for the reduced torque output within
the bilateral movement.

Dickin & Too 2006

The purpose of this study was to determine if a bilateral deficit is exhibited during
maximal eccentric actions and if the deficit changed as a function of movement velocity
and how the bilateral deficit in a concentric action was affected with different movement
velocities when preceded by a maximal eccentric action. Eighteen females (23.5 ± 3.28
years) performed a total of 18 sets of 3 concentric and eccentric randomized actions at
each of the randomized movement velocities (30, 60, 90, 120, 150, and 180° s⁻¹). The
results showed the presence of a bilateral deficit for all velocities (18, 20, 20, 17, 22 and
25%; 30-180° s⁻¹) during the concentric action, along with the presence of a bilateral
deficit (18-25%) with in the eccentric action at all velocities. The authors suggest this
was due to the reduced activation/neural drive of the contractile elements during bilateral
muscle actions, or possibility the stretch reflex contributes differently during unilateral
and bilateral movements.

Hakkinen et al. 1996b

This study examined force productions during bilateral and unilateral conditions.
A total of 48 subjects (58.1 ± 4.1 years) participated in this study, with 12 males (44-57)
in the middle age group (M50), 12 females (43-57) in the middle age group (F50), 12
males in the elderly group (M70), and 12 females in the elderly group (F70). Utilizing a
dynamometer, each subject completed 2-4 maximal isometric contractions, during a time
period of 2.5-5.0 seconds for both the bilateral and unilateral conditions to determine peak force. The results showed the presence of bilateral force facilitation (bilateral is greater than the sum of the unilateral movement) in the M50, M70, and W50 groups. The authors stated the results of this study indicates the central nervous system is capable of activating both bilateral muscle groups simultaneously, and to the same degree, to that of unilateral activation. 

Hakkinen et al. 1997

This study examined the age-related changes in force productions during isometric and dynamic actions of the knee extensors within bilateral and unilateral conditions. This study was broken into two experiments with a total of 58 subjects (10 young males 29 ± 3 years [M30], 12 middle-aged males 50 ± 4 years [M50], 12 middle-aged females 48 ± 5 years [W50], 12 elderly males 67 ± 4 years [M70] and 12 elderly females 68 ± 4 years [W70]) participating in the first experiment. Within this experiments, a knee extension 1RM was determined under bilateral and both unilateral conditions. The bilateral condition was tested first, followed by the unilateral conditions with 2 minutes rest between each 1RM attempt. For the second experiment, 10 male (29 ± 5 years) subjects were tested for peak force was determined during a maximal voluntary isometric contraction for the bilateral and both unilateral conditions. Utilizing a dynamometer, each subject completed 2-4 maximal isometric contractions, during a time period of 2.5-5.0 seconds for both the bilateral and unilateral conditions to determine peak force. Within both experiments, the results indicated the presence of bilateral facilitation within the concentric 1RM and isometric measurement for all groups. Based on these results, the authors indicated the central nervous system in a simple single joint
isometric and maximal 1RM concentric force production of the knee extensors were capable of bilateral muscle group simultaneous activation, independent of age and sex of the subject.

*Kuruganti & Seaman 2006*

The study examined the presence of bilateral deficit during isokinetic knee extension and flexion in an adolescent female population compared to previously collected data from adult (n = 8, 31 ± 7 years) and older (n = 7, 63 ± 6 years) female populations. Eight adolescent females (15 ± 1 years) completed 2 maximal voluntary isokinetic contractions at 45°·s⁻¹ for the bilateral and both unilateral conditions, with a two minute rest period between each condition. The contraction with the greatest torque production during both extension and flexion was used for analysis. The results showed a bilateral deficit for both knee extension and flexion within all three groups (adolescent: 25.2% & 22.9%; adult: 20.7% & 29.2%; older: 31% & 32.9%).

*Owings & Grabiner 1998*

This study examined if older adults demonstrate a bilateral deficit during maximum voluntary isometric knee extensions performed in a ramp and hold fashion. Thirty-five older adults (72.1 ± 5.7 years) performed three trials of maximum voluntary isometric contractions of the knee extensor muscles under three different randomized conditions (bilateral, unilateral right, unilateral left). Subjects were instructed to generate each maximal contraction over a period of 3 seconds. The results indicated the presence of a bilateral deficit (9.7 ± 9.5%) in the older population of subjects and suggest the restrictions of high threshold motor units are not the cause of bilateral deficits. The researchers also indicate the degree of the bilateral deficit is independent of strength.
Summary

The bilateral deficit is the phenomenon in which the sum of the forces produced unilaterally (right and left separately) is greater than the force produced bilaterally (right and left together) during maximal contractions of the limbs. With in the lower limbs this phenomenon has been shown to occur in both athletic and non-athletic populations; in both male and female populations; and in both young and elderly populations (Botton et al. 2013, Brown et al. 1994, Costa et al. 2015, Cresswell & Ovedal 2002, Dickin & Too 2006, Kuruganti & Seaman 2006, Owings & Grabiner 1998). Researchers have also shown the presence of bilateral facilitation (Hakkinen et al. 1996b, Hakkinen et al. 1997). Bilateral facilitation is when the sum of forces produced by the individual limbs bilaterally is greater than the sum of the forces produced unilaterally, during maximal contractions of the same movement. The absence of a bilateral deficit and bilateral facilitation has also been shown (Botton et al. 2015). The bilateral deficit has been suggested to be independent of strength (Owings & Grabiner 1998) and result from neural mechanisms such as neural inhibition, reduced activation/neural drive ((Botton et al. 2013, Cresswell & Ovedal 2002, Dickin & Too 2006), or even as a result of fiber type characteristics (Brown et al. 1994).
Unilateral vs. Bilateral Training within the Lower Limbs

Weir et al. 1997

This study examined the effects of unilateral concentric leg extension weight training and detraining on bilateral deficit. Sixteen subjects were divided into two groups (control n = 8, training n = 8). All subjects were tested (pre-training and post-training) for maximal unilateral isometric strength, utilizing a dynamometer, at three different joint angles (15°, 45°, and 75°) in each limb as well as for the one-repetition maximum (1RM) strength measure of each limb bilaterally and individually, using a plate-loaded leg extension machine. The training group (n = 8) performed 8 weeks of unilateral (non-dominant limb) concentric weight training, three times per week, performing 3 to 5 sets (1st week – 3 sets, 2nd week – 4 sets, 3rd–8th week – 5 sets) of 6 repetitions utilizing 80% of the subject’s 1RM. The trained limb 1RM was re-measured every 2 weeks for the training group to adjust training loads. The results indicated the presence of a bilateral deficit for the 1RM measurement for both groups during the pre-training measure and the 8 weeks of unilateral training caused an increase in bilateral and both unilateral 1RM strength measures within the training group. The training results were also not joint angle specific as isometric strength increased for all three angles tested. There were also alterations in the unilateral-bilateral relationships as the differences in 1RM strength of the dominant and non-dominant limb seen at pre-training were reversed when measured at post-training with the non-dominant (trained) limb becoming the strongest.

Kuruganti et al. 2005
This study examined the effects of a 6-week bilateral leg strength-training program on bilateral lateral deficit in younger and older adults. Thirty-three subjects were placed in two age groups (younger 28 ± 5 years [male = 5, female = 11], older 64 ± 6 years [male = 10, female = 7]). Each subject performed 2 maximum voluntary contractions for bilateral and both unilateral conditions, with the contraction with the greatest torque being used for analysis. Each training session consisted of 2-3 sets of 8 to 12 bilateral knee extensions and flexions, utilizing a dynamometer at 45°·s⁻¹, with a 2 minute break between contractions. The results showed the presence of a bilateral strength deficit during isokinetic knee extensions (26.1%) and flexions (33.6%) in both young and old adults, but it is reduced with resistance training (extensions 13.6 ± 16.1%, flexion 3.7 ± 13.6%). Age and gender did not have an effect on the improvements. The researchers suggest the strength improvements appear to be caused by improved motor unit recruitment strategy.

Janzen et al. 2006

The study examined the presence of a bilateral deficit and whether unilateral or bilateral training was more beneficial. Fifty post-menopausal females (~57 years) were randomly placed into a bilateral training group (n = 14), unilateral training group (n = 12) or a control group (n = 24). Pre-training assessment showed a 1RM strength knee extension bilateral deficit in the bilateral (5.1%) and unilateral (2.6%) training groups. The training groups performed each exercise 8 to 10 repetitions for 2 sets, 3 times per week for 26 weeks with at least one day of rest between training sessions. Exercises included leg press, knee extension, hamstring curl, lat pull-down, biceps curl, shoulder press, chest press, back extension, unilateral hip extension, flexion adduction and
abduction. The unilateral training was done on both sides separately. The results showed bilateral training had the greatest affect on reducing the bilateral deficit within the knee extension 1RM strength where as unilateral training had minimal effects.

*Botton et al. 2015*

This study examined unilateral vs. bilateral training in the knee extensor muscles. Forty-three females (18-30 years) were randomly assigned to a unilateral training group (UG: n = 14), a bilateral training group (BG: n = 15) or a control group (CG: n = 14). Knee extensor 1RM and maximal isometric strength were measured for each subject for the bilateral and both unilateral conditions. The two training groups performed 2 training sessions a week for a total of 12 weeks. Exercises performed were knee extension, bilateral knee flexion, bench press, lateral pull-down, hip abduction, hip adduction, crunch, biceps flexion, and triceps extension. Training for weeks 1-3 was 2 sets of 12-15RM; weeks 4-6 was 3 sets of 9-12RM; weeks 7-9 was 3 sets of 7-10RM; and weeks 10-12 was 4 sets of 5-8RM, with the intensity being the same for both training groups. Pre-training 1RM assessments show the presents of no bilateral deficit within either of the training groups, but at post-testing, the UG showed a significant bilateral deficit (-6.5 ± 7.8%) where as the BG showed a significant bilateral facilitation (5.9 ± 9%). Both training groups showed an increase in both the 1RM and isometric strength values, with the UG having greater unilateral isometric strength increases than the BG.

*Beurskens et al. 2015*

This study examined the age-related difference and the training-induced effects on maximal isometric force productions (MIF) and bilateral deficit (BLD) of the leg extensors. Fifty-three males (60-80 years) were randomly assigned to one of three groups,
bilateral heavy-resistance strength training (HRT: n = 19), unilateral balance training (BAL: n = 14) or a control group (CON: n = 20). The additions of fourteen younger (20-30 years) males (YA) were also included for baseline age cross-sectional comparison. MIF testing was performed on a leg-press, with each foot resting on a one-dimensional force plate with each subject completed 3-4 maximal isometric leg extensor contractions for the bilateral and both unilateral conditions. The training groups trained 3 times per week for 13 weeks, with the HRT group utilized 80% of their 1RM for 3 sets of 10 repetitions for leg press, leg-extension, calf raise and foot dorsi-flexor exercises with 2 minutes rest between sets. Training loads were adjusted weekly. For the BAL group balance training were conducted on wobble boards, soft mats and uneven surfaces. The initial testing resulted in the presence of a bilateral deficit for the HRT group (18.7 ± 6.2%), the BAL group (11.9 ± 5.9%), the control group (19.3 ± 11.3%) and the YA group (3.9 ± 5.9%). After training the HRT group showed the greatest reduction in bilateral deficit (post-testing 5.1 ± 6.8%), with the BAL group also showing a reduction (post-training 7.2 ± 5.5%). These results show both heavy-resistance training and unilateral balance training can both have a positive affect on the bilateral deficit in older males.

**Summary**

In general, resistance training has been shown cause skeletal muscle and performance adaptations (Kraemer et al. 1995), resulting from both neural adaptations and skeletal muscle hypertrophy (Aagaard et al. 2002, Staron et al. 1994). Resistance training has also been shown to cause changes in observed populations with an expressed lower limb bilateral deficit. Training studies examining the effects of resistance training
on lower limb bilateral deficit have lasted 6 to 26 weeks and have included both unilateral and bilateral training. Unilateral training has resulted in the reversal of dominant and non-dominant limb strength within the unilateral-bilateral relationship (Weir et al. 1997), where as bilateral training has been shown to reduce or have the greatest affect on reducing the lower limb bilateral deficit (Kuruganti et al. 2005, Jazen et al. 2006, Beursken et al. 2015). These training method effects on the bilateral deficit phenomenon appear to be consistent across genders and age (Janzen et al. 2006). However, other researchers (Botton et al. 2015) have shown unilateral training to cause the expression of a bilateral deficit and bilateral training to cause the expression of a bilateral facilitation.
Neuromuscular Responses within the Bilateral Deficit of the Lower Limbs

_Botton et al. 2015_

This study compared neuromuscular adaptations with unilateral vs. bilateral training in the knee extensor muscles. Forty-three females (18-30 years) were randomly assigned to a unilateral training group (UG: n = 14), a bilateral training group (BG: n = 15) or a control group (CG: n = 14). Knee extensor 1RM and maximal isometric strength were measured for each subject for the bilateral and both unilateral conditions. Electromyographic (EMG) activity was recorded from the vastus lateralis and rectus femoris of the left and right limbs during maximal isometric strength testing. The two training groups performed 2 training sessions a week for a total of 12 weeks. Exercises performed were knee extension, bilateral knee flexion, bench press, lateral pull-down, hip abduction, hip adduction, crunch, biceps flexion, and triceps extension. Training for weeks 1-3 was 2 sets of 12-15RM; weeks 4-6 was 3 sets of 9-12RM; weeks 7-9 was 3 sets of 7-10RM; and weeks 10-12 was 4 sets of 5-8RM, with the intensity being the same for both training groups. Pre-training 1RM assessments show the presents of no bilateral deficit within either of the training groups, but at post-testing, the UG showed a significant bilateral deficit (-6.5 ± 7.8%) where as the BG showed a significant bilateral facilitation (5.9 ± 9%). The UG was the only group to show a significant increase (39.6%) in muscle electrical activity. This study shows both unilateral and bilateral training can cause specific performance increases.

_Cresswell & Ovedal 2002_

This study examined if the neural control of the knee extensors and flexors is altered during homologous muscle bilateral efforts. Twenty-eight (15-males, 13-females)
subjects (24 ± 3 years) performed maximal unilateral and bilateral isokinetic leg extensions at a velocity of 60° s\(^{-1}\) through a 90° range of motion of the knee joint for 3 trials for each of the 3 conditions (unilateral-right, unilateral-left, bilateral). Surface EMG data was collected from the vastus lateralis and biceps femoris of both limbs. There was a 17% bilateral deficit. The results showed less vastus lateralis EMG activity in both legs (right 13.9 ± 9.1%, left 8.2 ± 7.4%) during the bilateral condition, but no significant difference was seen with in the biceps femoris. The researchers suggested this less than maximal efferent drive to the quadriceps muscles was the cause of the observed bilateral deficit and not the antagonistic muscle activity of the hamstring muscles.

**Hakkinen et al. 1996b**

This study examined the phenomenon of the bilateral deficit by recording electromyographic activity during bilateral and unilateral conditions. A total of 48 subjects (58.1 ± 4.1 years) participated in this study, with 12 males (44-57) in the middle age group (M50), 12 females (43-57) in the middle age group (F50), 12 males in the elderly group (M70), and 12 females in the elderly group (F70). Utilizing a dynamometer, each subject completed 2-4 maximal isometric contractions, during a time period of 2.5-5.0 seconds for both the bilateral and unilateral conditions to determine peak force. EMG activity was recorded from the vastus lateralis, vastus medialis and rectus femoris muscles of both limbs. The results showed no difference in EMG activity for the three muscles of both limbs between the unilateral and bilateral isometric contractions, for all four groups. The authors suggest these results show the central nervous system would be capable of maximal activation of the two bilateral quadiceps
muscle groups simultaneously and/or that probably no decrease in activation was related to peripheral neural control during the bilateral contractions. 

**Hakkinen et al. 1997**

This study investigated the phenomenon of the bilateral deficit by recording electromyographic activity during isometric and dynamic actions of the knee extensors. This study was broken into two experiments with a total of 58 subjects (10 young males 29 ± 3 years [M30], 12 middle-aged males 50 ± 4 years [M50], 12 middle-aged females 48 ± 5 years [W50], 12 elderly males 67 ± 4 years [M70] and 12 elderly females 68 ± 4 years [W70]) participating in the first experiment. Within this experiments, a knee extension 1RM was determined under bilateral and both unilateral conditions. The bilateral condition was tested first, followed by the unilateral conditions with 2 minutes rest between each 1RM attempt. For the second experiment, 10 male (29 ± 5 years) subjects were tested for peak force during a maximal voluntary isometric contraction for the bilateral and both unilateral conditions. Utilizing a dynamometer, each subject completed 2-4 maximal isometric contractions, during a time period of 2.5-5.0 seconds for both the bilateral and unilateral conditions to determine peak force. EMG activity was recorded during the bilateral and both unilateral contractions from the vastus lateralis, vastus medialis and rectus femoris of both limbs. Within both experiments, the results indicated the presences of bilateral facilitation with in the concentric 1RM and isometric measurement for all groups. The EMG data showed the maximal averaged EMG activity for the knee extensor muscles were the same/or slightly greater for the bilateral action than the corresponding unilateral activation of the same muscles. The authors suggest these results show the central nervous system would be capable of maximal activation of
the two bilateral quadiceps muscle groups simultaneously and/or that probably no
decrease in activation was related to peripheral neural control during the bilateral
contractions.

Kuruganti & Seaman 2006

The study examined the presence of bilateral deficit during isokinetic knee
extension and flexion in an adolescent female population compared to previously
collected data from adult (n = 8, 31 ± 7 years) and older (n = 7, 63 ± 6 years) female
populations. Eight adolescent females (15 ± 1 years) completed 2 maximal voluntary
isokinetic contractions at 45°s⁻¹ for the bilateral and both unilateral conditions, with a
two minute rest period between each condition. EMG activity was recorded from the
vastus lateralis and biceps femoris of both the right and left lower limb. The results
showed no significant difference in EMG amplitude between the bilateral and unilateral
conditions, across all three age groups, for any of the contractions. The authors suggest
the bilateral deficit present in this study may not be due to a limitation in neural
mechanisms such as reduced motor unit activation.

Vandervoort et al. 1984

This study examined the neuromuscular differences between unilateral and
bilateral leg extension maximal voluntary contraction. Thirteen subjects (20-24 years)
performed maximal voluntary bilateral and both unilateral contractions on a leg-press
training machine at 0, 15, and 380°s⁻¹. EMG activity was recorded from the vastus
medialis, vastus lateralis and rectus femoris of the right leg. The results show
significantly greater electrical activity was recorded from the sampled quadriceps
muscles of the right leg during the unilateral contractions at all three velocities. The
researchers suggest the reduction in bilateral excitation did not change with velocity and could potentially be due to a reduced activation (lack of recruitment/suboptimal firing frequency) of the fast twitch motor units during a bilateral contraction, along with the central nervous systems inability to fully coordinate a bilateral leg press movement.

Howard & Enoka 1991

The purpose of this study was to determine whether the bilateral deficit is due to neural mechanisms. A total of twenty-two different male subjects (19-39 years) participated in the two experiments within this study (experiment 1; n = 18, experiment 2; n = 12). During experiment one, three groups of subjects (untrained, cyclists, and weight lifters) performed maximal one or two limb isometric task with a two-limb combination of either both legs or the left arm and the right leg. EMG activity was collected from the vastus lateralis and biceps femoris of each leg and from the biceps and trieps brachii of the left arm. The untrained group displayed a force production bilateral deficit, the cyclists group did not, however, the weight lifter group displayed a bilateral facilitation. The EMG data showed a bilateral deficit for the cyclists but not for the untrained group, with the weight lifters having facilitation. The arm-leg task did not result in any significant differences. The second experiments involved a bilateral deficit group (n = 6) and a bilateral facilitation group (n = 6). The subjects performed maximal left leg contractions while the right leg either rested or was electrically stimulated. Within this experiment, all subjects produced an increase in the maximal voluntary left leg force during right leg stimulation, with the bilateral facilitation groups showing the greatest increase. Based on these results, the researchers suggested the bilateral deficit requires the activation of homologous musculature on the opposite sides of the body in order for
the phenomenon to be expressed and are dependent on factors that influence the integration of neural signals from peripheral and central sources.

**Jakobi & Cafarelli 1998**

The purpose of this study was to determine whether there is a bilateral deficit in the knee extensors of untrained young male subjects during isometric contractions and whether this deficit is associated with a decreased activation of the quadriceps, increased activation of the antagonist muscle, or an alteration in motor unit firing rates. Twenty male (27.5 ± 1.8 years) subjects performed bilateral and both unilateral isometric knee extensions (90°) at 25, 50, 75, and 100% maximal voluntary contraction. EMG data were collected from the vasuts lateralis and the biceps femoris of both limbs. Quadriceps activity was also assessed with an interpolated twitch technique. The results showed no bilateral deficit within force production, EMG, motor unit firing rates, coactivation and no difference within the degree of voluntary muscle activation.

**Summary**

Within the bilateral deficit phenomenon, electromyography (EMG) has been used to better understand the neural mechanisms behind this phenomenon. The expression of a bilateral deficit is suggested to require the activation of homologous musculature on the opposite sides of the body (Howard & Enoka 1991). Collected EMG data from the lower limbs has shown the occurrence of a bilateral deficit (Kuruganti et al. 2006, Howard & Enoka 1991), no bilateral deficit (Jakobi & Cafarelli 1998, Howard & Enoka 1991) and bilateral facilitation (Hakkinen et al. 1997, Howard & Enoka 1991). Bilateral contractions have resulted in less EMG activity of both legs (Cresswell & Ovedal 2002), with unilateral contractions showing greater EMG activity (Botton et al. 2015, Vandervoort et
Decreases in EMG activity of the quadriceps muscles during a bilateral contraction has been attributed to less efferent drive, instead of antagonistic activation of the hamstring muscles (Cresswell & Ovedal 2002). Researchers have also shown no differences within EMG activity, leading researchers to suggest the central nervous system is capable of maximal activation of bilateral muscle groups (Hakkinen et al. 1996b).
CHAPTER THREE: METHODS

Research Design

The subjects visited the lab on a total of seven occasions, with at least 24 hours between each visit (Figure 1). Visit one consisted of signing the informed consent document and receiving an overview of the testing procedures. Visit two, the familiarization visit (FAM\textsubscript{VISIT}), was used to record the subject’s EMG and MMG signals in both the right and left vastus lateralis (VL) while performing isometric, seated leg extension bilateral and unilateral maximum isometric voluntary contractions (MVIC), in a randomized order. The subjects then performed the dynamic, seated leg extension bilateral and unilateral 1RM strength (in a randomized order), while also recording the subject’s EMG and MMG signals of the VL for the right and left lower limb. This familiarization visit was used to determine if the subject had a lower limb BLD. Visit three was the pre-test visit, and followed the same testing procedures as the familiarization visit. Visits four through six included the training sessions, with one randomly selected group (n = 12) training bilaterally (BL group) and the other randomly selected group (n = 12) training unilaterally (UL group). Each subject performed 5 sets of 6 repetitions utilizing 65% of their 1RM for resistance, with 60 seconds of rest between each set. Visit seven was the MVIC and 1RM post-test, following the same procedures as the familiarization and pre-test visit. The University of Kentucky’s Institutional Review Board approved all testing procedures for Human Subjects prior to beginning the study.

Subjects
Twenty-four (14 males, 10 females) subjects (mean ± SD age: 22.9 ± 3 yrs; height 173 ± 9.2 cm; body mass 72.3 ± 15.2 kg) participated in this study. The subjects were physically active, but did not participate in a resistance-training program within the previous 3 months. The subjects had no known cardiovascular, pulmonary, metabolic muscular, and/or coronary heart disease. The subjects were asked to continue with the same weekly exercise and physical activity schedule but to abstain from exercising the day prior to each testing session. All of the subjects completed a health history questionnaire and signed a written informed consent document before testing.

**Determination of Subject’s Bilateral and Unilateral MVIC of the Leg Extensors**

The subjects performed 5 submaximal isometric muscle actions of the leg extensors at approximately 50% of their maximal effort, followed by 2-min of rest. After the warm-up, 2, 6-s MVICs were performed bilaterally and unilaterally, at a knee joint angle of 120° (180° = full extension), with a 2-min rest after each MVIC. The order of the bilateral and unilateral trials was randomized. During each trial, EMG and MMG signals were recorded from the vastus lateralis (VL) of each limb.

**Determination of Subject’s Seated Leg Extension Bilateral and Unilateral 1RM**

The bilateral (BL\(_{1RM}\)) and unilateral summed (US\(_{1RM}\)) 1RM as well as unilateral right (UR\(_{1RM}\)) and unilateral left (UL\(_{1RM}\)) 1RM were measured. The subject first performed a warm-up set of 8-10 reps, using only the machine as resistance, followed by a 1-minute rest. The second warm-up set of 8-10 reps was performed at a resistance at an estimated 50% of the subject’s 1RM, and was followed by another 1-minute rest. The
third warm-up set of 3-5 reps, was performed a resistance that was 5-10kg higher than the previous warm-up set and was followed by another 1-minute rest. The next set was the first test set, at an estimated near maximal resistance (90-95% 1RM) for 2-3 reps followed by a 2-minute rest. For the next test set, the resistance was increased by 5-10kg from the first test set, and performed for 1 repetition. At this point, 5-10kg of resistance was added after each successful repetition, with 2-minute rest between each attempt, until failure to successfully perform a repetition. The resistance of the last successful repetition was considered the subject’s 1RM, with the goal of achieving this within 5 sets (Baechle 2008). This procedure was used for both the bilateral and unilateral testing on visit three and four. The order of bilateral and unilateral trials was randomized. During each trial, EMG and MMG signals were recorded from the vastus lateralis of each lower limb.

*Bilateral Deficit and Bilateral Index*

The bilateral deficit was examined using the bilateral index calculation presented by Howard & Enoka (1991):

\[
\text{BI (\%)} = \left( 100 \times \frac{\text{bilateral}}{\text{right unilateral} + \text{left unilateral}} \right) - 100.
\]

*Electromyographic and Mechanomyographic Measurements*

A bipolar (30 mm center-to-center) wired surface EMG electrode (foam circular 38 mm diameter silver/silver chloride, AccuSensor, Lynn Medical, Wixom, MI) arrangement was placed over the vastus lateralis (VL) on both the left and right leg according to SENIAM guidelines (Hermens et al. 1999), with the reference electrodes placed on the anterior superior iliac spine of both the left and right leg. EMG signals were
amplified (gain x1000) using differential amplifiers (EMG 100, Biopac Systems, Inc., Santa Barbara, CA). The MMG accelerometer (Model: EGAS-S704-10_Rev C, Measurement Specialties, France) was placed between the two EMG electrodes. Impedance was reduced with shaving, skin abrasion and cleaning the electrode placement locations with isopropyl alcohol. The EMG and MMG signal were recorded during the bilateral and unilateral MVIC and DCER, concentric leg extension contractions.

**Signal Processing**

The raw EMG and MMG signals were recorded and digitized at 2000Hz with a 12-bit analog-to-digital converter (Model MP150, Biopac Systems, Inc., Santa Barbara, CA) and stored in a personal computer (HP Pavilion) for subsequent analyses. All signal processing was performed using custom programs written with LabVIEW programming software (National Instruments, Austin, TX). The EMG and MMG signals were zero-meaned and digitally bandpass filtered (fourth-order Butterworth) at 10-500 Hz and 5-100 Hz, respectively. The epochs used for analysis of the EMG AMP (µV RMS), EMG MPF (Hz), MMG AMP (rms in m/s²), and MMP MPF (Hz) included only the middle third of the full range of motion for the concentric muscle action. Each signal was normalized to its respective MVIC (bilateral or unilateral).

**Training Sessions**

During each training session, the subjects began by performing a self-selected warm-up routine. Each subject then performed a warm-up set of 10 repetitions using only the machine as resistance. After 60 seconds of rest, the subject performed 5-6
repetitions, utilizing 40-45% of their 1RM for resistance. After another 60 seconds of rest, the subjects then performed 5 sets of 6 repetitions, utilizing 65% of their 1RM for resistance, with 60 seconds of rest between each set. To be considered a successful rep, the subject must have moved the weight through the entire concentric phase of the lift from 90 degrees of flexion to full knee extension (full extension equals 180 degrees) and lowered the weight through the eccentric phase under control.

Statistical Analyses

Four separate 4-way (group [bilateral trained, unilateral trained] x time [pre-test, post-test] x limb [right and left] x mode [bilateral and unilateral testing]) mixed model ANOVAs were used to examine changes in the neuromuscular responses for EMG MPF, EMG AMP, MMG MPF, MMG AMP. A 3-way (time [pre- vs. post-test] X group [bilateral trained vs. unilateral trained] X mode [BL1RM vs. US1RM]) mixed model ANOVA was performed to examine changes in bilateral strength. A 3-way (time [pre- vs. post-test] X group [bilateral trained vs. unilateral trained] X Limb [Right Leg vs. Left Leg]) mixed model ANOVA was used to examine changes in unilateral strength. A 2-way (time [pre-test, post-test] X group [bilateral trained vs. unilateral trained] mixed model ANOVA was performed to examine changes in the bilateral index. Follow up three-, two- or one-way repeated measures and/or mixed model ANOVAs, Bonferroni corrected paired, and independent samples t-tests were performed when appropriate. An alpha level of P ≤ 0.05 was considered statistically significant for all ANOVAs. The reliability of each variable from FAMVISIT to pre-test was examined using intraclass correlation coefficients (ICC) model 2,1 (Weir 2005) and standard error of the
measurement (SEM), which was used to calculate the minimum difference (MD). Weir (2005) defined the MD as “…the difference needed between separate measures on subject for the difference in the measures to be considered real” (p. 238). All statistical analyses were performed with Statistical Package for the Social Sciences software (v.25.0. IBM SPSS Inc., Chicago, Illinois, USA).
Figure 1. Timeline for testing and training.
CHAPTER FOUR: RESULTS

Reliability

The FAMVISIT and Pre-test visits for all 24 subjects were used to determine the test-retest reliability for the strength (BLIRM, ULIRM, URIRM, and USIRM) and neuromuscular (EMG, MMG MPF and AMP) measures. The intraclass correlation coefficients (ICC) for strength outcomes from FAMVISIT to Pre-test (Table 1) indicated each assessment was highly reliable (ICC = 0.97, 0.99, 0.97, 0.98). The ICC values were used to determine the standard error of the measurement (SEM) and minimum difference (MD) values for each of the strength measures (Table 1). For all 24 subjects (Table 1), 2 subjects met or exceeded the MD for BLIRM (9.9 kg), 2 subjects met or exceeded the MD for ULIRM (4.4 kg), 3 subjects met or exceeded the MD for URIRM (5.64 kg), and 1 subject met or exceeded the MD for USIRM (9.13 kg) from FAMVISIT to Pre-test. The intraclass correlation coefficients (ICC) from FAMVISIT to Pre-test visits for the bilateral index (BI) indicated a moderate reliability (0.46), with an SEM value of 3.14kg and a MD of 8.7%. The neuromuscular intraclass correlation coefficients (ICC) from FAMVISIT to Pre-test (Table 3, 4, 5, 6) indicated poor reliability for the EMG MPF (-0.07 to 0.36); moderate reliability for the EMG AMP (0.51 to 0.86); poor reliability for the MMG MPF (0.07 to 0.56); and moderate to excellent reliability for the MMG AMP (0.47 to 0.90). After the FAMVISIT subjects were randomly placed in either the bilateral trained group (n = 12) or the unilateral trained group (n = 12). There were no significant differences between the groups for BLIRM (p = 0.142), ULIRM (p = 0.144), URIRM (p = 0.15), and USIRM (p = 0.144) during the initial Familiarization visit.
**Bilateral Strength**

The 3-way mixed model ANOVA showed no 3-way interaction (time [pre- vs. post-test] X group [BL trained vs. UL trained] X mode [BL<sub>1RM</sub> vs. US<sub>1RM</sub>]; p = 0.079). However, there were 2-way interactions for time X group (p = 0.008, F = 8.483, η<sup>p</sup><sup>2</sup> = 0.278) and for time X mode (p = 0.034, F = 5.122, η<sup>p</sup><sup>2</sup> = 0.189). Thus, the model was decomposed with separate 2-way, time X mode ANOVAs for each group. For the BL trained group, there was a 2-way, time X mode interaction (p = 0.004, F = 13.636, η<sup>p</sup><sup>2</sup> = 0.553). The follow-up pairwise comparisons indicated the US<sub>1RM</sub> was significantly greater than the BL<sub>1RM</sub> at Pre-test (p = 0.001, Figure 2), but there was no difference between BL<sub>1RM</sub> and US<sub>1RM</sub> at post-test (p = 0.905). In addition, there was a significant increase in BL<sub>1RM</sub> (p = 0.006, Table 2, Figure 2), but not the US<sub>1RM</sub> (p = 0.726, Table 2, Figure 2) from pre-test to post-test. For the UL trained group, there was no significant 2-way, time X mode interaction (p = 0.805). There was, however, a main effect for time (p = 0.0001, F = 50.001, η<sup>p</sup><sup>2</sup> = 0.82), but not for mode (p = 0.089). The bilateral strength, collapsed across mode (BL<sub>1RM</sub> and US<sub>1RM</sub>), increased from 76.26 kg to 82.97 kg from Pre-test to Post-test (Table 2, Figure 3).

Overall for the bilateral strength measures from pre-test to post-test 2 subjects (UL trained) met or exceeded the MD (9.9kg) for the BL<sub>1RM</sub> and 5 subjects (1 BL trained, 4 UL trained) met or exceed the MD (9.1kg for the US<sub>1RM</sub>.

**Unilateral Strength**

The 3-way mixed model ANOVA showed no time [pre- vs. post-test] X group [BL trained vs. UL trained] X Limb [Right Leg vs. Left Leg] interaction (p = 0.134).
However, there was a 2-way interaction for time X group (p = 0.002, F = 12.807, $\eta^2 = 0.368$) and a main effect for limb (p = 0.048, F = 4.403, $\eta^2 = 0.167$). From Pre-test to Post-test, the BL trained group (Table 2, Figure 4) showed no significant (p = 0.723) change in unilateral limb strength (collapsed across limb: unilateral left + unilateral right / 2 at pre-test and post-test). The UL trained group, however, showed a significant (p = 0.0001) increase in unilateral limb strength (collapsed across limb: unilateral left + unilateral right / 2 at pre-test and post-test) from Pre-test to Post-test (Table 2, Figure 5). The main effect for limb indicated the $UR_{1RM}$ (36.86 kg) was greater than $UL_{1RM}$ (36.02 kg), collapsed across group and time.

Overall for the unilateral strength measures from pre-test to post-test 8 subjects (2 BL trained, 6 UL trained) met or exceeded the MD (4.4kg) for the $UL_{1RM}$ and 1 subject (BL trained) met or exceeded the MD (5.6kg) for the $UR_{1RM}$.

**Bilateral Index**

The 2-way ANOVA showed a significant (p = 0.035, F = 5.046, $\eta^2 = 0.187$), time X group interaction. From pre-test to post-test, the BI significantly (p = 0.001) increased (indicating a decrease in the bilateral deficit) for the BL trained group (Table 2, Figure 6). However, there was no change (p = 0.653) in the BI for the UL trained group (Table 2, Figure 6).

**Electromyography Amplitude (EMG AMP)**

The 4-way mixed model ANOVA showed no time [pre- vs. post-test] X group [BL trained vs. UL trained] X limb [right vs. left] X mode [unilateral summed vs. bilateral summed] interaction (p = 0.441) for the normalized EMG AMP. There were no
3-way interactions for time X limb X group (p = 0.67), time X mode X group (p = 0.914), limb X mode X group (p = 0.824); and time X limb X mode (p = 0.469). There were no 2-way interactions for time X group (p = 0.192), limb X group (p = 0.747), mode X group (p = 0.176), time X limb (p = 0.559), time X mode (p = 0.367); and limb X mode (p = 0.369). However, there was a main effect for group (p = 0.05, F = 4.313, $\eta^2_p = 0.164$) and mode (p = 0.0001, F = 17.076, $\eta^2_p = 0.437$), but not for time (p = 0.636) or limb (p = 0.437). The main effect for group indicated the normalized EMG AMP for the UL trained group (226%) was greater than the BL trained group (163%), collapsed across time, mode, and limb (Figure 7, Table 7, 8). The main effect for mode indicated the normalized EMG AMP bilateral movement (210%) was greater than unilateral movement (180%), collapsed across time, group and limb (Figure 8).

**Electromyography Mean Power Frequency (EMG MPF)**

The 4-way mixed model ANOVA showed no time [pre- vs. post-test] X group [BL trained vs. UL trained] X limb [right vs. left] X mode [unilateral summed vs. bilateral summed] interaction (p = 0.215) for the normalized EMG MPF. There were no 3-way interactions for time X limb X group (p = 0.457), time X mode X group (p = 0.262), limb X mode X group (p = 0.615); or time X limb X mode (p = 0.916). There were no 2-way interactions for limb X group (p = 0.365), mode X group (p = 0.451), time X limb (p = 0.322); or time X mode (p = 0.632). However, there were 2-way interactions for time X group (p = 0.028, F = 5.526, $\eta^2_p = 0.201$) and for limb X mode (p = 0.033, F = 5.202, $\eta^2_p = 0.191$). Thus, the model was decomposed with separate 3-way, time X mode X limb ANOVAs for each group. Both the BL trained (p = 0.373) and UL trained (p =
0.392) groups showed no 3-way interactions. However, the BL trained group did show a significant main effect for time (p = 0.029, F = 6.277, \( \eta^2 = 0.363 \)), resulting in a significant decrease in EMG MPF (collapsed across limb and mode) from Pre-test (112%) to Post-test (105%) (Table 8). The UL trained group, however, showed no significant (p = 0.368) change in EMG MPF (collapsed across limb and mode) from Pre-test (108%) to Post-test (111%) (Figure 9, Table 7).

**Mechanomyography Amplitude (MMG AMP)**

The 4-way mixed model ANOVA showed no time [pre- vs. post-test] X group [BL trained vs. UL trained] X limb [right vs. left] X mode [unilateral summed vs. bilateral summed] interaction (p = 0.592) for the normalized MMG AMP (Table 7, 8). There were no significant 3-way interactions for time X limb X group (p = 0.775), time X mode X group (p = 0.514), limb X mode X group (p = 0.738); and time X limb X mode (p = 0.644). There were no significant 2-way interactions for time X group (p = 0.712), limb X group (p = 0.778), mode X group (p = 0.368), time X limb (p = 0.713), time X mode (p = 0.137); and limb X mode (p = 0.722). There were also no significant main effects for time (p = 0.906), limb (p = 0.931), mode (p = 0.197) or group (p = 0.249).

**Mechanomyography Mean Power Frequency (MMG MPF)**

The 4-way mixed model ANOVA showed no time [pre- vs. post-test] X group [BL trained vs. UL trained] X limb [right vs. left] X mode [unilateral summed vs. bilateral summed] interaction (p = 0.772) for the normalized MMG MPF. There were no 3-way interactions for time X limb X group (p = 0.653), time X mode X group (p =
0.584), limb X mode X group (p = 0.756); or time X limb X mode (p = 0.081). There were no 2-way interactions for time X group (p = 0.102), limb X group (p = 0.135), mode X group (p = 0.957), time X limb (p = 0.835), or limb X mode (p = 0.362). However, there was a 2-way interaction for time X mode (p = 0.007, F = 8.688, η² = 0.283). From Pre-test (111%) to Post-test (97%), the UL movement (Figure 10, Table 7, 8) showed a significant (p = 0.022) decrease in MMG MPF (collapsed across group and limb). The BL movement (Figure 10, Table 7, 8), however, showed no significant (p = 0.974) change in EMG MPF (collapsed across group and limb) from Pre-test (104%) to Post-test (104%). There were no main effects for time (p = 0.156), limb (p = 0.551), mode (p = 0.705) or group (p = 0.57).

Overall, for the bilateral neuromuscular measures from pre-test to post-test, 1 subject (BL trained) met or exceeded the MD (42%) for the left limb EMG MPF, 3 subjects (UL trained) met or exceeded the MD (144%) for the left limb EMG AMP, 3 subjects (1 BL trained, 2 UL trained) met or exceeded the MD (194%) for the right limb MMG AMP, 2 subjects (1 BL trained, 1 UL trained) met or exceeded the MD (274%) for the left limb MMG AMP, and no subjects met or exceeded the MD for the right limb EMG MPF (39%), EMG AMP (158%), MMG MPF (89%), or the left limb MMF MPF (89%). For the unilateral neuromuscular measures of the right limb, 7 subjects (3 BL trained, 4 UL trained) met or exceeded the MD (22%) for EMG MPF, 1 subject (UL trained) met or exceeded the MD (158%) for EMG AMP, 2 subjects (1 BL trained, 1 UL trained) met or exceeded the MD (92%) for MMG MPF, and 4 subjects (2 BL trained, 2 UL trained) met or exceeded the MD (108%) for MMG AMP. For the unilateral neuromuscular measures of the left limb, 4 subjects (2 BL trained, 2 UL trained) met or
exceeded the MD (31%) for EMG MPF, 2 subjects (UL trained) met or exceeded the MD (75%) for EMG AMP, 4 subjects (1 BL trained, 3 UL trained) met/exceeded the MD (83%) for MMG MPF, and 1 subject (BL trained) met or exceeded the MD (208%) for MMG AMP.
Table 1. Individual Bilateral (BL\_IRM), Unilateral Left (UL\_IRM), Unilateral Right (UR\_IRM) and Unilateral Summed (US\_IRM) 1 repetition maximum (1RM) values (kg) during the dynamic, seated leg extension 1RM measurements for the Familiarization (FAM\_VISIT) and Pre-test visits (N = 24).

<table>
<thead>
<tr>
<th>Subject</th>
<th>BL_IRM (kg)</th>
<th>UL_IRM (kg)</th>
<th>UR_IRM (kg)</th>
<th>US_IRM (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FAM_VISIT Pre-test</td>
<td>FAM_VISIT Pre-test</td>
<td>FAM_VISIT Pre-test</td>
<td>FAM_VISIT Pre-test</td>
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<tr>
<td>1</td>
<td>92.99</td>
<td>92.99</td>
<td>52.16</td>
<td>49.90</td>
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<tr>
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Mean ± SD, Intra-class correlation coefficient (ICC), standard error of the measurement (SEM) and minimum difference (MD) values for Familiarization and Pre-test.

*Indicates ≥ MD value between Familiarization and Pre-test.
Table 2. Mean ± SD values (kg) of the Bilateral and Unilateral trained groups for the bilateral (BL), unilateral left (UL), unilateral right (UR), unilateral summed (US) and the absolute bilateral deficit (BD_{ABS}) during the dynamic, seated leg extension 1RM measurements for Pre-test and Post-test.

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Bilateral index (BI\%) = \left(100 \times \frac{\text{bilateral}}{\text{right unilateral} + \text{left unilateral}}\right) - 100

See Results section and Figures for indications of significant findings.
Table 3. Individual, normalized (%MVIC) electromyographic (EMG) mean power frequency (MPF) and EMG amplitude (AMP) of the right and left limb during the bilateral (BL) 1 repetition maximum (1RM) dynamic, seated leg extension measurements for the Familiarization (FAMVISIT) and Pre-test visits (N = 24).

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| Mean ± SD | 1.13 ± 0.13 | 1.12 ± 0.12 | 2.03 ± 0.19 | 2.17 ± 0.19 | 1.10 ± 0.13 | 1.08 ± 0.15 | 2.09 ± 0.97 | 2.07 ± 0.81 |
| ICC       | -0.16      | 0.76       | -0.07       | -0.07       | 0.13       | 0.15       | 0.97       | 0.68       |
| SEM       | 0.14       | 0.57       | 0.15       | 0.15       | 0.52       | 0.52       | 0.52       | 0.52       |
| MD        | 0.39       | 1.58       | 0.42       | 1.44       | 0.42       | 1.44       | 0.42       | 1.44       |

Mean ± SD, Intra-class correlation coefficient (ICC), standard error of the measurement (SEM) and minimum difference (MD) values for Familiarization and Pre-test. Each signal was normalized to its respective value at MVIC.

*Indicates ≥ MD value between Familiarization and Pre-test.
Table 4. Individual, normalized (%MVIC) electromyographic (EMG) mean power frequency (MPF) and EMG amplitude (AMP) of the right and left limb during the unilateral (UL\textsubscript{1RM} & UR\textsubscript{1RM}) dynamic, seated leg extension 1 repetition maximum (1RM) measurements for the Familiarization (FAM\textsubscript{VISIT}) and Pre-test visits (N = 24).

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Mean ± SD, Intra-class correlation coefficient (ICC), standard error of the measurement (SEM) and minimum difference (MD) values for Familiarization and Pre-test. Each signal was normalized to its respective value at MVIC.

*Indicates ≥MD value between Familiarization and Pre-test.
Table 5. Individual, normalized (%MVIC) mechanomyographic (MMG) mean power frequency (MPF) and MMG amplitude (AMP) of the right and left limb during the bilateral (BL\textsubscript{1RM}) dynamic, seated leg extension 1 repetition maximum (1RM) measurements for the Familiarization (FAM\textsubscript{VISIT}) and Pre-test visits (N = 24).

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Mean ± SD, Intra-class correlation coefficient (ICC), standard error of the measurement (SEM) and minimum difference (MD) values for Familiarization and Pre-test. Each signal was normalized to its respective value at MVIC.

*Indicates ≥MD value between Familiarization and Pre-test.
Table 6. Individual, normalized (%MVIC) mechanomyographic (MMG) mean power frequency (MPF) and MMG amplitude (AMP) of the right and left limb during the unilateral (UL\textsubscript{IRM} and UR\textsubscript{IRM}) dynamic, seated leg extension 1 repetition maximum (1RM) measurements for the Familiarization (FAM\textsubscript{VISIT}) and Pre-test visits (N = 24).

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| Mean ± SD | 0.94 ± 0.30 | 1.17 ± 0.53 | 1.24 ± 1.29 | 1.18 ± 1.10 | 0.94 ± 0.42 | 1.17 ± 0.55 | 1.31 ± 0.75 |
| ICC      | 0.38        | 0.33        | 0.90        | 0.56        | 1.08        | 0.47        |
| SEM      | 0.33        | 0.39        | 0.39        | 0.56        | 0.30        | 0.75        |
| MD       | 0.92        | 0.83        | 0.90        | 0.77        | 2.08        |

Mean ± SD, Intra-class correlation coefficient (ICC), standard error of the measurement (SEM) and minimum difference (MD) values for Familiarization and Pre-test. Each signal was normalized to its respective value at MVIC.

*Indicates ≥MD value between Familiarization and Pre-test.
Table 7. Mean ± SD normalized (%MVIC) electromyographic (EMG) and mechanomyographic (MMG) amplitude (AMP) and mean power frequency (MPF) values of the unilateral trained (UL) group during the bilateral (BL<sub>1RM</sub>) and unilateral (UR<sub>1RM</sub> and UL<sub>1RM</sub>) dynamic, seated leg extension 1 repetition maximum (1RM) measurements for Pre-test and Post-test.

<table>
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<td>EMG MPF</td>
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<td>MMG AMP</td>
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<td>1.49 ± 1.02</td>
<td>1.46 ± 1.34</td>
<td>1.29 ± 0.77</td>
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</table>

Each signal was normalized to its respective value at MVIC.
Table 8. Mean ± SD normalized (%MVIC) electromyographic (EMG) and mechanomyographic (MMG) amplitude (AMP) and mean power frequency (MPF) values of the bilateral trained (BL) group during the bilateral (BL_{1RM}) and unilateral (UR_{1RM} and UL_{1RM}) dynamic, seated leg extension 1RM measurements for Pre-test and Post-test.

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<td>Pre-test</td>
<td>Post-test</td>
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<tr>
<td>EMG MPF</td>
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<td>1.09 ± 0.09</td>
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<tr>
<td>EMG AMP</td>
<td>1.68 ± 0.63</td>
<td>1.83 ± 0.42</td>
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<tr>
<td>MMG MPF</td>
<td>1.00 ± 0.38</td>
<td>1.08 ± 0.24</td>
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<tr>
<td>MMG AMP</td>
<td>1.44 ± 1.60</td>
<td>1.42 ± 0.75</td>
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Each signal was normalized to its respective value at MVIC.
Figure 2. Mean ± SD of the bilateral (BL) and unilateral summed (US) 1RM values for the bilateral trained group during the dynamic, seated leg extension 1RM

*Significantly (p ≤ 0.05) greater than BL 1RM at Pre-test.
Figure 3. Marginal mean (collapsed across mode) bilateral strength values for the unilateral trained group during the dynamic, seated leg extension 1RM
*Significant (p ≤ 0.05) main effect for time, Post-test greater than Pre-test.
Figure 4. Mean ± SD of the marginal means (collapsed across limb = UL\textsubscript{1RM} and UR\textsubscript{1RM} combined/2) unilateral 1RM values for the bilateral trained group during the dynamic, seated leg extension 1RM.
Figure 5. Mean ± SD of the marginal means (collapsed across limb = UL_{1RM} and UR_{1RM} combined/2) unilateral 1RM values for the unilateral trained group during the dynamic, seated leg extension 1RM.

*Significantly (p ≤ 0.05) greater than Pre-test.
Figure 6. One-repetition maximum (1RM) bilateral index values from pre-test to post-test for the bilateral and unilateral trained groups.

Bilateral index (BI%) = \( \left( 100 \times \frac{\text{bilateral}}{\text{right unilateral} + \text{left unilateral}} \right) - 100 \)

*Significantly (p ≤ 0.05) greater than Pre-test for the BL trained group.
Figure 7. Mean ± SD of the normalized EMG AMP fractional values for the bilateral (BL) trained and unilateral (UL) trained groups collapsed across time, mode and limb, during the dynamic, seated leg extension 1RM.

*Significantly (p ≤ 0.05) greater than the BL trained group.
Figure 8. Mean ± SD of the bilateral (BL) and unilateral (UL) movement for the normalized EMG AMP fractional values, collapsed across time, group and limb, during the dynamic, seated leg extension 1RM.

*Significantly (p ≤ 0.05) greater than unilateral.
Figure 9. Mean ± SD of the normalized EMG MPF fractional values for the bilateral (BL) trained and unilateral (UL) trained groups collapsed across mode and limb, during the dynamic, seated leg extension 1RM.

*Significantly (p ≤ 0.05) less than Pre-test.
Figure 10. Mean ± SD of the normalized MMG MPF fractional values for the bilateral (BL) and unilateral (UL) movement collapsed across group and limb, during the dynamic, seated leg extension 1RM.

*Significantly (p ≤ 0.05) less than Pre-test.
CHAPTER FIVE: DISCUSSION

In the present study, 24 subjects performed dynamic, seated leg extensions to determine bilateral 1RM (BL\textsubscript{1RM}), unilateral left leg 1RM (UL\textsubscript{1RM}) and unilateral right leg 1RM (UR\textsubscript{1RM}) during a Familiarization and Pre-test visit on two separate occasions. The ICC values for the 1RM tests for dynamic, seated leg extension during the BL\textsubscript{1RM} (0.97), UL\textsubscript{1RM} (0.99), UR\textsubscript{1RM} (0.97), unilateral left and right summed (US\textsubscript{1RM}, 0.98) were considered “excellent” for each assessment (Koo & Li 2016). Previous VST studies have reported ICC values from 0.85 to 0.99 for isokinetic forearm flexion and leg extension exercises (Beck et al. 2007, Traylor et al. 2014, Brown et al. 2003). In addition, ICC values of 0.99 have been reported for DCER 1RM testing (Byrd et al. 2018). Although the ICC values were consistent with previous strength assessments, there was systematic error (FAM\textsubscript{VISIT} to Pre-test; BL\textsubscript{1RM} p=0.0001, UL\textsubscript{1RM} p=0.611, UR\textsubscript{1RM} p=0.002, US\textsubscript{1RM} p=0.026) in 1RM test-retest measures in the present study. These findings indicated the need for at least one familiarization session for untrained subjects when utilizing lower body DCER exercise, and were consistent with the recommendations of Levinger et al. (2007). The SEM and MD for the BL\textsubscript{1RM}, UL\textsubscript{1RM}, UR\textsubscript{1RM}, and US\textsubscript{1RM} SEM (3.57kg; 5.4%, 1.59kg; 4.5%, 2.03kg; 5.8%, and 3.29kg; 4.7%) and MD (9.9kg; 15.1%, 4.4kg; 12.6%, 5.6%; 16.1% and 9.1kg; 13%) fell within the ranges (SEM 2.4 – 14.4%; MD: 6.6 – 36.3kg) previously reported for dynamic strength assessments (Byrd et al. 2018, Sofi et al 2007). Furthermore, 2 subjects met or exceeded the MD for BL\textsubscript{1RM} (9.9 kg), 2 subjects met or exceeded the MD for UL\textsubscript{1RM} (4.4 kg), 3 subjects met or exceeded the MD for UR\textsubscript{1RM} (5.6 kg), and 1 subject met or exceeded the MD for US\textsubscript{1RM} (9.1 kg) from Familiarization to Pre-test. Weir (2005) defined the MD as “…the difference needed
between separate measures on subject for the difference in the measures to be considered real” (p. 238). Thus, 4 to 12% of the subjects in the present study demonstrated strength values from the Familiarization to Pre-test that were greater than the value considered to be a real difference. Considered together, the ICC, SEM, and MD values were consistent with those previously reported for 1RM DCER testing, but the systematic error identified the need for at least one familiarization session for testing untrained subjects.

**Bilateral Strength**

The findings from this study indicated there were increases for BL\(_{1RM}\) and US\(_{1RM}\) in untrained subjects as a result of VST lower body DCER exercise that were dependent on the training group (BL vs. UL). Specifically, the BL group demonstrated a significant increase (6.8%) in BL\(_{1RM}\), but no significant increase in US\(_{1RM}\) (0.7%). In contrast, the UL group demonstrated an 8.7% increase in bilateral strength collapsed across testing mode (BL\(_{1RM}\) and US\(_{1RM}\)) (Figure 3). Overall, 8% (2 subjects- UL trained) of the subjects met or exceeded the MD for the BL\(_{1RM}\) (9.9kg) and 21% (5 subjects-1 BL trained, 4 UL trained) of the subjects met or exceeded the MD for the US\(_{1RM}\) (9.1kg) pre- to post-test.

Previous research has shown peak torque increases of 2.4% and 4.5% in the forearm flexors of women and men after 3 isokinetic training sessions (Traylor et al. 2012), with upper body DCER VST resulting in 1RM strength increases of 3.5% (Byrd et al. 2018). In addition, VST studies examining lower body bilateral leg extensors performance have observed 1.3% to 2.8% (Brown & Whitehurst 2003), 6% (Cramer et al. 2007), 22.1% (Prevost et al. 1999), and 40.2% (Coburn et al. 2006) increases in peak torque production at various training velocities after only 2 to 3 training sessions. Thus, the 6.8% and 8.7%
mean increases in 1RM strength ($US_{1RM}$ & $BL_{1RM}$) in the present study were consistent
with the strength increases (1.3% to 40.2%) previously reported for 2 to 3 isokinetic or
DCER training sessions (Brown & Whitehurst 2003, Traylor et al. 2012, Cramer et al.
2007, Byrd et al. 2018, Prevost et al. 1999, Coburn et al. 2006). Furthermore, the current
findings indicated training group dependent responses in bilateral strength adaptations.
That is, the BL training was effective to increase $BL_{1RM}$, but not $US_{1RM}$, whereas $BL_{1RM}$
and $US_{1RM}$ increased at equal rates as a result of UL training.

**Unilateral Strength**

The present study indicated there were increases in unilateral strength ($UL_{1RM}$ and
$UR_{1RM}$) in the untrained subjects as a result of VST lower body DCER exercise that were
dependent on training group (BL vs. UL). Specifically, the UL group demonstrated an
8% (Figure 5) increase in unilateral strength collapsed across limb ($UL_{1RM}$ and $UR_{1RM}$),
but no significant increase was observed for the BL group (0.7%) from pre-test to post-
test (Figure 4). Overall, 33% (2 BL trained, 6 UL trained) of the subjects met or exceeded
the MD for the $UL_{1RM}$ (4.4kg) and 4% (1 subject- BL trained) of the subjects met or
exceeded the MD for the $UR_{1RM}$ (5.6kg). In addition, the current study showed the right
limb ($UR_{1RM}$) to be 2.3% stronger than the left limb ($UL_{1RM}$) collapsed across group and
time, with 93% of the subjects reporting the right limb as the dominant limb. These
findings were consistent with those of Costa et al. (2016) that also showed the dominant
limb to be 2.6% stronger than the non-dominant limb. The increases in $UL_{1RM}$ as a result
of UL training in the present study were consistent with the findings of Costa et al.
(2016) who examined the effects of lower body DCER VST on unilateral leg extensors
performance, and reported increases in 1RM strength of 22.3% within the trained limb (dominant limb). In addition, previous investigators (Coburn et al. 2006) have shown that non-dominant limb strength increased from 11.5% to 40.2% as a result of unilateral non-dominant VST. However, no previous studies have compared changes in UL\textsubscript{1RM} between UL and BL training or UL training of both limbs. Thus, the current findings supported those of others (Costa et al. 2016) and indicated the dominant limb to be stronger than the non-dominant limb. Furthermore, the current findings indicated a training group dependent response in unilateral strength adaptations, where the UL training, was effective in increasing unilateral strength (collapsed across UL\textsubscript{1RM} and UR\textsubscript{1RM}), but BL training was not.

Inter-limb strength discrepancies have been suggested to provide information that can affect how clinicians provide treatment (Pietrosimone et al. 2012), as impairments in quadriceps muscle strength have been determined as possible predictors of physical function within individuals with knee injury (Fitzgerald et al. 2004). Such dysfunction could possibly affect the ability of the lower limbs to diminish energy during performance task such as landing from a jump (Palmieri-Smith et al. 2007). Thus, it may be important to consider unilateral strength discrepancies related to limb dominance when assessing strength and designing training programs for improved strength and performance. In addition, Costa et al. (2016) showed a 16.7% strength increase in the non-dominant contralateral limb (untrained limb) after dominant limb VST DCER training, a phenomenon known as “cross-education” (Munn et al. 2004, Scripture et al. 1894). However, the inter-limb strength discrepancy increased from 2.6% to 7.6% (Costa et al. 2016). In contrast, Weir et al. (1997) showed that after 8 weeks of unilateral, non-
dominant limb training resulted in the reversal of the dominant and non-dominant limb strength. These previous findings (Weir et al. 1997) suggested unilateral strength training could reverse inter-limb strength discrepancies when training only the weaker limb. However, the volume of unilateral, non-dominant limb training should be carefully considered as VST was effective at increasing strength in the non-dominant limb (Coburn et al. 2006), but 8 weeks of training reversed the inter-limb strength discrepancy (Weir et al. 1997). Future studies should examine the number of training sessions necessary to increase non-dominant limb strength to the same level of the dominant limb. Furthermore, studies should examine the type (unilateral versus bilateral) of training necessary to maintain strength at equal values between limbs after strength discrepancies have been addressed.

Bilateral Index

In this study, a BLD was defined as a BI value less than zero and a bilateral facilitation was defined as a BI value greater than zero. At pre-test, the BL and UL training groups had BI of -5.15% and -3.17%, respectively. Previous researchers have reported the bilateral deficits to between -3 to -25% (Archontides & Fazey 1993, Botton et al. 2013, Brown et al. 1994, Costa et al. 2015, Cresswell & Ovedal 2002, Dickin & Too 2006, Kuruganti & Seaman 2006, Owings & Grabiner 1998, Howard & Enoka 1991). In the present study, BL training resulted in a 5.5% increase in the BI, which corresponded to a decrease of the BLD, whereas UL training resulted in a non-significant 0.4% increase in the BI (Figure 6). This is consistent with previous studies which have suggested bilateral training to have the greatest affect on reducing the lower limb bilateral
deficit (Kuruganti et al. 2005, Jazen et al. 2006, Beursken et al. 2015). A large BLD has been shown to be associated with lower performance in the sprint start (total impulse force on sprint blocks and lower block velocity), which is related to the overall sprint (60m and 100m) performance (Bracic et al. 2010). Thus, the results of the present study suggested that bilateral, but not unilateral, VST may improve muscle function associated with a BLD (decrease the BLD) within a limited time frame.

**Neuromuscular (EMG and MMG) Responses**

Strength increases for the leg extensors after VST have been accompanied by changes in the electromyography (EMG) and mechanomyography (MMG) signals (Traylor et al. 2012, Traylor et al. 2014, Coburn et al. 2006, Cramer et al. 2007). Electromyography and MMG provide information that reflects changes in neuromuscular responses and early phase resistance training adaptations. Specifically, the amplitude (AMP) of the EMG signal reflects global motor unit activation and the mean power frequency (MPF) reflects the conduction velocity of the action potential along the sarcolemma (Basmanjian 1985, DeLuca 1997, Traylor et al. 2014). The use of MMG provides the mechanical counterpart to the motor unit electrical activity measured by EMG (Beck et al. 2005, Traylor et al. 2014). The MMG AMP reflects motor unit recruitment and the MMG frequency domain provides qualitative information regarding the global firing rate of the unfused activate motor units (Orizio 1993, Beck et al. 2005, Beck et al. 2007).

In the present study, the BL group showed an increase in BL_{1RM}, with no change in unilateral strength (UR_{1RM} & UL_{1RM}), which reflected an increase in the BI (i.e., the BI
became less negative or positive and equals a decrease in the BD) as a result of bilateral VST DCER training. The neuromuscular results of this study indicated no significant changes in the EMG AMP, MMG AMP or MMG MPF for the BL group; however, there was a significant decrease in EMG MPF (6.3%) from pre-test to post-test (Figure 8). It is likely, however, this change did not reflect a neuromuscular adaptation that would explain the changes in strength in the BL group. Specifically, a decrease in EMG MPF is associated with a decrease in the conduction velocity of the action potential along the sarcolemma (Basmanjian 1985, DeLuca 1997, Traylor et al. 2014). The conduction velocity of the action potential can be affected by internal pH and ion gradients within the active muscle (Juel 1988). Specifically, studies examining isolated muscles from mice have shown the propagation velocity of the action potential to be dependent on the potassium ($K^+$) ion gradient and internal pH of the active muscle (Juel 1988). However, previously, increases in EMG MPF were demonstrated with increased strength as a result of isokinetic VST of the leg extensor muscles. (Coburn et al. 2006, Cramer et al. 2007). Thus, the reported decrease in this study for EMG MPF was more likely a reflection of the poor test-retest reliability and large inter-individual variability demonstrated in the frequency domain of the EMG signal, than an adaptation as a result of the BL VST.

The UL group in this study showed increases in both bilateral (BL$_{1RM}$ and US$_{1RM}$) and unilateral (UR$_{1RM}$ & UL$_{1RM}$) strength measures, but no change in the BI as a result of unilateral VST DCER training. The neuromuscular results of this study indicated no significant changes in the EMG or MMG AMP and MPF domains. Previous investigators (Beck et al. 2007) using the VST model to examine adaptations in the forearm flexors and extensors have also reported no significant changes in EMG activity, but these
responses were noted in conjunction with no increases in strength after VST. Thus, the EMG and MMG signals may not be sensitive to detect potential neuromuscular adaptations associated with the strength increases observed within the UL group after unilateral VST DCER training.

Another point of interest presented in this study was that the bilateral movement resulted in a 16.7% larger normalized EMG AMP than the unilateral movement (Figure 8), which suggested greater overall motor unit activation during the bilateral movement. However, previous studies have shown bilateral contractions to result in less EMG activity than unilateral contractions, leading researchers to attribute the difference to the presence of less efferent drive during bilateral contractions (Botton et al. 2015, Vandervoort et al. 1984). One possible reason the findings of the current study were not consistent with those previously reported may be related to the subject population in this study having a known lower limb bilateral deficit, whereas this was not examined within previous VST studies (Coburn et al. 2006, Cramer et al. 2007). Another unique difference for the unilateral movements (UR1RM & UL1RM collapsed across group and limb) in this study was an observed decrease in MMG MPF from pre-test to post-test DCER VST. In contrast, previous VST studies have shown increases within the MMG MPF signal within both upper and lower body measures (Cramer et al. 2007, Traylor et al. 2014). The observed decreases in the frequency domains (MPF) of both EMG and MMG signals in this study, despite increased strength, may indicate that the signals were not sensitive to detect small changes in motor unit activation strategies. It is also possible that the strength increases realized as a result of 3 DCER training sessions may be due to factors other than changes in motor unit activation strategies of the leg extensors. The
discrepancy between the current findings and those previously reported also indicated the potential for the different neuromuscular responses (i.e., motor unit activation strategies) that are specific to the type of muscle contractions (DCER vs. isokinetic). Specifically, the DCER VST training in this study resulted in responses that differed (i.e., no change in EMG or MMG AMP and decreases to the frequency domains of both signals) from those reported for isokinetic VST training (Cramer et al. 2007, Traylor et al. 2014). These muscle contraction specific motor unit activation strategies may elude to the “neural adaptations” attributed to significant strength increases observed within the first few weeks of training (Aagaard et al. 2002, Staron et al. 1994, Moritani & Devries 1979), and may potentially be further defined as the optimization of motor unit activation strategies that provides the greatest motor unit synchronization for the specific movement before muscle hypertrophy is needed to meet the demand of the external stress/resistance being placed upon the contracting muscle.

In the current study, 0% to 29% of the subjects met or exceeded the MD of the neuromuscular parameters and only 21% of the subjects met or exceeded the MD of at least one of the strength and one of the neuromuscular mean power frequency (MPF) parameters. This suggested that, although there was a significant change in the frequency domains (MPF) of both EMG and MMG within this study, these variations did not reflect meaningful adaptations in the motor unit activation strategies to explain the changes in strength after 3 bilateral or unilateral DCER VST training sessions within subjects with a lower limb BLD.

The BLD is currently described as a strength deficit. In this study, however, there was a reversal of a lower limb BLD after 3 DCER training sessions. Thus, it would
appear the BLD is actually a neuromuscular issue that presents itself as an external strength deficit, as hypertrophy within the active muscle is suggested to not be the dominant factor for observed strength increases until after 8-12 weeks (Jones & Rutherford 1987, Moritani & Devires 1979). Future studies should examine the effects of different loads used during DCER training within the VST model as previous studies have shown the use of a single bout of resistance training using a light (20% 1RM) vs. heavy (80% 1RM) load to have different corticospinal responses (Mason et al. 2019). This indicates a more meaningful neuromuscular response may be observed with the use of a greater %1RM load instead of the 65% used in this study, which was sufficient enough to cause strength changes but was insufficient to elicit meaningful neuromuscular changes.
Limitations

• In this study, all of neuromuscular measures were taken from the VL and the responses observed after VST may not be generalized to the other quadriceps muscles.

• The leg extension machine used within this study was not fully adjustable for the varying height of the subjects, and therefore the optimal set-up for each subject may not have been achieved.

• In this study, subjects were randomly placed in either the BL or UL group, leading to groups to not have equal number of sexes within the groups.

• In this study, the sensitivity to the observed strength increases where limited to 1kg, there by any strength increase less than 1kg was not detectable.
Summary

The primary finding from the current study was that bilateral and unilateral DCER training increased strength after 3 training sessions. The bilateral DCER training resulted in a bilateral, but not unilateral strength increase and unilateral DCER training resulted in both bilateral and unilateral strength increases. However, bilateral training was the only mode of training that significantly decreased the bilateral deficit, as previously hypothesized, but unilateral training did not cause an increase in the bilateral deficit as hypothesized. There were also observed decreases within the frequency domains of both the EMG and MMG signals, which are typically associated with decreases in the action potential conduction velocity and motor unit firing rate, respectively. These responses were not consistent with our hypotheses regarding the typical changes in neuromuscular responses associated with a neural adaptation (i.e., increases in EMG and MMG AMP and/or MPF). Nevertheless, these MPF decreases do not appear to be the mechanism behind the observed strength increases as only a small (4% to 17%) percentage of the subjects showed these changes.
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EDUCATION

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PUBLICATIONS


