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The Cross Education of Neuromuscular Economy

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THE CROSS EDUCATION OF NEUROMUSCULAR ECONOMY

by

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ABSTRACT

Cross education is the phenomenon by which the untrained limb will experience a gain in strength following a unilateral resistance training program. However, little is known as to the underlying adaptation occurring in the untrained limb. **Purpose:** To examine the effect of dynamic unilateral resistance training on the strength and neuromuscular adaptations of both the trained and untrained legs. **Methods:** Eight previously untrained males (22.38±2.92 y, 1.73±0.08 m, 75.26±14.53 kg) completed a four-week unilateral resistance training program, while another eight untrained males (24.00±4.57 y, 1.84±0.05 m, 94.21±16.14 kg) served as controls. Isometric leg extension strength, leg press 1 repetition maximum (1RM), leg extension 1RM, root mean square of the maximal electromyographic amplitude (EMG), submaximal EMG, dynamic neuromuscular economy (NME) and the slope of NME-power output relationship were determined before and after training to assess the changes in strength and neuromuscular adaptations of the vastus lateralis (VL) and rectus femoris (RF) in both the trained and untrained legs. The unilateral resistance training program was conducted on the dominant leg (DOM) in the unilateral resistance training group (URT) and was compared to the dominant leg of the control group (CON). Cross education was measured in the nondominant leg (NON) for both groups. The unilateral resistance training program was completed three days per week for a total of twelve training sessions. Exercises included in the training program were unilateral leg press, unilateral leg extension, bilateral chest press and bilateral low row. All data was analyzed using one-way analysis of covariance of the post-testing values using the pre-testing values as the covariate. Further analysis of the EMG and NME data was performed using magnitude-based inferences. **Results:** The URT group improved their isometric (DOM:11.03%, NON:4.98%), leg press (DOM:77.63%, NON:64.88%) and leg extension (DOM:46.76%, NON:16.43%) strength after the four weeks of resistance training. There was no difference between the groups in isometric strength in the dominant (*p*=0.188) or nondominant (*p*=0.948) leg. For leg extension 1RM, there was a significant difference between groups in the dominant leg (*p*=0.018), but not the nondominant leg (*p*=0.482). However, there were significant group differences in both the dominant (*p*=0.003) and nondominant (*p*=0.034) leg for leg press 1RM. In terms of maximal EMG, the training groups improved in the vastus lateralis (DOM:29.81%, NON:31.44%) and rectus femoris (DOM:20.71%, NON:6.26%) individually, as well as in total EMG (DOM:24.78%, NON:17.57%). There was a *Likely Positive* or *Very Likely Positive* effect of unilateral resistance training on the changes in maximal EMG of the vastus lateralis and rectus femoris in both the dominant and nondominant legs. There was a *Likely Positive* effect of unilateral resistance training on the submaximal EMG of the dominant vastus lateralis at 75 and 125 watts. Conversely, in the rectus femoris, there was *Unclear* effects of unilateral resistance training on the submaximal EMG of the dominant leg. There was no consistent effect of unilateral resistance training on submaximal EMG values of the vastus lateralis in the nondominant leg. However, the rectus femoris in the nondominant leg experienced a *Likely Positive* effect of unilateral resistance training on submaximal EMG. NME improved in the URT group in the VL at 75 (DOM:9.73%, NON:13.42%), 100 (DOM:8.76%, NON:8.21%), and 125(DOM:24.26%, NON:12.8%) watts and in the RF at 75 (DOM:22.25%, NON:15.73%), 100(DOM:24.85%, NON:17.05%) and 125 (DOM:30.99%) watts. In terms of neuromuscular economy, there was a *Likely Positive* or *Very Likely Positive* effect of unilateral resistance training on most measures of NME on both the vastus lateralis and rectus femoris in both the dominant and nondominant legs. In terms of NME slope, there was only a *Likely Positive* effect of unilateral resistance training on the dominant vastus lateralis. **Conclusion:** Based on these results, it appears that the cross education of strength from unilateral resistance training is modality-specific. Furthermore, the NME of both the vastus lateralis and rectus femoris in both legs appear to improve following unilateral resistance training. However, in the nondominant leg, the improvement in NME appears to be due solely to the increase in maximal EMG, whereas the improved NME in the dominant leg is due to both an increase in maximal EMG and a decrease in submaximal EMG.

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CHAPTER I: INTRODUCTION

Cross education is the ability of an untrained limb to experience a strength gain when the contralateral limb is trained unilaterally. Cross education has been shown to occur in the muscles of the hand(Yue & Cole, 1992), elbow (Farthing, Borowsky, Chilibeck, Binsted, & Sarty, 2007; Farthing et al., 2011; Khouw & Herbert, 1998; Moritani, 1979; Munn, Herbert, Hancock, & Gandevia, 2005; Shaver, 1970; Shaver, 1975), and knee (Carolan & Cafarelli, 1992; Evetovich et al., 2001; Garfinkel & Cafarelli, 1992; Hortobagyi, Lambert, & Hill, 1997; Kannus et al., 1992; Komi, Viitasalo, Rauramaa, & Vihko, 1978; Narici, Roi, Landoni, Minetti, & Cerretelli, 1989; Ploutz, Tesch, Biro, & Dudley, 1994; Tracy et al., 1999; Zhou, Oakman, & Davie, 2002). When analyzing these studies, the effect of unilateral resistance training (URT) on the maximal voluntary strength of the untrained limb has been shown to range from 3-15% (Carolan & Cafarelli, 1992; Evetovich et al., 2001; Garfinkel & Cafarelli, 1992; Kannus et al., 1992; Komi et al., 1978; Narici et al., 1989; Ploutz et al., 1994; Shima et al., 2002; Tracy et al., 1999), however some studies have reported changes greater than 20% (Farthing, Chilibeck, & Binsted, 2005; Farthing et al., 2007; Fimland et al., 2009; Hortobagyi et al., 1997; Moritani, 1979; Zhou et al., 2002).

Many studies have examined cross education of the knee extensor muscles after completing isometric URT (Carolan & Cafarelli, 1992; Garfinkel & Cafarelli, 1992; Kannus et al., 1992; Komi et al., 1978) or isokinetic URT (Evetovich et al., 2001; Hortobagyi, Scott, Lambert, Hamilton, & Tracy, 1999; Hortobagyi et al., 1997). However, only two studies, to our knowledge, have assessed the effectiveness of dynamic URT on cross education in the knee extensors (Coburn et al., 2006; Tracy et al., 1999). Coburn et al. (2006) did not significantly improve strength in the untrained limb when individuals completed eight weeks of URT with the nondominant leg. Tracy et al. (1999) showed dynamic lower body URT for nine weeks to increase contralateral knee extensor isotonic strength in older adult men and women; however no examination into the neuromuscular mechanisms was performed. Further understanding of the mechanisms behind cross education is needed to properly explain the phenomenon of cross education. Neuromuscular adaptations are considered a likely mechanism behind cross education (Carroll, Herbert, Munn, Lee, & Gandevia, 2006; Lee & Carroll, 2007).

Neuromuscular adaptations have been shown to occur after completing bilateral resistance training. Electromyography (EMG) analysis has shown a significant increase in maximal muscle activation during isometric, isokinetic and a 1 repetition maximum (1RM)of the knee extensor muscles after 14 weeks (Aagaard et al., 2000) or 16 weeks (Häkkinen & Komi, 1982) of bilateral resistance training. Similar neuromuscular adaptations have been argued to be the primary mechanism behind cross education (Carroll et al., 2006; Lee & Carroll, 2007). Maximal muscle activation of the untrained limb has been examined after URT. A significant increase in the maximal muscle activation in the untrained limb has been seen after only 6 weeks of URT (Farthing et al., 2007; Shima et al., 2002). Also, after 6 weeks of URT, there were no significant changes in the muscle thickness of the untrained arm, implying that the cross education of strength is primarily due to neuromuscular adaptations rather than hypertrophic gains (Farthing et al., 2007). Similarly, Moritani et al. (1979) saw significant increases in the strength and maximal muscle activation of the untrained arm, but no change in cross-sectional area after 8 weeks of URT. While the cross education of maximal muscle activation has been well established, only one study has examined the effect of URT on contralateral limb muscle activation at submaximal intensities. Ploutz and colleagues (Ploutz et al., 1994) observed reduced activation at the same absolute submaximal intensities in the untrained limb following 9 weeks of URT (Ploutz et al., 1994). Another study by Tillin et al. (2011) examined EMG activity during submaximal isometric knee extensions with no significant change observed in the untrained limb after 4 weeks of URT. However, the submaximal loads were relative to the participant's new maximum after training which means that each trial was performed at a higher absolute load. Thus, it is unknown if the resistance training had an effect on muscle recruitment at the same absolute loads. Cadore et al. (Cadore et al., 2010) defined the term neuromuscular economy (NME) as "lower muscle activation, represented by EMG signal amplitude, necessary to perform the same absolute load". To date, the concept of NME has not been used to examine the effects of URT and study cross education.

NME can also be defined as the amount of muscle activation required to move a specific load, where an enhanced economy would require less muscle activation to move the same load. Cadore et al. (Cadore, Pinto et al., 2011b) determined dynamic NME by utilizing EMG during submaximal trials on a cycle ergometer. NME of the vastus lateralis (VL) at 50 watts has been shown to be negatively correlated to 1RM and maximal voluntary contraction (MVC) in the elderly (Cadore et al., 2011b) which means that individuals with higher strength values requires lower muscle activation at a submaximal intensity when compared to weaker individuals. The effect of resistance training on isometric NME was first examined by Cadore et al. (Cadore et al., 2010). Following 12 weeks of strength training, improved isometric NME during submaximal isometric knee extension was observed in older adults (65.5 ± 5 years old)(Cadore et al., 2010). Furthermore, 12 weeks of resistance training has been shown to improve dynamic NME of the VL at 100 watts (Cadore, Pinto et al., 2011a). Concurrent training, consisting of 40 minutes of full body resistance training and 30 minutes of cycle ergometry 3 days a week, for 12 weeks has also been shown to improve dynamic NME during a cycling trial in both the VL and rectus femoris (RF) (Cadore et al., 2011a; Cadore et al., 2012).

To better understand the mechanisms behind cross education, this study utilized dynamic NME to determine if any neuromuscular adaptations occurred in the untrained leg in response to URT. Changes in dynamic NME may provide evidence regarding the mechanisms of cross education.

Purpose

1. To determine the effects of 4 weeks of URT on the NME of each leg.
2. To investigate the effects of 4 weeks of URT on the PKF of each leg.
3. To examine the effects of 4 weeks of URT on the strength and of each leg.

Hypotheses

1. After 4 weeks of URT the strength, peak isometric force (PKF), maximal EMG and NME of the trained leg will be increased.
2. After 4 weeks of URT, a cross education effect will occur. The strength, PKF, maximal EMG and NME of the untrained leg will be increased because of this cross education.
3. The changes in strength, PKF, maximal EMG and NME will be greater in the trained leg than the untrained leg.
4. Strength, PKF, maximal EMG and NME will not change in the control group.

Operational Definitions

1. Cross Education – The phenomenon in which an untrained limb will experience adaptations in strength, muscular activation and NME when the homologous muscle group of the contralateral limb is trained unilaterally.

2. Maximal Voluntary Contraction – PKF of the knee extensors record with the knee and hip at angles of 110º.
3. Maximal/submaximal EMG – The EMG root mean square amplitude values during MVC and NME tests, respectively.
4. Neuromuscular Economy – Muscle activation while cycling at 75, 100 and 125 watts normalized to muscle activation during a maximal isometric contraction activation.
5. Dominant Leg – Leg dominance was determined via the Waterloo Footedness Questionnaire. All participants in the URT group were trained on the dominant leg.

Abbreviations

URT – Unilateral Resistance Training

CON – Control Group

MVC – Maximal Voluntary Contraction

PKF – Peak Isometric Force

LP – Leg Press

LE – Leg Extension

EMG – Electromyography

1RM – 1 Repetition Maximum

NME – Neuromuscular Economy

RF – Rectus Femoris

VL – Vastus Lateralis

DOM – Dominant Leg

NON – Nondominant Leg

Delimitations

Twenty men between the age of 18 and 35 were recruited for this study. All participants completed a Confidential Medical and Activity Questionnaire, Physical Activity Readiness Questionnaire, Dietary Recall and a written informed consent prior to testing. To be included into this study, participants had to be healthy and free of disease or injury. Participants were excluded from the study if they had performed resistance exercise training within the last year or were currently meeting or exceeding 150 minutes of moderate or 75 minutes of vigorous cardiovascular activity per week. Participants were also free from nutritional supplements for 3 months before enrolling in this study. Nutritional supplements that lead to exclusion from this study included, but were not limited to, protein powders or bars, creatine and branched chain amino acids.

Assumptions

Theoretical Assumptions

1. Participants accurately and truthfully answered the Confidential Medical and Activity Questionnaire and Physical Activity Readiness Questionnaire.
2. Participants did not consume nutritional supplements throughout the duration of the study or 3 months prior to enrolling.
3. Participants did not engage in exercise programs outside of the study.
4. Participants gave maximal effort on the all testing measures.
5. Participants maintained a similar diet throughout the duration of the study.
6. Participants completed all URT sessions.
7. Participants maintained a relatively standard sleep cycle.

Statistical Assumptions

1. The sample was randomly selected from the population.
2. Participants were randomly placed into their respective group.

Limitations

1. Participants were recruited primarily from the University of Central Florida; therefore the process of participant selection may not be truly random.
2. Participants were only those who volunteered for the study, which may limit a truly random selection.
3. The untrained leg of the participants in the URT group may have been utilized and stimulated outside of the URT sessions via daily activity.
4. Due to the amount of time required with pre-testing, post-testing and the 4 week intervention period, participant withdrawal from the study occurred.
5. Actual dietary consumption was not measured and daily dietary fluctuations may have occurred throughout the study.

CHAPTER II: REVIEW OF LITERATURE

Cross education after unilateral resistance training

Komi, Viitasalo, Rauramaa, Vihko, 1978

Effect of isometric strength training on mechanical, electrical and metabolic aspects of muscle function

This study utilized 12 weeks of unilateral isometric knee extension training to assess the cross education of strength and EMG activity. Six sets of twins were recruited for this study with one of each set being placed in each group. The training group completed four resistance training sessions per week throughout the twelve weeks for a total of 48 training sessions. During the first two weeks of training, participants completed 5 maximal contractions per session. An extra contraction was added to each workout with each week of training. Maximal isometric strength was tested on the same dynamometer that was used during training. The trained leg experienced a 20% increase in maximal isometric strength, while the untrained leg experienced an 11% increase in strength. Maximal EMG activity was recorded during these maximal isometric contractions. The trained leg experienced a 38% increase in maximal EMG activity of the RF, while the untrained leg did not experience any significant change. EMG activity was also recorded during submaximal contractions. The force during these contractions was the same absolute intensity before and after training. While not significant, there was a trend towards lower EMG activity at the same absolute load in both the trained and untrained leg. This would be an indication of isometric NME. Although the results were not significant, there is promise that NME adaptation may be able to cross over to the untrained limb.

Moritani, Toshio, deVries, Herbert, 1979

Neural factors versus hypertrophy in the time course of muscle strength gain

The primary purpose of this study was to assess the neuromuscular and hypertrophic adaptations to URT in the trained and untrained arms. Seven males and eight females volunteered for this study. Five participants completed 8 weeks of URT. Training sessions were completed 3 days per week and consisted of 2 sets of elbow flexion for 10 repetitions at a load equal to 66% of the individuals 1RM. Participants were tested every two weeks on maximal isometric elbow flexion, muscle cross sectional area, maximal muscle activation level, and efficiency of electrical activity. Further analysis showed the contributions of neural factors and muscle hypertrophy on the increases in strength. Results showed significant improvements in strength, cross sectional area, muscle activation and efficiency of electrical activity in the trained arm. The untrained arm experienced significant changes in maximal strength and activation level, but no changes in cross sectional area or efficiency of electrical activity. When comparing the changes in neural factors and muscle hypertrophy throughout the training period, the trained arm experienced changes in both, with greater changes in neural factors during the first two weeks. However, the untrained arm experienced changes in the neural factors throughout all 8 weeks of training, with no significant change in muscle hypertrophy. In summary, the cross education of strength appears to be primarily due to increased muscular activation rather than increased muscle size.

Narici, Roi, Landoni, Minettis, Cerretelli, 1989

Changes in force, cross-sectional area and neural activation during strength training and detraining of the human quadriceps

The focus of this study was to examine the changes in MVC, maximal EMG activity, and cross-sectional area of the quadriceps following 60 days of unilateral isokinetic training. Training occurred 4 days per week and consisted of six sets of 10 repetitions of maximal isokinetic knee extension on the dominant leg only. The trained leg experienced significant increases in MVC (20.8% ± 5.4%), maximal EMG (42.4% ± 16.5%) and cross-sectional area (8.5% ± 1.4%) after 60 days of training. The untrained leg experienced no change in cross-sectional area, while MVC (8.7% ± 4.3%) and maximal EMG (24.8% ± 10%) showed a trend towards increasing, only to a non-significant level. While not significant, the changes in MVC and EMG in the absence of changes in cross-sectional area support the neural mechanism of cross education.

Carolan, Cafarelli, 1992

Adaptations in coactivation after isometric resistance training

The primary aim of this study was to determine the neuromuscular adaptations that occur after 8 weeks of unilateral isometric resistance training. Twenty males were recruited for this study and randomly assigned to either complete 8 weeks of training or serve as a control. Three training sessions were completed each week, with 30 maximal isometric knee extensions being performed during each session. Before and after training, all participants were tested on maximal voluntary knee extension of each leg. During the MVCs, the EMG activity of the VL and biceps femoris was measured. The control group experienced no changes in MVC or EMG activity. In the training group, MVC knee extension significantly increased in both the trained and untrained legs (32.8% and 16.2%, respectively). EMG activity in the VL remained unchanged in the trained and untrained legs. However, EMG activity of the biceps femoris during maximal knee extension decreased in both the trained and untrained legs (20% and 13%, respectively). In conclusion, the primary neuromuscular adaptation that occurred in both the trained and untrained legs with 8 weeks of isometric resistance training was a decrease in coactivation of the hamstrings during knee extension.

Kannus, Alosa, Cook, Johnson, Renstrom, Pope, Beynnon, Yasuda, Nichols, Kaplan, 1992

Effect of one-legged exercise on the strength, power and endurance of the contralateral leg

The purpose of this study was to utilize combined isokinetic and isometric leg extension (LE) and flexion on cross education. Ten males and ten women participated in this study and were randomly assign to either a training or control group. The training intervention consisted of 3 days per week for 7 weeks, with both isokinetic and isometric strength training being performed during all training sessions. Strength testing was completed with both isometric and isokinetic peak torque. The trained leg experienced significant improvements in both isometric and isokinetic peak torque in the quadriceps (34% and 11%, respectively) and hamstrings (20% and 5%, respectively). The untrained leg demonstrated cross education by experiencing a significant increase in isometric and isokinetic peak torque, but only in the quadriceps (12% and 9%, respectively). The untrained hamstring did not show any significant change in isometric or isokinetic peak torque. Similar results were seen in terms of isokinetic power. The trained leg experienced significant changes in isokinetic power in the quadriceps and hamstrings, whereas the untrained leg only revealed significant changes in the quadriceps. This study further analyzed the data by looking for any potential relationships between changes in the trained and untrained legs. When analyzing strength parameters, there was a significant positive correlation between percent change in the trained and untrained quadriceps and hamstrings (r=0.50 and r=0.66, respectively). Similar correlations between trained and untrained quadriceps and hamstrings were seen when analyzing power measures (r=0.48 and r=0.75, respectively). While this study only utilized isometric and isokinetic training and testing, a clear cross education effect of strength and power was seen in the untrained quadriceps muscles. Further, a positive relationship was seen between changes in the trained and untrained legs, indicating that greater increases in strength in the trained leg may be needed to experience changes in the untrained leg.

Tracy, Ivery, Hurlbet, Martel, Lemmer, Siegel, Metter, Fozard, Fleg, Hurley, 1999

Muscle quality. II. Effects of strength training in 65- to 75-yr-old men and women

The primary purpose of this study was to examine the differences in muscle quality of the knee extensors after URT in elderly men and women. Muscle quality was defined as both isometric and isotonic strength divided by muscle volume. Twelve elderly men and eleven elderly women completed testing to determine isometric force, isokinetic peak torque and 1RM of the knee extensors before and after a nine week URT program. URT was performed three days per week and consisted of five sets of unilateral knee extension performed by the dominant leg. The isometric force, isokinetic peak torque and 1RM significantly increased in the trained leg of elderly males (11.4%, 7.2%, and 25.3%, respectively). The 1RM of the trained leg in women also significantly increased (31.0%), with no change in isometric or isokinetic strength. Both males and females experienced a significant increase in the 1RM of the untrained leg (9.2% and 9.5%, respectively). Despite the greater increase in the 1RM of the trained leg in males, there was a similar increase in 1RM in the untrained leg of males and females. The trained leg in both males and females experienced a significantly greater increase in 1RM when compared to the untrained leg. In conclusion, nine weeks of URT increased the maximal isotonic force of the knee extensors in the untrained leg of men and women. This is one of the only studies to utilize dynamic unilateral resistance exercise to assess cross education in the legs.

Evetovich, Housh, Housh, Johnson, Smith, Ebersole, 2001

The effect of concentric isokinetic strength training of the quadriceps femoris on electromyography and muscle strength in the trained and untrained limb

The primary aim of this study was to assess the efficacy of unilateral concentric isokinetic training at increasing peak torque and maximal EMG activity of the VL. Twenty adult men were assigned to either a training or control group. The participants had not engaged in resistance training for at least one year. The training period was twelve weeks in length with three training sessions per week. The training sessions consisted of four-to-six sets of ten maximal concentric-only isokinetic LE of the nondominant leg. Testing of peak torque and maximal EMG amplitude was measured at 0, 4, 8 and 12 weeks. Peak torque in the trained leg significantly increased after 4 weeks of training and continued to increase through 12 weeks (15.5%). The untrained leg showed a significant increase in peak torque after 12 weeks of training (5.5%). Neither the trained or untrained leg showed any changes in maximal EMG amplitude. The lack of adaptations in the untrained leg may be due to the training of the nondominant limb, use of isokinetic training, measuring only EMG activity in the VL, or a combination of the three.

Shima, Ishida, Katayama, Morotome, Sato, Miyamura, 2002

Cross education of muscular strength during unilateral resistance training and detraining

The purpose of this study was to assess MVC and maximal muscle activation after 6 weeks of URT of the plantar flexor muscles. Fifteen untrained males completed 4 training sessions per week, which consisted of 3 sets of 10-12 repetitions at 70-75% of each participant's 1RM. The maximal voluntary isometric contraction of the plantar flexor muscles significantly increased in both the trained and untrained limbs (18.9% and 7.8%, respectively). Maximal EMG was also significantly increased in the trained and untrained limbs (48.2% and 20.8%, respectively). Voluntary activation was measured by comparing voluntary activation to an electrically stimulated twitch and expressed as a percentage. The voluntary activation of both the trained and untrained legs significantly increased after training (4.6% and 3.6%, respectively). In summary, this study utilized 6 weeks of progressive resistance training to increase the isometric strength, maximal EMG and percent of muscle activated in the untrained plantar flexors.

Zhou, Oakman, Davie, 2002

Effects of unilateral voluntary and electromyostimulation training on muscular strength on the contralateral limb

The primary aim of this study was to see if unilateral electromyostimulation training would provide a similar cross education as unilateral isometric training. Thirty males volunteered for this study with three even groups of ten. One group completed 4 weeks of unilateral isometric knee extension, while another completed 4 weeks of unilateral electromyostimulation of the knee extensors. The third group served as controls and participated in no training. All training was completed 3 days per week for a total of 12 training sessions. An isometric training session consisted of 5 sets of 8 repetitions at 65% of MVC. Similarly, in the electromyostimulation group each training session consisted of 40 stimulated isometric contractions at a force equivalent to 65% of the individual's MVC. Maximal isometric and isokinetic torque was measured on each leg individually, as well as maximal EMG activity of the RF, VL and vastus medialis during those tests. Both the isometric and electromyostimulation groups experienced similar significant increases in in isometric and isokinetic strength in the trained leg (Isometric group: 24.5% and 22.3%, respectively; Electromyostimulation: 21.1% and 21.7%, respectively). Also, both groups experienced similar cross education of isometric strength, but not isokinetic strength. In terms of EMG, a trend existed in the trained and untrained legs for maximal EMG of the VL, RF and vastus medialis to increase during a maximal isometric contraction. In conclusion, after only 4 weeks of URT a cross education effect was seen in isometric strength. While there were no significant changes in maximal EMG, the trend towards greater muscle activation in the untrained limb is promising. By increasing the intensity at which training is completed or having a larger sample size, the trends may have become statistically significant improvements.

Farthing, Chilibeck, Binsted, 2005

Cross education of arm muscular strength is unidirectional in right-handed individuals

In this study, the primary focus was to assess the directionality of cross education. Thirty-nine right-handed females were randomized into a left-handed training, right-handed training, or nontraining group. Both training groups completed 6 week of maximal isometric ulnar deviation. The training intervention consisted of 4 training sessions per week, for a total of

24 sessions, completing 2-6 sets of 8 repetitions. The trained arm in both the right-handed and left-handed training groups experienced a significant increase in maximal isometric strength (26.3% and 36.1%, respectively). However, only the right-handed training group had a significant increase in strength in the untrained arm (39.0%). In summary, cross education appears to be more likely to occur when URT is performed on the dominant arm. This finding could explain why previous studies, which did not account for handedness, did not see any cross education adaptations.

Munn, Herbet, Hancock, Gandevia, 2005

Training with unilateral resistance exercise increases contralateral strength

The focus of this study was to assess different URT volumes and contraction types on cross education. One hundred fifteen participants were randomized into either a control group or to complete 6 weeks of URT. Within the training groups were four subgroups: one set at high speed, one set at slow speed, three sets at high speed and three sets at slow speed. The high speed groups completed lifts with 1 second concentric and eccentric phases, while the slow speed utilized 3 second concentric and eccentric phases. Training sessions for all 4 training groups occur 3 days per week and consisted of 6-8 repetition of elbow flexion. Before and after training, all participants completed a 1RM test of elbow flexion. In the trained arm, a single set at slow speed resulted in a 25% increase in 1RM, whereas three sets at slow speed increased strength by 48%. High speed increased strength gains by 11% in the trained arm. In the untrained arm, performing three sets produced significantly greater increases in strength than completing only one set. Training at high speed or slow speed did not significantly change the cross education of strength. Also, a significant relationship was present between the changes in strength in the trained and untrained arms. These findings have a large impact on the prescription of URT to experience the greatest cross education.

Coburn, Housh, Housh, Malek, Beck, Cramer, Johnson, Donlin, 2006

Effects of leucine and whey protein supplementation during eight weeks of unilateral resistance training

This study was primarily focused on assessing the effect of leucine and whey protein supplementation on URT. Thirty-three men (22.4 ± 2.4 years) were split into three groups: supplementation, placebo and control. Both the supplementation and placebo groups completed 8 weeks of URT on a LE machine. The nondominant limb, determined by kicking preference, was trained 3 days per week for during the 8 week training period. The training sessions consisted of 3-5 sets of 6 repetitions at 80% of the participant's 1RM. The number of sets increased from 3 during the first week to 4 during the second week and ultimately 5 during weeks 3-8. In this study, they were testing the strength and cross sectional area of both the trained and untrained legs. The supplementation group had the greatest change in 1RM in the trained leg compared to the placebo and control groups. However, the placebo group did have a significantly greater change in 1RM strength of the trained leg compared to the control group. Both the supplementation and placebo groups experienced significant increases in the cross-sectional area of all four quadriceps muscles of the trained leg. When looking at the untrained leg, only the supplementation group experienced an increase in 1RM. However, no significant changes were seen in the cross-sectional area in any muscles for either the supplementation or placebo group. The training program used in this study did not elicit cross education of strength. This may be due to the use of only the LE exercise throughout the training program. The lower total training volume may not be sufficient to cause hormonal release which would have a systemic effect on the untrained limb. In our current study, we will be utilizing both the LE and leg press (LP) exercises to increase training volume.

Farthing, Borowsky, Chilibeck, Binsted, Sarty, 2007

Neuro-physiological adaptations associated with cross education of strength

This study assessed isometric strength, muscle thickness and maximal EMG activity of the wrist muscles after 6 weeks of unilateral maximal isometric training. Twenty-three females completed 6 weeks of unilateral maximal isometric ulnar deviation 4 days a week for a total of 24 training sessions. Post-testing revealed a significant increase in strength and muscle thickness in the trained arm (44.7% and 8.4%, respectively). The untrained arm experienced a significant increase in strength (45.8%) but not muscle thickness. Both the trained and untrained arms significantly increased maximal EMG activity. This result supports the claim that the cross education of strength is primarily due to neuromuscular adaptations rather than hypertrophic gains.

Fimland, Helgerud, Solstad, Iversen, Leivseth, Hoff, 2009

Neural adaptations underlying cross education after unilateral strength training

The purpose of this study was to assess the neural adaptations of cross education after 4 weeks of isometric strength training. Twenty-six recreationally active individuals were randomized into either a training or control group. All participants completed maximal isometric plantar flexion strength testing. During this test, EMG activity was recorded from both the gastrocnemius and soleus. The 4 weeks of resistant training consisted of six sets of six unilateral maximal isometric plantar flexion contractions. Training sessions were completed 4 days per week for a total of 16 sessions. After the training period, maximal isometric strength of the plantar flexors significantly increased in the trained and untrained legs of the training group (38.6% and 27.3%, respectively). Moreover, the maximal EMG activity in the soleus and gastrocnemius of the trained leg significantly increased after training (22.5% and 37.4%, respectively). Also, the untrained leg showed similar increases in the maximal EMG activity of the soleus (27.3%). While there was an increase in maximal EMG activity of the untrained gastrocnemius (10.4%), it was not significant. In conclusion, this study showed that cross education of strength and neuromuscular adaptations can occur in as little as 4 weeks of URT.

Farthing, Krentz, Magnus, Barss, Lanovaz, Cummine, Esopenko, Sarty, Borowsky, 2011

Changes in functional magnetic resonance imaging cortical activation with cross education to an immobilized limb

In this study, URT was used as an intervention to prevent strength decreases to an immobilized limb. Fourteen individuals volunteered for this and had their nondominant arm put in a cast for 3 weeks. During this time, half of the individuals completed URT on their dominant free arm. The resistance training was completed 5 days per week with each session consisting of 3 set of eight repetitions on a handgrip dynamometer. An additional set was added during each training session. Testing consisted of isometric handgrip strength, muscle thickness assessed by ultrasound, maximal muscle activation assessed by EMG, and functional magnetic resonance imaging to assess cortical activation. The individuals who trained increased isometric handgrip strength in the dominant trained arm (10.7%), whereas the non-training group did not experience any significant strength change in their dominant arm. Also, the training group maintained the strength in the immobilized arm, while the non-training group experienced a significant decrease (-11.0%) in strength in the immobilized arm. No significant changes were seen the muscle thickness of the trained arm. Also, there were no group differences in the muscle thickness of the immobilized arm. However when all subjects were pooled together, the immobilized arm experienced a significant decrease (-3.3%) in muscle thickness. No significant changes were seen in the maximal EMG of either arm in either group. However, maximal EMG showed an increasing trend in training group and a decreasing trend in the non-training group, pooled across arms. In terms of motor cortex activation, the training group experienced a significant increase after training in activation during maximal isometric contraction of the untrained arm. The non-training group did not experience any change in motor cortex activation after training during immobilized arm maximal isometric contraction. In summary, 3 weeks of unilateral isometric resistance training during limb immobilization can prevent the loss of strength in the immobilized arm. However, a decrease in muscle thickness will still occur, which may indicate that neuromuscular adaptations are occurring during the URT.

Tillin, Pain, Folland, 2011

Short-term unilateral resistance exercise training affects the agonist-antagonist but not the force-agonist activation relationship

The aim of this study was to assess the effects of a 4 week unilateral isometric resistance training program on the EMG activity of the knee extensors. Nine recreationally active males completed this study, with all participants completing testing and training. The training period was 4 weeks in length with 4 sessions being completed each week for a total of 16 training sessions. Each training session consisted of four sets of 10 unilateral isometric knee extensions. After training, the trained and untrained legs experienced significant increases in maximal isometric voluntary knee extension (20% and 8%, respectively). As expected, the trained leg had a significantly higher increase than the untrained leg. Knee extensor maximal EMG experienced a 26% increase in the trained leg, while the knee extensors in the untrained leg did not experience a significant change in maximal EMG. Also, EMG activity of the knee extensors was recorded at isometric contractions of 20%, 40%, 60% and 80% of MVC. In the trained leg, the EMG activity significantly increased at all submaximal intensities (26-31%). The untrained leg knee extensors only increased EMG activity when tested at 20% of MVC (15.7%). However, the increase in EMG activity at submaximal intensities is most likely due to the fact that the absolute submaximal loads after training were higher than the pre-training loads. Therefore, the changes in EMG after training when trying to move the same absolute load needs additional investigation.

Neuromuscular adaptations to resistance exercise

Hakkinen, Komi, 1983

Electromyographic changes during strength training and detraining

The purpose of this study was to examine the neuromuscular adaptations to 16 weeks of lower body resistance training and 8 weeks of detraining. Fourteen untrained males completed the training, while 10 recreationally active males served as the control group. The primary exercise during the training sessions was a dynamic barbell back squat with a load between 80 and 100% of the 1RM. Testing was conducted every 4 weeks throughout the training and detraining period. Maximal isometric bilateral LE force, dominant unilateral isometric LE force and averaged maximal integrated EMG activity of the RF, vastus medialis and VL was recorded during testing sessions. The training group experienced a significant increase in isometric force at the end of the 16-week training period (21.1%) and a significant decrease during the 8-week detraining period (-12.0%). The decrease in strength did not return below pre-training values and were still significantly higher than baseline. Also, maximal EMG activity of the RF and VL significantly increased after the 16-week resistance training program (22.7% and 23.3%, respectively). The average integrated EMG from all three muscles showed a significant increase with 16 weeks of resistance training (12.5%) and a significant decrease with 8 weeks of detraining (-5.6%). Further analysis revealed that the average integrated EMG versus unilateral LE force curve shifted significantly to the right with training. This means that less muscular activation was needed during a contraction of the same absolute load after training. When analyzing average integrated EMG compared to relative loads, there was a noticeable but non-significant shift to the right. This would indicate more muscle activation to lift the same relative load after training; however this is most likely explained by relative loads being elevated due to a higher MVC. This adaptation to resistance training could be considered a form of isometric NME as less muscle was needed to lift the same absolute loads.

Aagaard, Simonsen, Andersen, Magnusson, Halkjær-Kristensen, Dyhre-Poulsen, 2000

Neural inhibition during maximal eccentric and concentric quadriceps contraction: effects of resistance training

The aim of this study was to assess neuromuscular activity during different contraction types after 14 weeks of resistance training. Fifteen men completed 38 training sessions during the 14 week period. During the first four weeks, participants completed 4 sets of 5 lower body exercises utilizing a 6-10 repetition maximum. The training program progressed to 5 sets with a 6-8 repetition maximum during the final 4 weeks. Maximal strength and neuromuscular activation during fast eccentric, slow eccentric, slow concentric and fast concentric contractions were recorded before and after training. Strength significantly improved during all 4 contractions after resistance training. Maximal muscle activation of the VL was significantly increased during all 4 contractions. Maximal activation of the RF was significantly increased in all contractions except during fast concentric contractions. In conclusion, 14 weeks of progressive resistance training can increase the maximal muscular activation of the VL and RF.

Del Balso, Cafarelli

Adaptations in the activation of human skeletal muscle induced by short-term isometric resistance training

The purpose of this study was to examine the effects of 4 weeks of isometric resistance training on strength, rate of force development and the potential neural adaptations that are occurring in untrained adult men. This study utilized a 4-week isometric training program of the plantar flexor muscles, with participants completing 3 sessions per week. Each session had the participant complete 6 sets of 10 maximal isometric contractions with 2 minutes between each set. The variables tested in this study included MVC, rate of force development, maximal EMG, voluntary activation and rate of activation. The results of the study showed that MVC and rate of force development both increased after 4 weeks of isometric training (20.0% and 42.5%, respectively). Interestingly, both MVC and rate of force development were significantly improved from baseline by the third training day (p<.005). The increase in MVC coincided with an increase in maximal EMG and voluntary activation (60.7% and 2.8%, respectively). Maximal EMG was significantly greater than baseline by the seventh day of training, while voluntary activation was significantly greater by the third training day (p<.001). There was also a significant increase in rate of muscle activation (48.7%) after 4 weeks of resistance training. Furthermore, the rate of activation had significantly improved by the third day of training. This study showed that strength changes can occur in untrained men after only 4 weeks of resistance training. Furthermore, the strength changes are most likely caused by the changes in muscular activation, which also occurred after 4 weeks of training.

Resistance exercise and movement economy

Ploutz, Tesch, Biro, Dudley, 1994

Effect of resistance training on muscle use during exercise.

This study utilized magnetic resonance imaging (MRI) to assess muscle activation and cross sectional area after 9 weeks of URT. Nine males completed 9 weeks, 2 sessions per week, of 3-6 sets of 12 repetitions of unilateral knee extension. Each participants completed unilateral 1RM and an MRI of each leg. The 1RM significantly increased in both the trained and untrained legs (14% and 7%, respectively). Also, the cross-sectional area of only the trained leg increased (5%), while the cross-sectional area of the untrained leg remained unchanged. This result supports the theory that cross education is caused by neuromuscular adaptations rather than hypertrophic adaptations. MRI contrast shift indicated muscle use after an acute bout of resistance exercise. The trained leg showed significantly less muscle with contrast shift at 50%, 75% and 100% of the pre-training 10RM loads after training for 9 weeks(-28.9%, -37.1% and -41.9%, respectively), indicating that less muscle was needed to lift the load. The untrained leg experienced a lesser but still significant change at 75% and 100% of the pre-training 10RM loads (-12.9% and -10.8%, respectively), indicating cross education in the ability to lift a load with less muscle being activated. In conclusion, this study provides evidence that cross education mechanisms are neuromuscular in nature and may result in a better economy of movement.

Sunde, Støren, Bjerkaas, Larsen, Hoff, Helgerud, 2010

Maximal strength training improves cycling economy in competitive cyclists

The primary focus of this study was to see how maximal strength training would affect cycling performance. The main variables this study examined were cycling economy and work efficiency at 70% of VO2max and time to exhaustion at maximal aerobic power. Eight competitive cyclists completed 8 weeks of maximal strength training in addition to their normal endurance training, while five cyclists did not add strength training. The strength training was completed 3 days per week, with each session composed of 4 sets of 4 repetitions of half squats. The strength training group experienced significant improvements in cycling economy at 70% VO_2max (6.9%), work efficiency (4.7%) and time to exhaustion (17.2%). Maximal oxygen uptake, cadence and body weight did not change in either group. This study shows that strength training can be used to improve aerobic exercise ability during cycling while not affecting maximal oxygen uptake.

Neuromuscular economy

Cadore, Pinto, Lhullier, Correa, Alberton, Pinto, Almeida, Tartaruga, Silva, Kruel, 2010

Physiological effects of concurrent training in elderly men.

The primary aim of this study was to see how strength, endurance and concurrent training affected neuromuscular and hormonal adaptations in older adult males. Twenty-nine elderly men were randomly assigned to complete strength, endurance or concurrent training 3 days per week for 12 weeks. Strength training consisted of 2-3 sets of 9 exercises, progressing from sets of 18-20 repetitions to 6-8 repetitions. The endurance training group completed 20-30 minutes of cycle ergometry at an intensity progressing from 80% to 100% of their heart rate at ventilatory threshold. The concurrent training group combined the two types of training on all training days. Knee extensor isometric NME was determined by obtaining EMG activity at each participant's MVC and then assessing EMG activity at 40%, 60% and 80% of their MVC. The same absolute load was used at post-testing. After the training period, the strength, endurance and concurrent training groups improved lower body 1RM (67.6%, 24.7% and 41.3%, respectively), while only the concurrent and strength training groups improved upper body 1RM (32.6% and 33.7%, respectively). Maximum isometric strength of the knee extensors was significantly increased only in the strength training group (13.3%). Similarly, the maximum EMG activity of the VL and RF only increased in the strength training group. The isometric NME for both the VL and RF at any intensity remained unchanged in the concurrent and endurance training groups. The isometric NME of the VL significantly decreased at 40%, 60% and 80% of MVC in the strength training group (-19.5%, -20.7% and -23.7%, respectively). The isometric NME of the RF showed a similar decrease at 60% and 80% intensities (-19.0% and -20.8%, respectively), but experienced no change at 40%. The only significant change in hormonal concentrations was a decrease in the free testosterone of the endurance training group. In conclusion, this study was the first, to our knowledge, to show that resistance exercise not only increases the maximal EMG activity, but also decreases submaximal EMG activity.

Cadore, Pinto, Alberton, Pinto, Lhullier, Tartargua, Correa, Almeida, Silva, Laitano, Kruel, 2011

Neuromuscular economy, strength, and endurance in healthy elderly men

The purpose of this study was to examine the relationships between dynamic NME, knee extensor dynamic and isometric strength and endurance measures in elderly men. Twenty-eight older adult males completed tests of maximal dynamic strength, muscular endurance, maximal isometric strength, maximal workload, peak oxygen uptake, ventilatory threshold and dynamic NME of the VL at 25, 50 and 75 watts. Pearson product-moment correlation test were used to examine relationships between the variables. Dynamic NME of the VL at 25, 50 and 75 watts were shown to have significantly negative relationship with 1RM (r=-0.45, r=-0.47 and r=-0.44, respectively), rate of force development (r=-0.48, r=-0.46 and r=-0.50, respectively) and MVC of the knee extensors (r=-0.52, r=-0.60 and r=-0.61, respectively), indicating that individuals who had higher 1RMs, rates of force development and MVCs activated less muscle during the submaximal cycle ergometer test.

Cadore, Pinto, Pinto, Alberton, Correa, Tartargua, Silva, Almeida, Trindade, Kruel, 2011

Effects of strength, endurance, and concurrent training on aerobic power, and dynamic neuromuscular economy in elderly men

This study compared the effectiveness of concurrent training with strength or endurance training alone in elderly men. Twenty-three older men trained 3 times a week for 12 weeks in their respective training group. Maximum aerobic workload, peak oxygen uptake and dynamic NME of the VL and RF at 50, 75 and 100 watts were measured before and after the training period. The endurance training group significantly reduced the amount of muscle activated in the RF at 50, 75 and 100 watts (-41.1%, -28.7% and -22.6%, respectively), whereas the concurrent training group only experienced a significant change in the dynamic NME of the RF at 75 and 100 watts (-25.9% and -34.4%, respectively). The strength training group did not improve dynamic NME in the RF at any wattage. The dynamic NME of the VL at any wattage was unchanged after strength, endurance or concurrent training. The lack of changes in the strength training group may be because the strength training program focused on muscular endurance with only the last two weeks at a repetition range lower than 10 repetition maximum. A strength training program that focuses more on muscular hypertrophy or strength may provide a greater stimulus to the neuromuscular system.

CHAPTER III: DESIGN AND METHODOLOGY

Participants

Nineteen participants were recruited for this study. Two participants in the control group did not complete the study due to attrition; therefore, a total of seventeen participants completed the study. All participants had not engaged in resistance training exercise within the last year. Participants were allowed to be currently engaged in cardiovascular training as long as the total volume did not exceed 150 minutes of moderate activity or 75 minutes of vigorous activity per week. Before enrolling in the study, all participants completed a Confidential Medical and Activity Questionnaire, as well as a Physical Activity Readiness Questionnaire (PAR-Q), to determine if they had any physical limitations that would keep them from performing the testing and/or training procedures. Potential participants were excluded from the study if they had been using any ergogenic nutritional supplement within the last three months, such as, but not limited, to protein powders and creatine. Throughout the study, participants were not allowed to use any ergogenic nutritional supplements or engage in any outside structured resistance training program. All participants provided informed consent before beginning the study.

Research Design

A randomized, controlled trial design was used to determine the effects of URT on the strength, muscle activation and NME of the trained and untrained legs. Each participant visited the Human Performance Laboratory for pre-testing, training sessions and post-testing. After completing pre-testing, participants were randomly assigned to either the unilateral resistance training (URT) or control (CON) group. Participants in the URT group completed 4 weeks of

URT. During these 4 weeks, the CON group did not engage in any structured physical activity. After the 4-week intervention period, all participants completed post-testing.

Variables

The independent variables included in this study were: (a) group [URT vs. CON] and (b) time [pre vs. post]. The dependent variables included in this study were: (a) MVC expressed as PKF, (b) maximal EMG of the RF and VL (c) NME of the RF and VL at 75 watts, 100 watts and 125 watts, and (d) 1RM on the LP and LE of both the trained and untrained legs. All dependent variables were measured on each leg individually.

Instrumentation

- A differential amplifier (MP150 BIOPAC Systems, Inc., Santa Barbara, CA) and software (AcqKnowledge v4.2, BIOPAC Systems, Inc., Santa Barbara, CA) was used to collect and analyze EMG data
- An isokinetic dynamometer (S4, Biodex Medical System, Inc., New York, NY, USA) was used to determine PKF of the knee extensors
- A cycle ergometer (Corival, Lode B.V., Gronigen, the Netherlands) was used to complete the NME cycling trials.
- A LE, LP, chest press and low row (Power Lift & Conner Athletics Products, Inc., Jefferson, IA, USA) was used to determine 1RM for each exercise, respectively.

Pre- and Post-Testing

Pre- and post-testing sessions occurred during the week before and after the training period, respectively. All tests within each of the two testing sessions were completed on the same day. Each participant completed an MVC test, NME test, exercise familiarization and

1RM testing, in that order. All tests were performed on both legs. Limb dominance was assessed via the Waterloo Footedness Questionnaire (Bryden, Lorin J Elias MP, 1998)Testing sessions required a maximum of two and a half hours to complete.

1 Repetition Maximum Methods

Maximal strength was determined on four different exercises through 1RM testing. The four exercises were unilateral LP and unilateral LE for each leg, as well as bilateral chest press and low row. Prior to beginning the test, each participant completed a general and specific warm up. The general warm up consisted of riding a cycle ergometer for 5 minutes at the participant's preferred resistance. The specific warm up consisted of 10 body weight squats, 10 alternating lunges, 10 walking knee hugs and 10 walking butt kicks. Each participant performed two warm-up sets using a resistance that was approximately 40-60% and 60-80% of their perceived maximum, respectively. The third set served as the first attempt at the participant's 1RM. If the set was successfully completed, then weight was added and another set was attempted. If the set was not successfully completed, then the weight was reduced and another set was attempted. A 3-5 min rest period was provided between each set. This process of adding and removing weight continued until a 1RM was reached. A maximum of 6 attempts were performed. Attempts not meeting the range of motion criterion for each exercise, as determined by the trainer, were discarded. All 1RM tests were completed under the supervision of Certified Strength and Conditioning Specialist.

Electromyography Methods

To assess EMG activity during the maximal voluntary isometric contraction and NME test, a bipolar surface electrode arrangement was placed over the VL and RF of both legs.

Electrode arrangement for each muscle was similar to the configuration previously reported by Surface Electromyography for the Non-Invasive Assessment of Muscles (Hermens et al., 1999). For the VL, electrodes were placed at approximately two-thirds of the line between anterior superior iliac spine and lateral superior aspect of the patella. For the RF, electrodes were place at the midpoint of the line between the inguinal crease and superior border of the patella. The reference electrode was placed over the lateral epicondyle of femur. The skin beneath the electrodes was shaved and cleaned with alcohol to keep inter-electrode impedance below 5,000 ohms. EMG signals were obtained with a differential amplifier (MP150 BIOPAC Systems, Inc., Santa Barbara, CA) sampled at 1,000 Hz. Files were then stored on an external drive for later analysis. EMG signals were band-pass filtered from 10 Hz to 500 Hz and expressed as root mean square (RMS) amplitude values by software (AcqKnowledge v4.2, BIOPAC Systems, Inc., Santa Barbara, CA).

Maximal Voluntary Isometric Contraction Methods

After previously stated electrode placement, participants completed an MVC test. Individuals were positioned in a BioDex S4 isokinetic dynamometer in a seated position with the hip at an angle of 110° and strapped to the machine at the waist and shoulders. Next, the evaluators were positioned the individual’s knee at an angle of 110° of extension (180° representing full extension). The participants were then instructed to exert their maximum strength when trying to extend the knee and to produce the strength as fast as possible. Researchers provided verbal encouragement throughout each trial to motivate participants to perform a maximal contraction. Participants were given three attempts on each leg, with each attempt lasting 5 seconds and there was a 3-minute rest interval between each attempt. The highest PKF of the three attempts was recorded. At the point of PKF, a 1-second slice of the

EMG signal was used to determine the maximal EMG activity. The highest EMG- RMS amplitude value from the three attempts was used as the participant's maximum EMG activity for each leg and muscle, respectively.

Neuromuscular Economy Methods

The NME test has been previously described by Cadore et al. (Cadore et al., 2011b). Briefly, participants performed three 3-minute trials of cycle ergometry at 75, 100 and 125 watts, respectively. The order of the three trials was randomized. A cadence between 70 and 75 rpm was maintained by each participant throughout each trial. During each trial, the EMG-RMS amplitude values were recorded from the middle two minutes of each trial and reported as a percent of maximal value obtained during the maximal isometric strength test. These values represent the participant's NME for each leg (DOM or NON), muscle (RF or VL) and at each intensity (75, 100, or 125 watts), respectively.

Familiarization Methods

During the pre-testing session, familiarization of the required exercises was performed. Each participant was instructed about proper form and cadence of each exercise. At this time they completed 1RM tests previously described above for the unilateral LE, unilateral LP, chest press, and seated row exercises. Participants were then randomly assigned into either the CON group or URT group.

Unilateral Training Methods

Throughout the four-week intervention period, each participant in the URT group reported to the Strength and Conditioning Laboratory three times per week (Monday, Wednesday, and Friday) for their exercise session. If a participant missed a training session, make up sessions were scheduled with laboratory staff to ensure that 12 total sessions were completed during the four weeks while still maintaining appropriate rest periods between training sessions. Prior to each session, participants completed a general and specific warm up. The general warm up consisted of a riding a cycle ergometer for 5 minutes at their preferred resistance. The specific warm up consisted of 10 body weight squats, 10 alternating lunges, 10 walking knee hugs and 10 walking butt kicks. During each training session, participants in the URT group performed a unilateral lower body and bilateral upper body resistance training routine. Exercise order and volume can be seen in Table 1. All exercises were completed for 3 sets of 8-10 repetitions at 80% of the participant's previously determined 1RM. In the event that a participant could not complete the minimum amount of repetitions, they were allowed up to 30 seconds to recover and resume the set. If the participant was still unable to complete the required number of repetitions, then the weight was reduced on subsequent sets. The rest interval between each set was 90 seconds. Unilateral lower body exercises were performed on the dominant limb. The load and number of repetitions for each exercise were recorded in workout logs. All training sessions were supervised by a Certified Strength and Conditioning Specialist. The untrained limb remained relaxed throughout the exercise protocol. Participants were able maintain recreational activities as usual, but were no allowed to participate in any structured exercise programs throughout the duration of this study.

Data Analysis

All data was analyzed using a one-way analysis of covariance (ANCOVA) of the post-testing values using the pre-testing values as the covariate. Results were considered significant at an alpha level of $p \leq 0.05$.

The effect of URT was analyzed using magnitude-base inferences calculated from 90% confidence intervals, as previously described by Batterham and Hopkins (2009). Changes from pre- to post-testing were analyzed to assess differences between groups. These values were then analyzed via a published spreadsheet, with the smallest non-trivial difference set at 20% of the grand standard deviation. All data was expressed with percent chances of a beneficial, trivial and negative outcome. Qualitative inferences, based on quantitative chances were assessed as: <1% almost certainly not, 1-5% very unlikely, 5-25% unlikely, 25-75% possibly, 75-95% likely, 95-99% very likely and >99% almost certainly.

CHAPTER IV: RESULTS

Seventeen participants completed this study. One participant in the URT group was not included in data analysis due his EMG data falling two standard deviations outside of the group mean; therefore, results are reported for 16 participants. Table 2 displays the mean and standard deviation (mean ± SD) values for the age, height and weight of our participants in each group.

Absolute Strength Measures

Table 3 displays the mean and standard deviation (mean ± SD) values for all the strength measures (PKF_{DOM}, PKF_{NON}, LP_{DOM}, LP_{NON}, LE_{DOM}, LE_{NON}) before and after training for both the URT and CON groups.

Maximum Voluntary Contraction

After accounting for pretest values, there were no significant differences for PKF_{DOM} (p=0.188) or PKF_{NON} (p=0.948) between the URT and CON groups following the intervention period. Figure 1 shows the adjusted post-training PKF_{DOM} and PKF_{NON} for the URT and CON groups, respectively.

1 Repetition Maximum

After accounting for pretest values, there was a significant difference between the URT and CON groups for LP_{DOM} (p=0.003) and LP_{NON} (p=0.034) following the intervention period. The URT group was significantly higher than the CON group for LP_{DOM} and LP_{NON}. Figure 2 shows the adjusted post-training LP_{DOM} and LP_{NON} for the URT and CON groups, respectively.

After accounting for pretest values, there was a significant difference between the URT and CON groups for LE_{DOM} (p=0.018) following the intervention period. The URT group was significantly higher than the CON group for LE_{DOM}. There was no difference for LE_{NON}

(*p*=0.482) between the URT and CON groups. Figure 3 shows the adjusted post-training $\mathrm{LE}_{\mathrm{DOM}}$ and $\mathrm{LE}_{\mathrm{NON}}$ for the URT and CON groups, respectively.

Maximal EMG Measures

Table 4 displays the mean and standard deviation (mean ± SD) values for all the maximal EMG measures ($\mathrm{MaxVL}_{\mathrm{DOM}}$, $\mathrm{MaxVL}_{\mathrm{NON}}$, $\mathrm{MaxRF}_{\mathrm{DOM}}$, $\mathrm{MaxRF}_{\mathrm{NON}}$, $\mathrm{MaxTotal}_{\mathrm{DOM}}$, $\mathrm{MaxTotal}_{\mathrm{NON}}$) before and after training for both the URT and CON groups. Table 5 displays the results from the Hopkins Magnitude-Based Inferences comparing the changes in maximal EMG values between the URT and CON groups.

Max EMG Vastus Lateralis

After accounting for pretest values, there were no significant differences between the URT and CON groups for $\mathrm{MaxVL}_{\mathrm{DOM}}$ (*p*=0.101) and $\mathrm{MaxVL}_{\mathrm{NON}}$ (*p*=0.062) following the intervention period. According to magnitude-based inferences, there was a *Likely Positive* (89.9%) and *Very Likely Positive* (96.0%) effect of URT on the changes in $\mathrm{MaxVL}_{\mathrm{DOM}}$ and $\mathrm{MaxVL}_{\mathrm{NON}}$, respectively. Figure 4 shows the adjusted post-training $\mathrm{MaxVL}_{\mathrm{DOM}}$ and $\mathrm{MaxVL}_{\mathrm{NON}}$ for the URT and CON groups, respectively.

Max EMG Rectus Femoris

After accounting for pretest values, there were no significant differences between the URT and CON groups for $\mathrm{MaxRF}_{\mathrm{DOM}}$ (*p*=0.162) and $\mathrm{MaxRF}_{\mathrm{NON}}$ (*p*=0.179) following the intervention period. According to magnitude-based inferences, there was a *Likely Positive* (88.1% and 83.1%, respectively) effect of URT on the changes in $\mathrm{MaxRF}_{\mathrm{DOM}}$ and $\mathrm{MaxRF}_{\mathrm{NON}}$. Figure 5 shows the adjusted post-training $\mathrm{MaxRF}_{\mathrm{DOM}}$ and $\mathrm{MaxRF}_{\mathrm{NON}}$ for the URT and CON groups, respectively.

Max EMG Total

After accounting for pretest values, there was no significant difference between the URT and CON groups for $\text{MaxTotal}_{\text{DOM}}$ (*p*=0.075) following the intervention period. There was a significant difference between the URT and CON groups for $\text{MaxTotal}_{\text{NON}}$ (*p*=0.016) following the intervention period. The URT group was significantly higher than the CON group for $\text{MaxTotal}_{\text{NON}}$. According to magnitude-based inferences, there was a *Likely Positive* (94.6%) and *Very Likely Positive* (98.3%) effect of URT on the changes in $\text{MaxTotal}_{\text{DOM}}$ and $\text{MaxTotal}_{\text{NON}}$, respectively. Figure 6 shows the adjusted post-training $\text{MaxTotal}_{\text{DOM}}$ and $\text{MaxTotal}_{\text{NON}}$ for the URT and CON groups, respectively.

Submaximal EMG Measures

Tables 6 and 7 display the mean and standard deviation (mean ± SD) values for all the submaximal EMG measures (75VL_{DOM}, $100\text{VL}_{\text{DOM}}$, $125\text{VL}_{\text{DOM}}$, 75VL_{NON}, $100\text{VL}_{\text{NON}}$, $125\text{VL}_{\text{NON}}$, 75RF_{DOM}, $100\text{RF}_{\text{DOM}}$, $125\text{RF}_{\text{DOM}}$, 75RF_{NON}, $100\text{RF}_{\text{NON}}$, $125\text{RF}_{\text{NON}}$) before and after training for both the URT and CON groups, respectively. Table 8 displays the results from the Hopkins Magnitude-Based Inferences comparing the changes in submaximal EMG values between the URT and CON groups.

Submaximal EMG Vastus Lateralis

After accounting for pretest values, there were no significant differences between the URT and CON groups for 75VL_{DOM} (*p*=0.339), $100\text{VL}_{\text{DOM}}$ (p=0.446) and $125\text{VL}_{\text{DOM}}$ (*p*=0.107). There was a *Likely Positive* (77.5% and 92.6%, respectively) effect of URT on the changes in 75VL_{DOM} and $125\text{VL}_{\text{DOM}}$. There was an *Unclear* effect of URT on the changes in $100\text{VL}_{\text{DOM}}$.

Figure 7 shows the adjusted post-training 75VL$_{DOM}$, 100VL$_{DOM}$ and 125VL$_{DOM}$ for the URT and CON groups, respectively.

After accounting for pretest values, there were no significant differences between the URT and CON groups for 75VL$_{NON}$ (p=0.638), 100VL$_{NON}$ (p=0.328) and 125VL$_{NON}$ (p=0.490). According to magnitude-based inferences, there was an *Unclear* effect of URT on the changes in 75VL$_{NON}$, 100VL$_{NON}$ and NME125VL$_{NON}$. Figure 8 shows the adjusted post-training 75VL$_{NON}$, 100VL$_{NON}$ and 125VL$_{NON}$ for the URT and CON groups, respectively.

Submaximal EMG Rectus Femoris

After accounting for pretest values, there were no significant differences between the URT and CON groups for 75RF$_{DOM}$ (p=0.493), 100RF$_{DOM}$ (p=0.336) and 125RF$_{DOM}$ (p=0.084). There was an *Unclear* effect of URT on the changes in 75RF$_{DOM}$, 100RF$_{DOM}$ and 125RF$_{DOM}$. Figure 9 shows the adjusted post-training 75RF$_{DOM}$, 100RF$_{DOM}$ and 125RF$_{DOM}$ for the URT and CON groups, respectively.

After accounting for pretest values, there were no significant differences between the URT and CON groups for 75RF$_{NON}$ (p=0.704), 100RF$_{NON}$ (p=0.281) and 125RF$_{NON}$ (p=0.603). According to magnitude-based inferences, there was a *Likely Positive* (88.5% and 89.3%, respectively) effect of URT on the changes in 75RF$_{NON}$ and 100RF$_{NON}$. There was an *Unclear* effect of URT on the changes in 125RF$_{NON}$ Figure 10 shows the adjusted post-training 75RF$_{NON}$, 100RF$_{NON}$ and 125RF$_{NON}$ for the URT and CON groups, respectively.

Neuromuscular Economy Measures

Table 9 and 10 display the mean and standard deviation (mean ± SD) values for all the NME measures (NME75VL$_{DOM}$, NME100VL$_{DOM}$, NME125VL$_{DOM}$, NMESlopeVL$_{DOM}$, NME75VL$_{\mathrm{NON}}$, NME100VL$_{\mathrm{NON}}$, NME125VL$_{\mathrm{NON}}$, NMESlopeVL$_{\mathrm{NON}}$,NME75RF$_{\mathrm{DOM}}$, NME100RF$_{\mathrm{DOM}}$, NME125RF$_{\mathrm{DOM}}$, NMESlopeRF$_{\mathrm{DOM}}$,NME75RF$_{\mathrm{NON}}$, NME100RF$_{\mathrm{NON}}$, NME125RF$_{\mathrm{NON}}$, NMESlopeRF$_{\mathrm{NON}}$) before and after training both the URT and CON groups, respectively. Table 11displays the mean and standard deviation (mean ± SD) values for all the NME slope measures (NMESlopeVL$_{\mathrm{DOM}}$, NMESlopeVL$_{\mathrm{NON}}$, NMESlopeRF$_{\mathrm{DOM}}$, NMESlopeRF$_{\mathrm{NON}}$) before and after training both the URT and CON groups, respectively. Table 12 displays the results from the Hopkins Magnitude-Based Inferences comparing the changes in NME values between the URT and CON groups. Table 13 displays the results from the Hopkins Magnitude-Based Inferences comparing the changes in NME slope values between the URT and CON groups.

Neuromuscular Economy Vastus Lateralis

After accounting for pretesting values, there were no significant differences between the URT and CON groups for NME75VL$_{\mathrm{DOM}}$ (*p*=0.166) and NME100VL$_{\mathrm{DOM}}$ (p=0.064). There was a significant difference between the URT and CON groups for NME125VL$_{\mathrm{DOM}}$ (*p*=0.033) with the URT group presenting significantly lower values than the CON group. According to magnitude-based inferences, there was a *Likely Positive* (90.9% and 88.8%, respectively) and *Very Likely Positive* (98.3%) effect of URT on the changes in NME75VL$_{\mathrm{DOM}}$, NME100VL$_{\mathrm{DOM}}$ and NME125VL$_{\mathrm{DOM}}$, respectively. After accounting for pretest slope, there was no significant difference between the URT and CON groups for NMESlopeVL$_{\mathrm{DOM}}$ (*p*=0.205). According to magnitude-based inferences, there was a *Likely Positive* (89.6%) effect of URT on the changes in NMESlopeVL$_{\mathrm{DOM}}$. Figure 11 shows the adjusted post-training NME75VL$_{\mathrm{DOM}}$, NME100VL$_{\mathrm{DOM}}$, NME125VL$_{\mathrm{DOM}}$ and NMESlopeVL$_{\mathrm{DOM}}$ for the URT and CON groups, respectively.

After accounting for pretest values, there was no significant difference between the URT and CON groups for $\mathrm{NME75VL}_{\mathrm{NON}}$ (*p*=0.394), $\mathrm{NME100VL}_{\mathrm{NON}}$ (p=0.564) and $\mathrm{NME125VL}_{\mathrm{NON}}$ (*p*=0.532). According to magnitude-based inferences, there was a *Likely Positive* (76.6% and 78.8%, respectively) effect of URT on the changes in $\mathrm{NME75VL}_{\mathrm{NON}}$ and $\mathrm{NME125VL}_{\mathrm{NON}}$. There was an *Unclear* effect of URT on the changes in $\mathrm{NME100VL}_{\mathrm{NON}}$. After accounting for pretest slope, there was no significant difference between the URT and CON groups for $\mathrm{NMESlopeVL}_{\mathrm{NON}}$ (p=0.354). According to magnitude-based inferences, there was an *Unclear* effect of URT on the changes in $\mathrm{NMESlopeVL}_{\mathrm{NON}}$. Figure 12 shows the adjusted post-training $\mathrm{NME75VL}_{\mathrm{NON}}$, $\mathrm{NME100VL}_{\mathrm{NON}}$, $\mathrm{NME125VL}_{\mathrm{NON}}$ and $\mathrm{NMESlopeVL}_{\mathrm{NON}}$ for the URT and CON groups, respectively.

Neuromuscular Economy Rectus Femoris

After accounting for pretest values, there was no significant difference between the URT and CON groups for $\mathrm{NME75RF}_{\mathrm{DOM}}$ (*p*=0.279) and $\mathrm{NME100RF}_{\mathrm{DOM}}$ (p=0.120). There was a significant difference between the URT and CON groups for $\mathrm{NME125RF}_{\mathrm{DOM}}$ (*p*=0.046) with the URT group presenting significantly lower values than the CON group. According to magnitude-based inferences, there was an *Unclear* effect of URT on the changes in $\mathrm{NME75RF}_{\mathrm{DOM}}$ and $\mathrm{NME100RF}_{\mathrm{DOM}}$. There was a *Likely Positive* (85.6%) effect of URT on the change in $\mathrm{NME125RF}_{\mathrm{DOM}}$. After accounting for pretest slope, there was a significant difference between the URT and CON groups for the $\mathrm{NMESlopeRF}_{\mathrm{DOM}}$ (*p*=0.017) with the URT group presenting significantly lower values than the CON group. According to magnitude-based inferences, there was an *Unclear* effect of URT on the change in $\mathrm{NMESlopeRF}_{\mathrm{DOM}}$. Figure 13 shows the adjusted post-training $\mathrm{NME75RF}_{\mathrm{DOM}}$, $\mathrm{NME100RF}_{\mathrm{DOM}}$, $\mathrm{NME125RF}_{\mathrm{DOM}}$ and $\mathrm{NMESlopeRF}_{\mathrm{DOM}}$ for the URT and CON groups, respectively.

After accounting for pretest values, there were no significant differences between the URT and CON groups for NME75RF$_{NON}$ (p=0.756), NME100RF$_{NON}$ (p=0.298) and NME125RF$_{NON}$ (p=0.435). According to magnitude-based inferences, there was a *Likely Positive* (94.9%) and *Very Likely Positive* (95.3%) effect of URT on the changes in NME75RF$_{NON}$ and NME100RF$_{NON}$, respectively. There was an *Unclear* effect of URT on the changes in NME125RF$_{NON}$. After accounting for pretest slope, there was no significant difference between the URT and CON groups for the NMESlopeRF$_{NON}$ (p=0.680). According to magnitude-based inferences, there was an *Unclear* effect of URT on the changes in NMESlopeRF$_{NON}$. Figure 14 show the adjusted post-training NME75RF$_{NON}$, NME100RF$_{NON}$, NME125RF$_{NON}$ and NMESlopeRF$_{NON}$ for the URT and CON groups, respectively.

CHAPTER V: DISCUSSION

The primary findings of this study were that four weeks of URT increased the strength of both the trained and untrained legs. Also, maximal EMG amplitude of both the dominant and nondominant legs increased with training. Further, there was an improvement in the NME of both the VL and RF in the dominant and nondominant legs at varying workloads.

Strength Measures

While many studies have examined URT, only two have utilized dynamic resistance training as the mode of exercise (Coburn et al., 2006; Tracy et al., 1999). In the current study, participants increased PKF, LP strength and LE strength in the dominant leg (11.03±7.68%, 77.63±44.66%, and 46.76±16.17%, respectively). However, in the nondominant leg, significant increases in strength were only seen in LP strength (64.88±54.09%), with no significant changes in PKF (4.98±14.25%) or LE strength (18.74±16.81%). Utilizing a similar population and training program, Coburn et al. (2006) reported lower changes in LE strength for the trained (22.4%) and untrained (2.8%, n.s.) legs. In contrast to the training program from Coburn et al. (2006), which only consisted of the LE for training, the current training program contained both LP and LE exercises. Increasing training volume, by including both the LP and LE exercises may have contributed to larger strength gains in the current study. Additionally, the current study trained the dominant leg, whereas Coburn et al. (2006) trained the nondominant leg. Previous research has shown the greatest cross education to occur when training the dominant limb (Farthing et al., 2005), which may account for the larger strength gains in the untrained leg seen in the current study.

The greatest strength changes seen in this study were in the dynamic movements (LP: 77.63%; LE: 46.76%, respectively). It is to be expected that peak isometric strength (11.03%) would not improve at the same rate of LP or LE strength since no isometric training was performed during the training period. Tracy et. al (1999) reported similar improvements in strength when performing 9 weeks of URT with older adults. Similarly, previous studies have shown that strength increases are specific to the action that is trained (Morrissey, Harman, & Johnson, 1995). The nondominant leg also achieved the greatest strength changes in the LP exercise (64.88%) with no significant improvements in isometric strength (4.98%). Our cross education in LP strength was similar to results seen following twelve weeks of eccentric URT (77%) (Hortobagyi et al., 1997). Previous research has shown that the untrained leg only improves strength in the modality in which the contralateral leg was trained (Tracy et al., 1999). Therefore, cross education of strength may be specific to the utilized modality.

The current study yielded consistently greater increases in strength in the untrained leg than previous URT studies. This may be due to the moderate to high intensity training program utilized or the use of dynamic constant external resistance training. All participants performed workouts at 80% of their 1RM with load progression occurring whenever 10 repetitions were completed for all three sets. Previously, training programs in URT studies focused on higher volume with sets reaching 10-20 repetitions (Tracy et al., 1999). Utilizing training at 80% of 1RM has been shown to be more effective at increasing strength than training with loads less than 80% (Hoffman, Wendell, Cooper, & Kang, 2003). Other URT studies have either used isometric (Carolan & Cafarelli, 1992; Garfinkel & Cafarelli, 1992; Komi et al., 1978), isokinetic (Evetovich et al., 2001; Hortobagyi et al., 1999; Hortobagyi et al., 1997; Narici et al., 1989) or concentric only (Ploutz et al., 1994) training. Dynamic resistance training utilizes both concentric and eccentric movements against a load and has been shown to increase strength greater than concentric only training (Dudley, Tesch, Miller, & Buchanan, 1991).

The physiological mechanisms for the changes in strength for the trained limb are most likely both muscular and neural, whereas the untrained limb would primarily respond via neural adaptations (Moritani, 1979). Previous research has demonstrated that during URT for four weeks, the trained limb experiences a near equal contribution from neural factors and hypertrophy; while the untrained limb relies on neural factors with little contribution from hypertrophy (Moritani, 1979). In the current study, maximal and submaximal recruitment was measured, but changes in muscle hypertrophy were not examined. Neural factors that may contribute to an increase in muscular strength include increased motor unit activation, firing rates or synchronization (Carroll et al., 2006).

This study showed that 4 weeks of dynamic URT resulted in significant increases in strength in both the dominant and nondominant legs. It was also shown that both the dominant and nondominant legs achieved the greatest strength gains in the modality in which the dominant leg was trained. These results imply that the cross education of strength follows the specificity principle and practitioners should keep this in mind when prescribing URT.

Maximal EMG Measures

In this study, ANCOVA revealed significant differences in total maximal EMG of the nondominant leg. However, magnitude-based inferences revealed a *Likely* or *Very Likely Positive* effect of URT on all maximal EMG measures of the VL and RF for both the dominant and nondominant legs. The previous research examining the cross education of EMG activity in the quadriceps has shown no significant changes (Carolan & Cafarelli, 1992; Evetovich et al., 2001; Garfinkel & Cafarelli, 1992; Hortobagyi et al., 1997; Komi et al., 1978; Narici et al., 1989; Tillin et al., 2011; Zhou et al., 2002). This is most likely due to the training protocol utilized in the current study which consisted of both concentric and eccentric muscle actions during dynamic resistance training. Eccentric exercise training has been shown to produce greater neural adaptations than concentric exercise training (Hortobagyi et al., 1997). It has also been hypothesized that concentric and eccentric contractions have unique motor unit recruitment patterns, with eccentric contractions selectively recruiting high-threshold motor units (Nardone, Romano, & Schieppati, 1989). Furthermore, previous research has shown that concentric and eccentric URT can increase maximal EMG amplitude of the untrained VL, with eccentric training producing significantly greater gains than concentric training (Hortobagyi et al., 1997). Therefore, utilizing both concentric and eccentric contractions, as in dynamic resistance training, should ensure maximal recruitment of all motor units within the muscle and produce the greatest neuromuscular gains in the untrained limb.

Maximal EMG can be increased through greater motor unit activation, motor unit synchronization, or motor unit firing rate (Gabriel, Kamen, & Frost, 2006). As these variables were not measured in the current investigation, the specific adaptation that occurred in the dominant and nondominant legs is unclear. Previous research has shown that when a limb is exercised unilaterally, the unused contralateral muscle group is activated while at rest (Hortobagyi et al., 1997; Houston, Froese, St P, Green, & Ranney, 1983; Zijdewind & Kernell, 2001). The magnitude of activity in the unused leg, relative to the activity in the active leg, is no more than 10% during leg extension and 20% during leg press (Houston et al., 1983). One previous study has shown an increase in voluntary activation, via a decrease in superimposed twitch, of the untrained muscle group after four weeks of URT (Lee, Gandevia, & Carroll, 2009).

Previous research has also shown that motor unit firing rate of the VL increases after six weeks of resistance training and may be the primary factor in early gains in muscular strength (Kamen & Knight, 2004). Furthermore, Milner-Brown et al. (1975) showed that motor units synchronization, the simultaneous firing of motor units, increased after six weeks of URT. There is evidence that resistance training can increase motor unit activation (Knight & Kamen, 2001), firing rate (Kamen & Knight, 2004) and synchronization (Milner-Brown & Lee, 1975); however, as none of these variable were measured in the current study, it is unclear what specific adaptation or combination of adaptations occurred.

This study showed that 4 weeks of URT elicits changes in the maximal EMG signals of the VL and RF of both the dominant and nondominant legs. This increase in maximal EMG is indicative of an increase in neural drive during maximal contraction. It is possible that this increase in neural drive is the primary adaptation occurring with the cross education of strength.

Submaximal EMG Measures

In the current study, no significant differences were observed in the submaximal EMG of the VL or RF in either the dominant or nondominant leg during the NME cycling test. Therefore, the URT did not change the amount of motor unit recruitment during the cycle ergometer trials. However, there was a *Likely Positive* effect of URT on submaximal EMG of the dominant VL at 75 and 125 watts and of the nondominant RF at 75 and 100 watts. A decrease in submaximal EMG activity may be due to increased muscle size, not measured in the current study, which would reduce the amount of muscle mass recruited during a submaximal effort. Previous research has observed an initial increase in the EMG/force relationship during the early stages of training followed by a reduction in the EMG/force relationship as training progressed (Häkkinen & Komi, 1982; Komi et al., 1978). This decrease in the EMG/force relationship is most likely due to muscle hypertrophy, which becomes the primary contributor to strength gains after 4 weeks of training (Moritani, 1979) because the decrease in submaximal EMG was not consistent across muscles or workloads, it is unclear what adaptation, if any, occurred in response to the URT program.

Neuromuscular Economy Measures

While there were no consistent changes in submaximal EMG, there were significant improvements in NME in both the VL and RF of the dominant leg at 125 watts. The significant improvements seen at 125 watts, the highest workload measured in this study, mirror previous studies on economy, which saw the greatest improvements at the highest intensities measured (Cadore et al., 2010; Cadore et al., 2011a; Häkkinen & Komi, 1982; Komi et al., 1978). Similar to the strength measures, adaptations in neuromuscular economy appear to be specific to the intensity of training. Further analysis through magnitude-based inferences revealed *Likely Positive* or *Very Likely Positive* effects of URT on most NME values of the dominant and nondominant legs, except for $NME75RF_{DOM}$, $NME100RF_{DOM}$, $NME100VL_{NON}$, and NME125RFNON. NME is a function of both submaximal and maximal EMG values; therefore, a decrease can occur with either a decrease in submaximal EMG or an increase in maximal EMG. Previous research on NME has defined it as the “lower muscle activation, represented by EMG signal amplitude, necessary to perform the same absolute load” (Cadore et al., 2011a). In the current study, a consistent increase in maximal EMG was observed with no significant changes in submaximal EMG. These results indicate that URT did not decrease submaximal muscle activation, but rather increased maximal muscle activation. Based on these results, NME should be defined as an individual’s relative muscle recruitment needed to complete a task. While the current investigation provides evidence that there may be a cross education of NME, it is most likely due to an increase in maximal recruitment of the untrained musculature rather than a decrease in submaximal recruitment. If this is the case, then the primary adaptations that occurred during the four weeks of URT in this study are related to increased neural drive in both the trained and untrained limb.

After examination of NME across the three submaximal cycling workloads, a significant decrease in the slope of the regression line after training was observed in the RF of the trained leg. Additionally, there was a *Likely Positive* effect of URT on the slope of the NME/workload relationship of the dominant VL. These results show that URT may decrease the rise in NME across increasing workloads. Previous work on NME of the VL has not reported slope values, but can be calculated from the presented data to be approximately 0.292 (Cadore et al., 2011a). Interestingly, the slope dropped to 0.226 after 12 weeks of resistance training (Cadore et al., 2011a). The slope of the currently reported pre-test NME for the VL when pooling both groups was 0.170. The reason for the lower slope is most likely due to the differences in the populations and relative workloads for these two studies. The current study examined untrained young adult males while the other study examined untrained older adult males. Future research should compare the age-related differences in NME.

In this study, NME does appear to improve with URT in the VL and RF of both the dominant and nondominant legs. However, with no changes in submaximal recruitment, the improvement in NME is most likely due to an increase in maximal EMG.

Future Research

This study has led to numerous questions that should be addressed in future research. Being one of the first studies to use dynamic URT to produce cross education, it will be important to determine how adjusting various training program variables will impact cross education. Comparing programs focused on high intensity or high volume protocols may provide more information on how to achieve the greatest cross education.

In the current study, the magnitude of cross education in young adult males was explored, but future studies should examine the practical applications of URT in both men and women. URT may be useful for injured athletes who are immobilized in one limb. Previous research has shown that URT can attenuate the loss of muscular strength and size of a casted arm (Farthing, 2009). Another population which could utilize URT would be individuals who have suffered a stroke and are currently suffering from a loss of strength and function on one side of their body. Training the unaffected side of the body may results in strength improvements on the affected side and, ultimately, improve quality of life.

Summary

In conclusion, this study showed that four weeks of dynamic URT resulted in increased strength and maximal EMG activity in both the trained and untrained legs. Furthermore, it appears that the cross education of strength is specific to the modality in which the contralateral limb was trained. The increase in maximal EMG activity may impact NME in both the trained and untrained legs more than submaximal EMG recruitment. The improvement in NME without consistent decreases in submaximal EMG recruitment implies that NME is a measure of relative activation as opposed to the previously stated “lower muscle activation” by Cadore et al (Cadore et al., 2011a). These results show that URT can be an effective means of improving the strength and neuromuscular activation of both the trained and untrained legs.

APPENDIX A: FIGURES

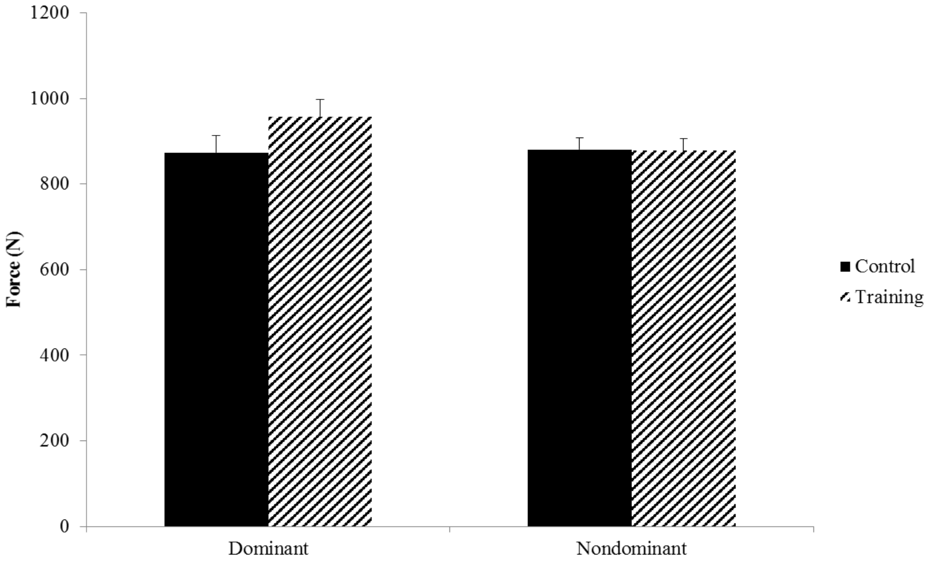


Figure 1: Adjusted mean values (+SEM) for posttest Peak Force of the Dominant and Nondominant Leg adjusted for the initial differences in pretest Peak Force (covariate; adjusted pretest mean=892.76 and 862.38, respectively). No significant differences between groups for the initial differences in pretest Peak Force (covariate; adjusted pretest mean=892.76 and 862.38, respectively). No significant differences between groups for Peak Force (p=.188 and .948, respectively).

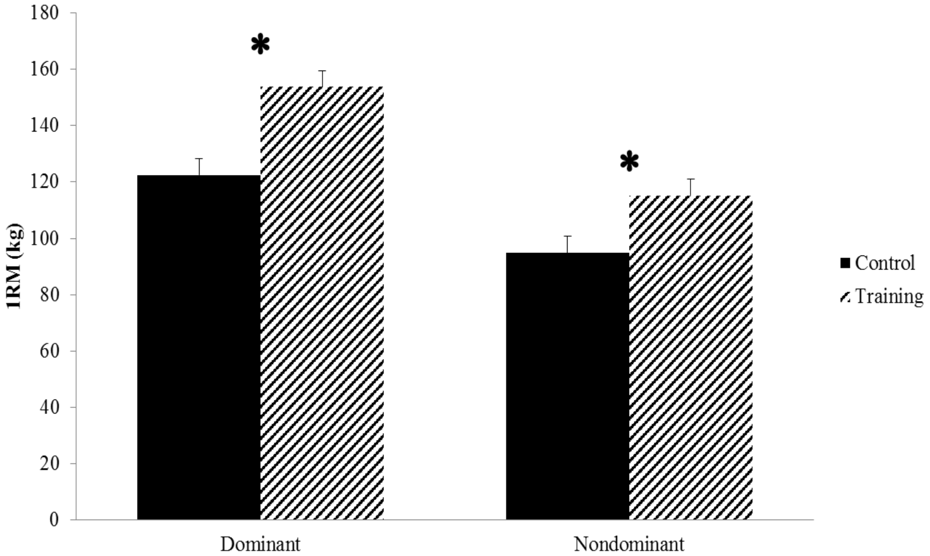


Figure 2: Adjusted mean values (+SEM) for posttest Leg Press of the Dominant and Nondominant Leg adjusted for the initial differences in pretest Leg Press (covariate; adjusted pretest mean=100.36 and 86.32, respectively). *Significant differences between groups in Leg Press for the Dominant and Nondominant legs (p=.003 and .034, respectively).

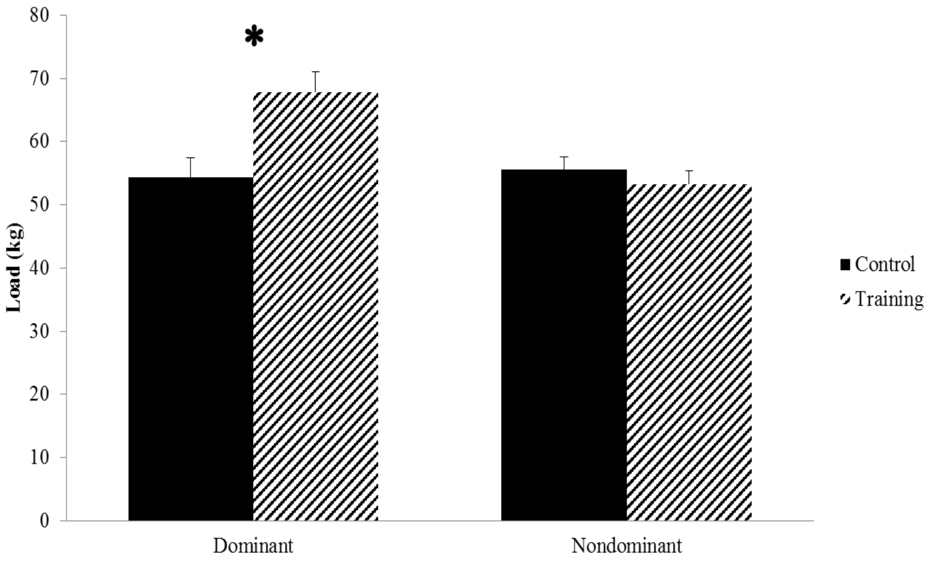


Figure 3: Adjusted mean values (+SEM) for posttest Leg Extension of the Dominant and Nondominant Leg adjusted for the initial differences in pretest Leg Extension (covariate; adjusted pretest mean=49.89 and 48.90, respectively). *Significant differences between groups in Leg Extension for the Nondominant leg (p=.482).

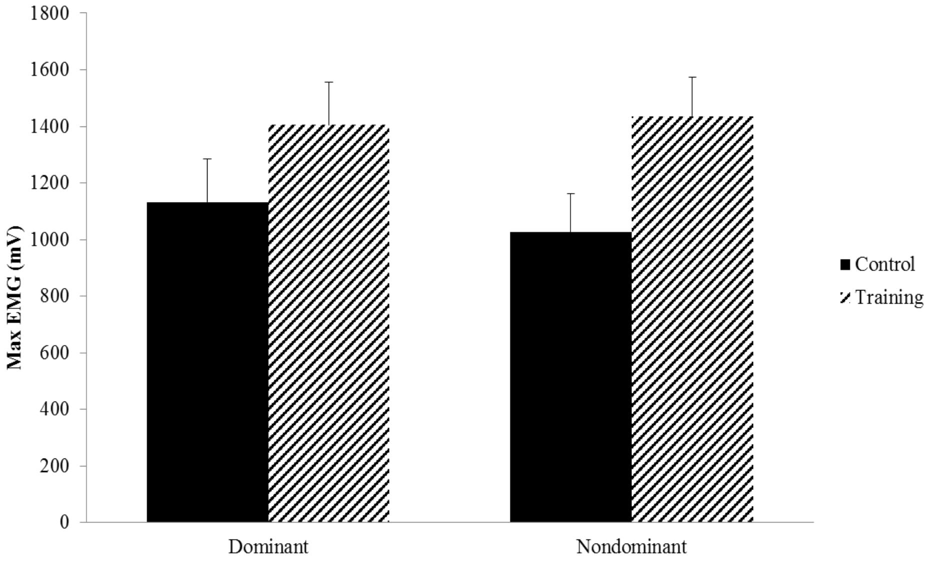


Figure 4: Adjusted mean values (+SEM) for posttest Max EMG VL of the Dominant and Nondominant Leg adjusted for the initial differences in pretest Max EMG VL (covariate; adjusted pretest mean=1122.40 and 1129.36, respectively). No significant differences between groups in Max EMG VL for the Dominant and Nondominant leg (p=.248 and .062, respectively).

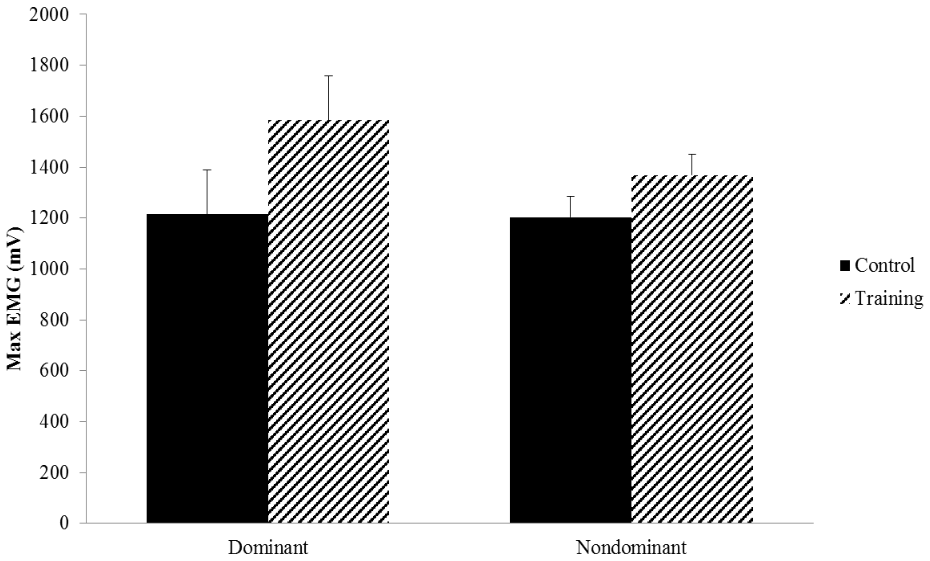


Figure 5: Adjusted mean values (+SEM) for posttest Max EMG RF of the Dominant and Nondominant Leg adjusted for the initial differences in pretest Max EMG RF (covariate; adjusted pretest mean=1337.39 and 1310.07, respectively). No significant differences between groups in Max EMG RF for the Dominant and Nondominant leg (p=.162 and .179, respectively).

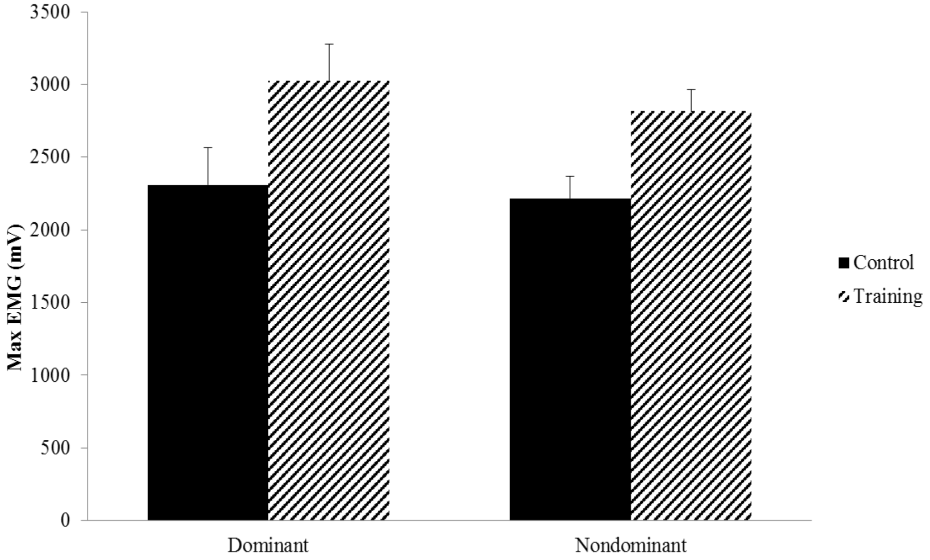


Figure 6: Adjusted mean values (+SEM) for posttest Max EMG Total of the Dominant and Nondominant leg adjusted for the initial differences in pretest Max EMG Total (covariate; adjusted pretest mean=2459.80 and 2439.42, respectively). *Significant differences between groups in Max EMG Total for the Nondominant leg (p=.016). No significant differences between groups in Max EMG Total for the Dominant leg (p=.075).

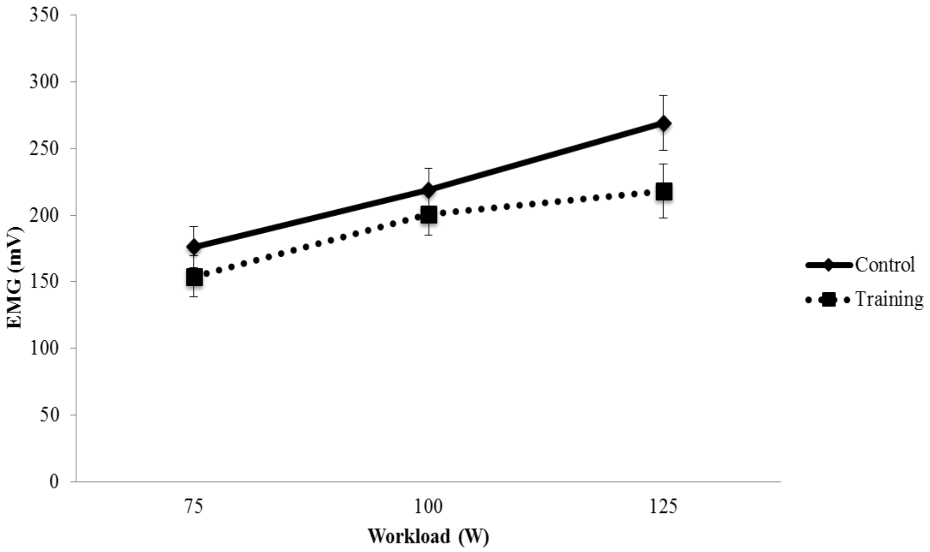


Figure 7: Adjusted mean values (+SEM) for posttest Submaximal EMG of the VL of the Dominant leg adjusted for the initial differences in pretest Submaximal EMG of the VL (covariate; adjusted pretest mean=148.16, 185.94 and 243.88, respectively). No significant differences between groups in Submaximal EMG of the VL for the Dominant leg (p=.339, .446 and .107, respectively).

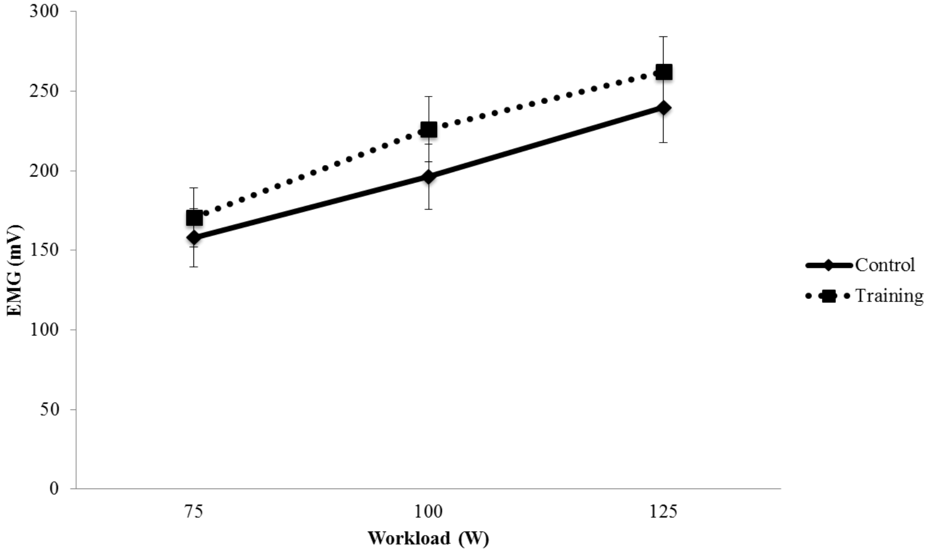


Figure 8: Adjusted mean values (+SEM) for posttest Submaximal EMG of the VL of the Nondominant leg adjusted for the initial differences in pretest Submaximal EMG of the VL (covariate; adjusted pretest mean=152.92, 193.17 and 241.63, respectively). No significant differences between groups in Submaximal EMG of the VL for the Nondominant leg (p=.638, .328 and .490, respectively).

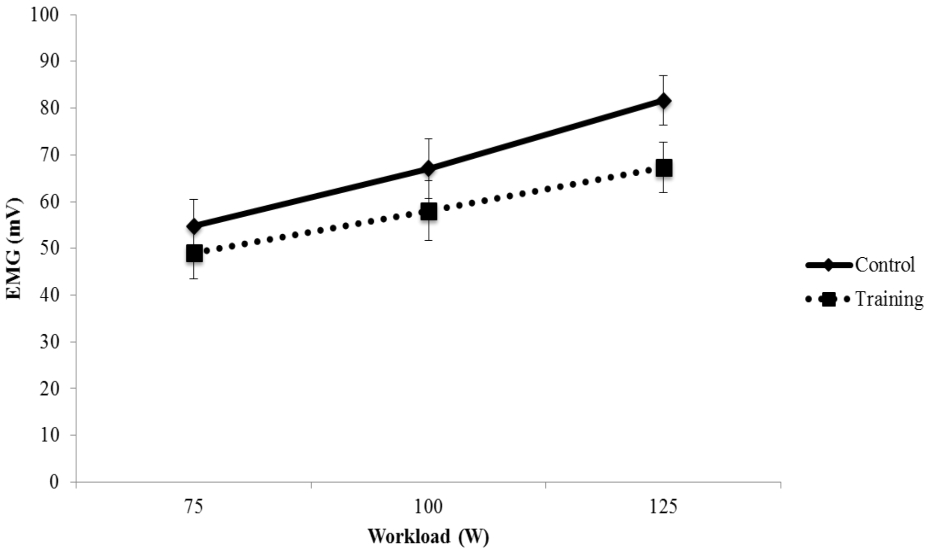


Figure 9: Adjusted mean values (+SEM) for posttest Submaximal EMG of the RF of the Dominant leg adjusted for the initial differences in pretest Submaximal EMG of the RF (covariate; adjusted pretest mean=63.65, 74.68 and 90.83, respectively). No significant differences between groups in Submaximal EMG of the RF for the Dominant leg (p=.493, .336 and .084, respectively).

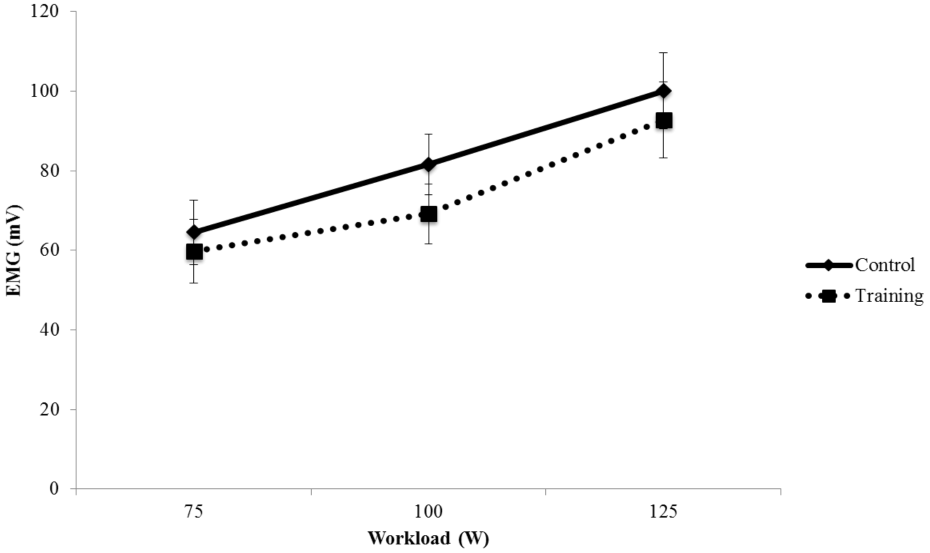


Figure 10: Mean values (+SEM) for posttest Submaximal EMG of the RF of the Nondominant leg adjusted for the initial differences in pretest Submaximal EMG of the RF (covariate; adjusted pretest mean=69.79, 81.65 and 99.79, respectively). No significant differences between groups in Submaximal EMG of the RF for the Nondominant leg (p=.704, .281 and .603, respectively).

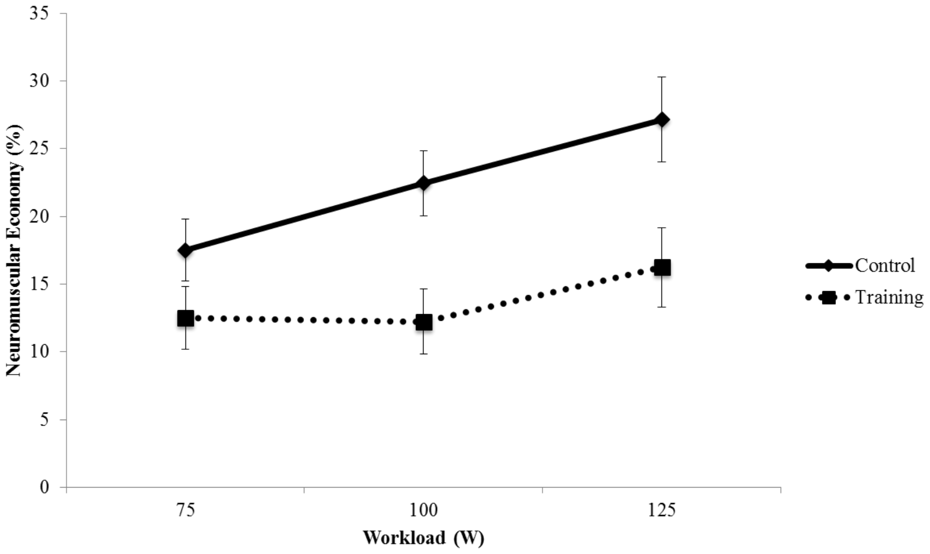


Figure 11: Adjusted mean values (+SEM) for posttest NME of the VL of the Dominant Leg at all workloads adjusted for the initial differences in pretest NME (covariate; adjusted pretest mean=13.87, 17.21, and 22.65, respectively). *Significant differences between groups in NME of the VL at 75W or 100W or in NME Slope (p=.166, .064 and .205, respectively).

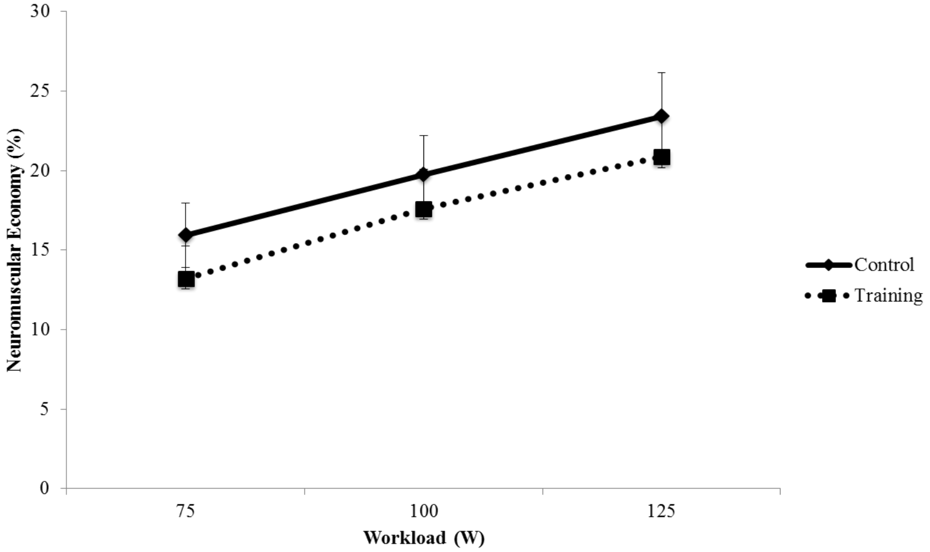


Figure 12: Adjusted mean values (+SEM) for posttest NME of the VL of the Nondominant Leg at all workloads adjusted for the initial differences in pretest NME (covariate; adjusted pretest mean=15.08, 18.60, and 23.64, respectively). No significant differences between groups in NME of the VL at 75W, 100W or 125W or in NME Slope (p=.394, .564, .532 and .354, respectively)

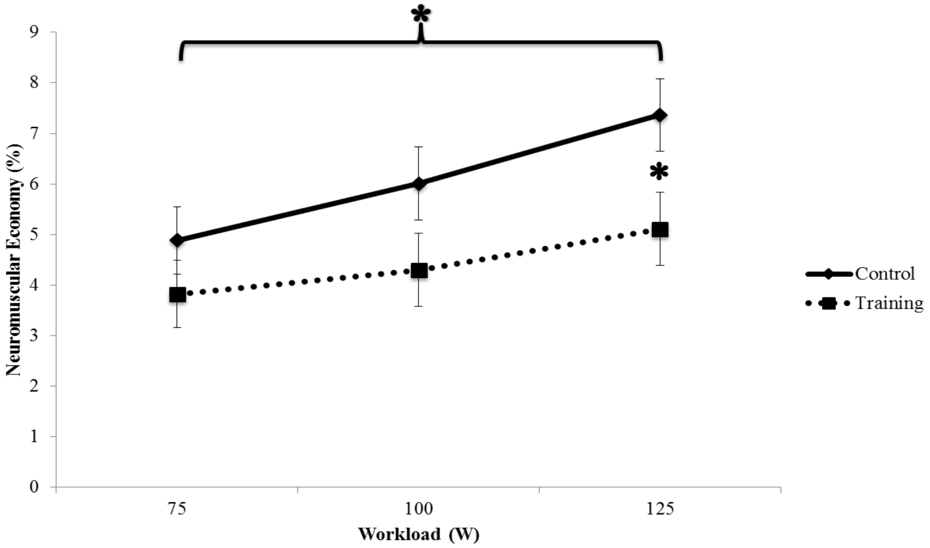


Figure 13: Adjusted mean values (+SEM) for posttest NME of the RF of the Dominant Leg at all workloads adjusted for the initial differences in pretest NME (covariate; adjusted pretest mean=5.69, 6.57, and 7.57, respectively). *Significant differences between groups in NME of the RF at 125W and NME Slope (p=.046 and .017, respectively). No significant differences between groups in NME of the RF at 75W or 100W (p=.279 and .120, respectively).

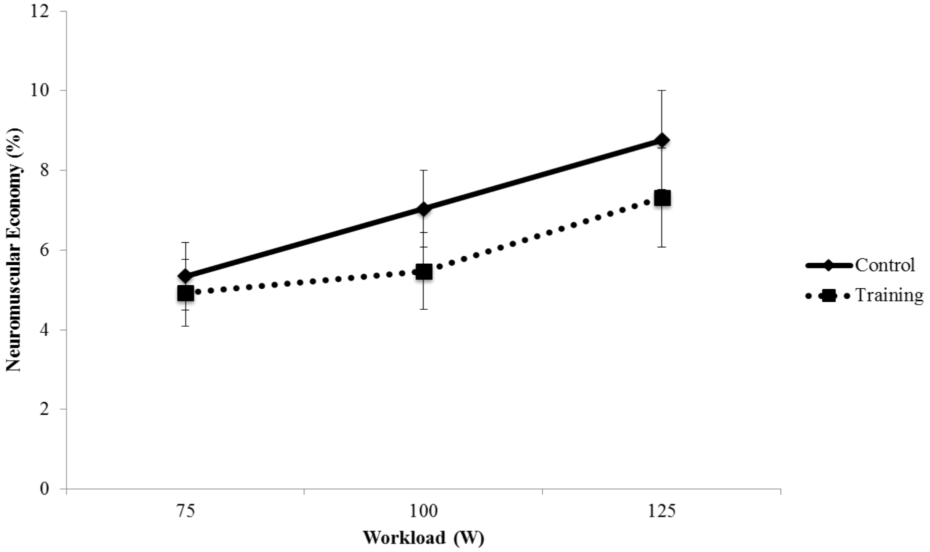


Figure 14: Adjusted mean values (+SEM) for posttest NME of the RF of the Nondominant Leg at all workloads adjusted for the initial differences in pretest NME (covariate; adjusted pretest mean=5.85, 6.75, and 8.09, respectively). No significant differences between groups in NME of the RF at 75W, 100W or 125W or in NME Slope (p=.756, .298, .435 and .680, respectively)

APPENDIX B: TABLES

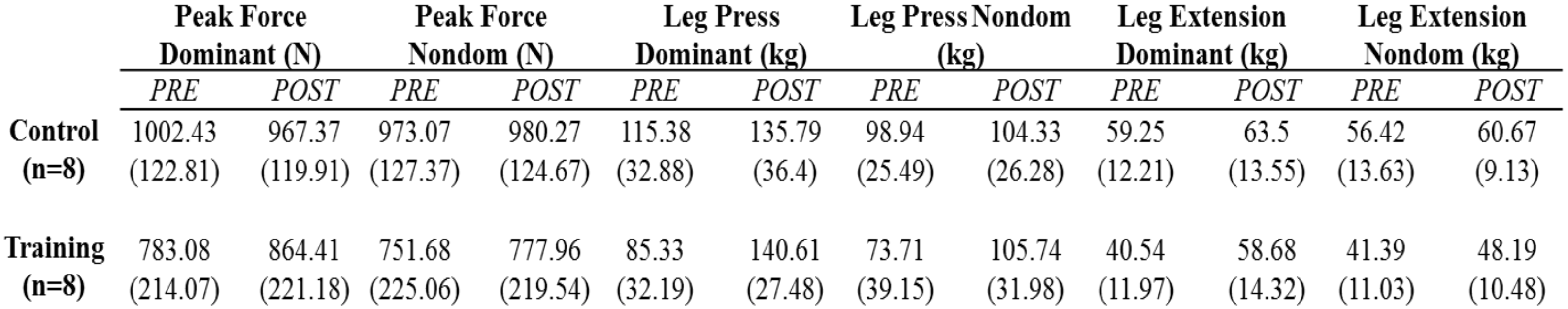
Table 1: Unilateral resistance training session

Exercise	Sets	Repetition Range	Intensity
Unilateral Jumps	3	8	-
Unilateral Leg Press	3	8-10	80% 1RM
Chest Press	3	8-10	80% 1RM
Unilateral Leg Extension	3	8-10	80% 1RM
Seated Row	3	8-10	80% 1RM

Table 2: Participant characteristics expressed as mean and (standard deviation)

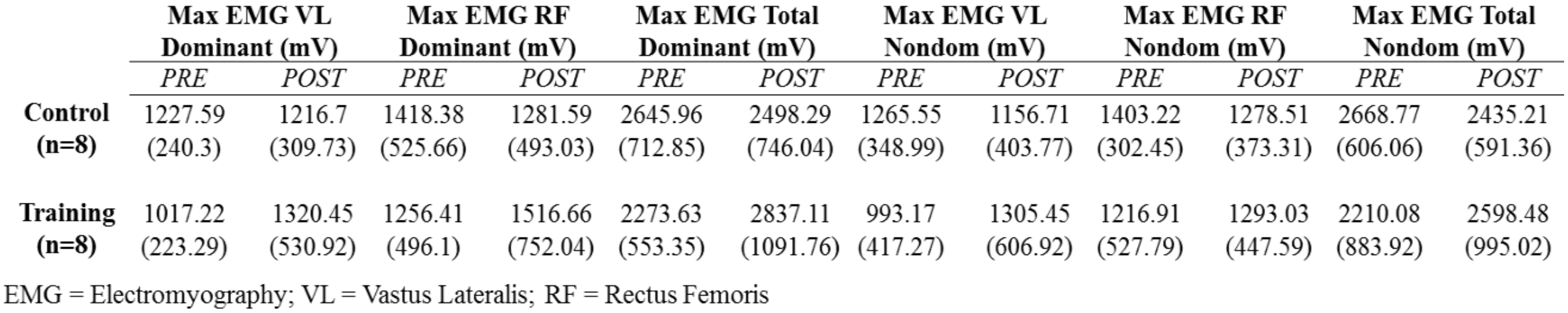
	Age (y)	Height (m)	Weight (kg)
Control (n=8)	24.00 (4.57)	1.84 (0.05)	94.21 (16.14)
Training (n=8)	22.38 (2.92)	1.73 (0.08)	75.26 (14.53)

Table 3: Mean and (SD) for all absolute strength values. Pre- and post-testing values for both the Control and Training groups are displayed.



	Peak Force Dominant (N)		Peak Force Nondom (N)		Leg Press Dominant (kg)		Leg Press Nondom (kg)		Leg Extension Dominant (kg)		Leg Extension Nondom (kg)	
	PRE	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*
Control (n=8)	1002.43 (122.81)	967.37 (119.91)	973.07 (127.37)	980.27 (124.67)	115.38 (32.88)	135.79 (36.4)	98.94 (25.49)	104.33 (26.28)	59.25 (12.21)	63.5 (13.55)	56.42 (13.63)	60.67 (9.13)
Training (n=8)	783.08 (214.07)	864.41 (221.18)	751.68 (225.06)	777.96 (219.54)	85.33 (32.19)	140.61 (27.48)	73.71 (39.15)	105.74 (31.98)	40.54 (11.97)	58.68 (14.32)	41.39 (11.03)	48.19 (10.48)

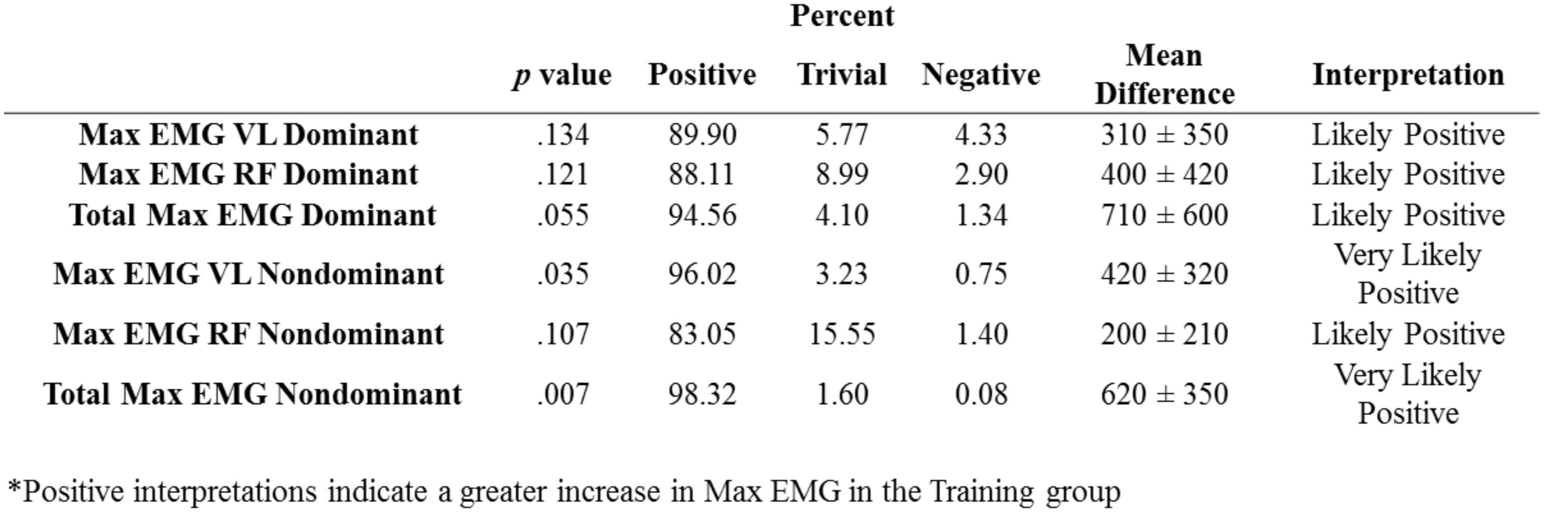
Table 4: Mean and (SD) for all Max EMG values. Pre- and post-testing values for both the Control and Training groups are displayed.



	Max EMG VL Dominant (mV)		Max EMG RF Dominant (mV)		Max EMG Total Dominant (mV)		Max EMG VL Nondom (mV)		Max EMG RF Nondom (mV)		Max EMG Total Nondom (mV)	
	PRE	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*
Control (n=8)	1227.59 (240.3)	1216.7 (309.73)	1418.38 (525.66)	1281.59 (493.03)	2645.96 (712.85)	2498.29 (746.04)	1265.55 (348.99)	1156.71 (403.77)	1403.22 (302.45)	1278.51 (373.31)	2668.77 (606.06)	2435.21 (591.36)
Training (n=8)	1017.22 (223.29)	1320.45 (530.92)	1256.41 (496.1)	1516.66 (752.04)	2273.63 (553.35)	2837.11 (1091.76)	993.17 (417.27)	1305.45 (606.92)	1216.91 (527.79)	1293.03 (447.59)	2210.08 (883.92)	2598.48 (995.02)

EMG = Electromyography; VL = Vastus Lateralis; RF = Rectus Femoris

Table 5: Magnitude-Based Inferences comparing the changes in Max EMG (mV) values between Control and Training groups.



			Percent			
	***p* value**	**Positive**	**Trivial**	**Negative**	**Mean Difference**	**Interpretation**
Max EMG VL Dominant	.134	89.90	5.77	4.33	310 ± 350	Likely Positive
Max EMG RF Dominant	.121	88.11	8.99	2.90	400 ± 420	Likely Positive
Total Max EMG Dominant	.055	94.56	4.10	1.34	710 ± 600	Likely Positive
Max EMG VL Nondominant	.035	96.02	3.23	0.75	420 ± 320	Very Likely Positive
Max EMG RF Nondominant	.107	83.05	15.55	1.40	200 ± 210	Likely Positive
Total Max EMG Nondominant	.007	98.32	1.60	0.08	620 ± 350	Very Likely Positive

*Positive interpretations indicate a greater increase in Max EMG in the Training group

Table 6: Mean and (SD) for all submaximal EMG values for the dominant leg. Pre- and post-testing values for both the Control and Training groups are displayed.

	75 VL Dominant (mV)		**100 VL Dominant (mV)**		**125 VL Dominant (mV)**		**75 RF Dominant (mV)**		**100 RF Dominant (mV)**		**125 RF Dominant (mV)**	
	PRE	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*
Control (n=8)	133.18 (59.23)	165.20 (60.89)	174.26 (65.04)	207.06 (82.81)	224.47 (83.97)	252.91 (97.84)	65.81 (29.06)	55.19 (20.93)	77.61 (25.00)	67.73 (21.21)	96.82 (28.17)	84.79 (24.54)
Training (n=8)	163.13 (69.40)	164.69 (63.82)	197.63 (70.08)	212.65 (78.66)	263.29 (67.60)	234.17 (66.35)	61.48 (23.66)	48.75 (9.06)	71.76 (23.81)	57.44 (14.14)	84.83 (20.06)	64.14 (11.82)

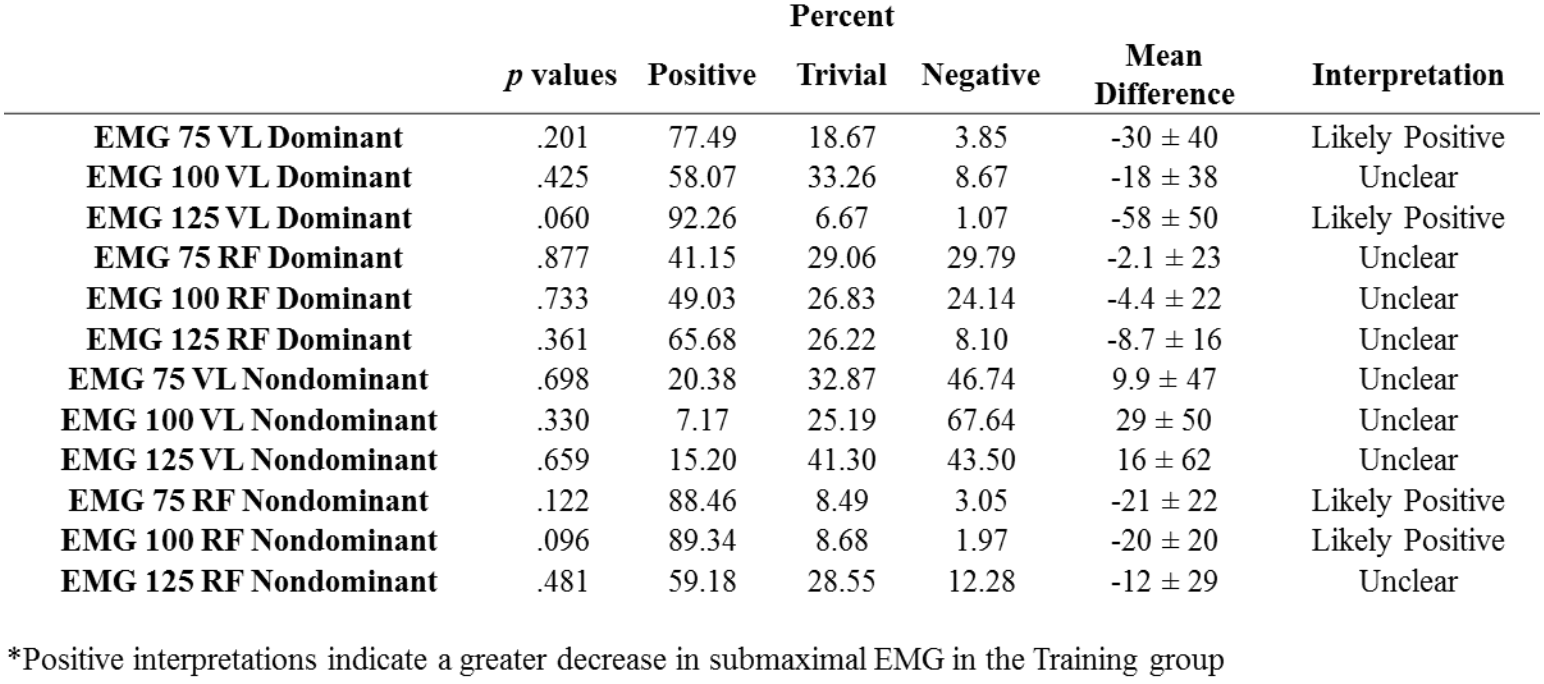
EMG = Electromyography; VL = Vastus Lateralis; RF = Rectus Femoris

Table 7: Mean and (SD) for all submaximal EMG values for the nondominant leg. Pre- and post-testing values for both the Control and Training groups are displayed.

	75 VL Nondom (mV)		**100 VL Nondom (mV)**		**125 VLNondom (mV)**		**75 RF Nondom (mV)**		**100 RF Nondom (mV)**		**125 RF Nondom (mV)**	
	PRE	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*
Control (n=8)	137.82 (52.26)	144.26 (55.38)	188.54 (76.82)	192.28 (72.16)	231.36 (104.91)	232.78 (84.21)	57.87 (14.62)	60.50 (25.15)	72.13 (20.16)	76.00 (28.73)	94.97 (34.12)	97.62 (35.45)
Training (n=8)	168.03 (66.29)	184.32 (87.28)	197.79 (81.21)	230.05 (104.68)	251.90 (118.14)	269.14 (108.29)	81.71 (27.23)	63.83 (17.44)	91.16 (31.64)	74.73 (21.16)	104.61 (48.07)	95.23 (31.32)

EMG = Electromyography; VL = Vastus Lateralis; RF = Rectus Femoris

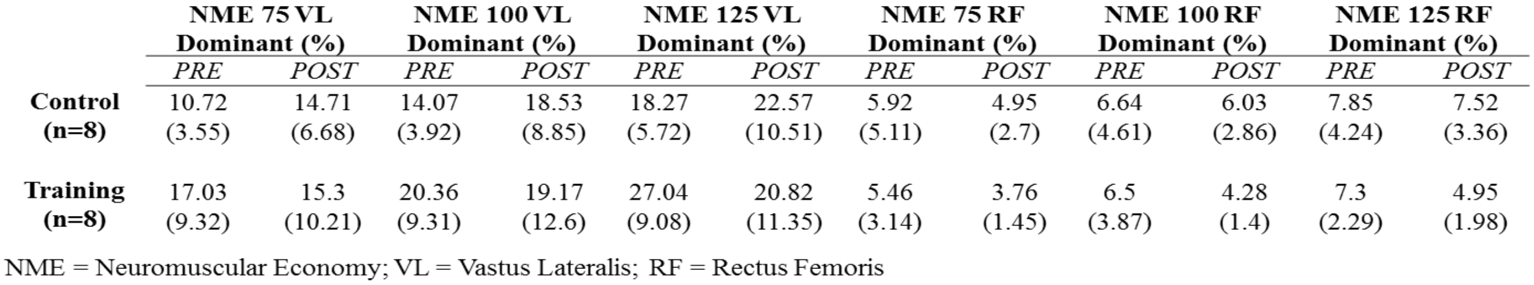
Table 8: Magnitude-Based Inferences comparing the changes in submaximal EMG (mV) values between Control and Training groups.



	p values	Percent Positive	Trivial	Negative	Mean Difference	Interpretation
EMG 75 VL Dominant	.201	77.49	18.67	3.85	-30 ± 40	Likely Positive
EMG 100 VL Dominant	.425	58.07	33.26	8.67	-18 ± 38	Unclear
EMG 125 VL Dominant	.060	92.26	6.67	1.07	-58 ± 50	Likely Positive
EMG 75 RF Dominant	.877	41.15	29.06	29.79	-2.1 ± 23	Unclear
EMG 100 RF Dominant	.733	49.03	26.83	24.14	-4.4 ± 22	Unclear
EMG 125 RF Dominant	.361	65.68	26.22	8.10	-8.7 ± 16	Unclear
EMG 75 VL Nondominant	.698	20.38	32.87	46.74	9.9 ± 47	Unclear
EMG 100 VL Nondominant	.330	7.17	25.19	67.64	29 ± 50	Unclear
EMG 125 VL Nondominant	.659	15.20	41.30	43.50	16 ± 62	Unclear
EMG 75 RF Nondominant	.122	88.46	8.49	3.05	-21 ± 22	Likely Positive
EMG 100 RF Nondominant	.096	89.34	8.68	1.97	-20 ± 20	Likely Positive
EMG 125 RF Nondominant	.481	59.18	28.55	12.28	-12 ± 29	Unclear

*Positive interpretations indicate a greater decrease in submaximal EMG in the Training group

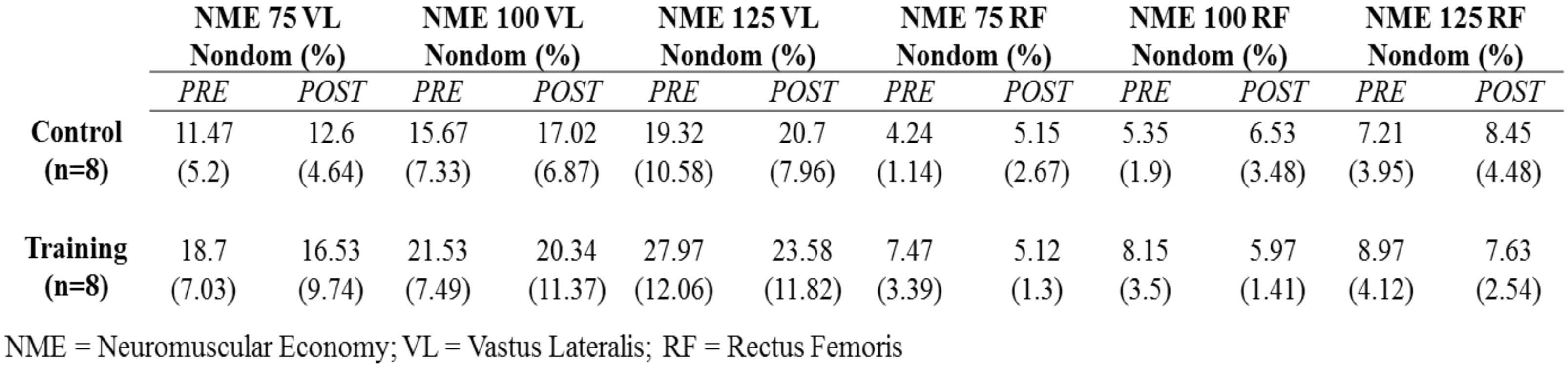
Table 9: Mean and (SD) for all neuromuscular economy values for the dominant leg. Pre- and post-testing values for both the Control and Training groups are displayed.



	NME 75 VL Dominant (%)		NME 100 VL Dominant (%)		NME 125 VL Dominant (%)		NME 75 RF Dominant (%)		NME 100 RF Dominant (%)		NME 125 RF Dominant (%)	
	PRE	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*
Control (n=8)	10.72 (3.55)	14.71 (6.68)	14.07 (3.92)	18.53 (8.85)	18.27 (5.72)	22.57 (10.51)	5.92 (5.11)	4.95 (2.7)	6.64 (4.61)	6.03 (2.86)	7.85 (4.24)	7.52 (3.36)
Training (n=8)	17.03 (9.32)	15.3 (10.21)	20.36 (9.31)	19.17 (12.6)	27.04 (9.08)	20.82 (11.35)	5.46 (3.14)	3.76 (1.45)	6.5 (3.87)	4.28 (1.4)	7.3 (2.29)	4.95 (1.98)

NME = Neuromuscular Economy; VL = Vastus Lateralis; RF = Rectus Femoris

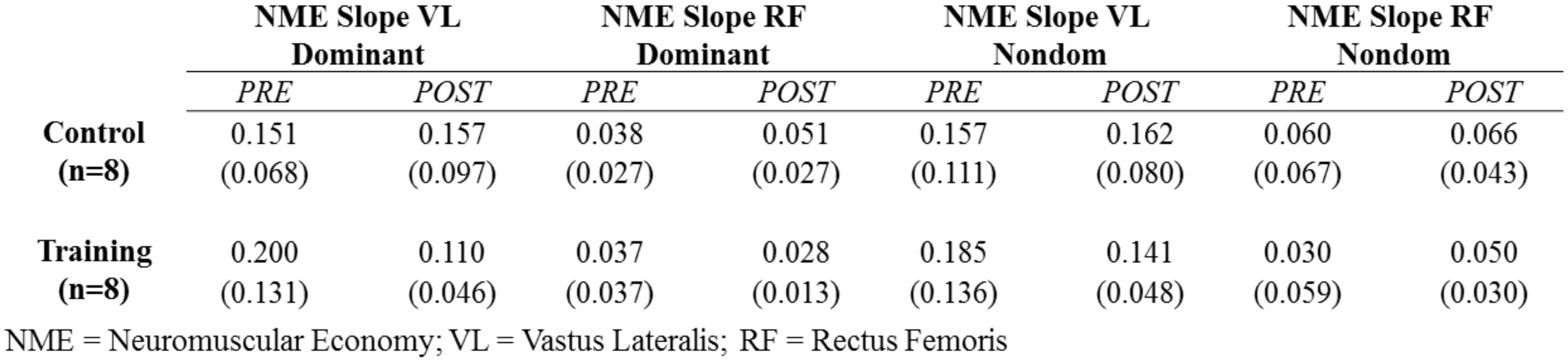
Table 10: Mean and (SD) for all neuromuscular economy values for the nondominant leg. Pre- and post-testing values for both the Control and Training groups are displayed.



	NME 75 VL Nondom (%)		NME 100 VL Nondom (%)		NME 125 VL Nondom (%)		NME 75 RF Nondom (%)		NME 100 RF Nondom (%)		NME 125 RF Nondom (%)	
	PRE	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*
Control (n=8)	11.47 (5.2)	12.6 (4.64)	15.67 (7.33)	17.02 (6.87)	19.32 (10.58)	20.7 (7.96)	4.24 (1.14)	5.15 (2.67)	5.35 (1.9)	6.53 (3.48)	7.21 (3.95)	8.45 (4.48)
Training (n=8)	18.7 (7.03)	16.53 (9.74)	21.53 (7.49)	20.34 (11.37)	27.97 (12.06)	23.58 (11.82)	7.47 (3.39)	5.12 (1.3)	8.15 (3.5)	5.97 (1.41)	8.97 (4.12)	7.63 (2.54)

NME = Neuromuscular Economy; VL = Vastus Lateralis; RF = Rectus Femoris

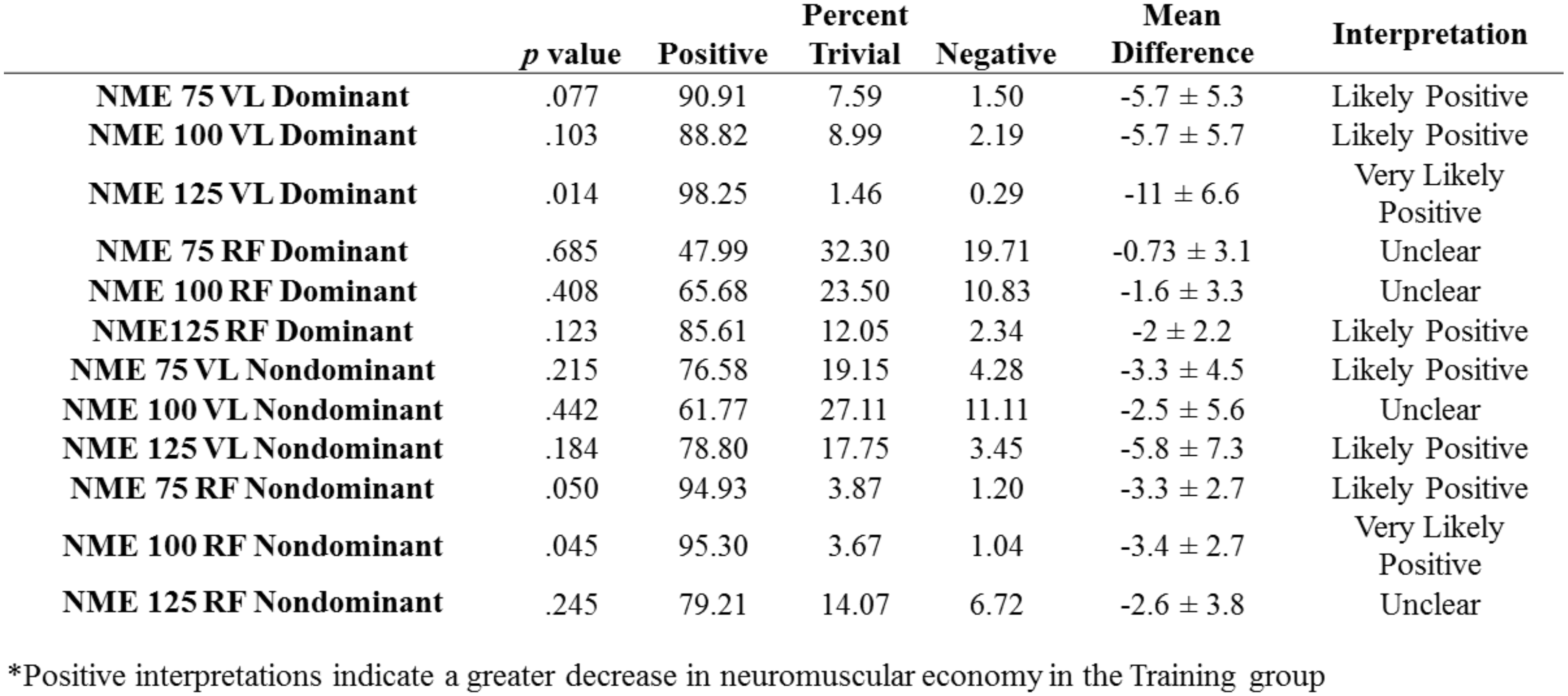
Table 11: Mean and (SD) for all neuromuscular economy slope values. Pre- and post-testing values for both the Control and Training groups are displayed.



	NME Slope VL Dominant		**NME Slope RF Dominant**		**NME Slope VL Nondom**		**NME Slope RF Nondom**	
	PRE	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*
Control (n=8)	0.151 (0.068)	0.157 (0.097)	0.038 (0.027)	0.051 (0.027)	0.157 (0.111)	0.162 (0.080)	0.060 (0.067)	0.066 (0.043)
Training (n=8)	0.200 (0.131)	0.110 (0.046)	0.037 (0.037)	0.028 (0.013)	0.185 (0.136)	0.141 (0.048)	0.030 (0.059)	0.050 (0.030)

NME = Neuromuscular Economy; VL = Vastus Lateralis; RF = Rectus Femoris

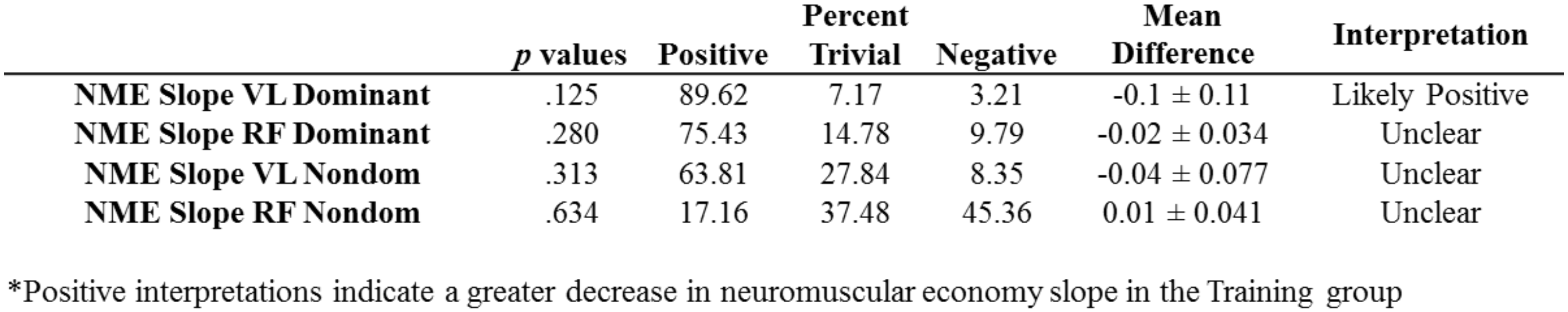
Table 12: Magnitude-Based Inferences comparing the changes in neuromuscular economy (%) values between Control and Training groups.



	p value	Positive	Percent Trivial	Negative	Mean Difference	Interpretation
NME 75 VL Dominant	.077	90.91	7.59	1.50	-5.7 ± 5.3	Likely Positive
NME 100 VL Dominant	.103	88.82	8.99	2.19	-5.7 ± 5.7	Likely Positive
NME 125 VL Dominant	.014	98.25	1.46	0.29	-11 ± 6.6	Very Likely Positive
NME 75 RF Dominant	.685	47.99	32.30	19.71	-0.73 ± 3.1	Unclear
NME 100 RF Dominant	.408	65.68	23.50	10.83	-1.6 ± 3.3	Unclear
NME125 RF Dominant	.123	85.61	12.05	2.34	-2 ± 2.2	Likely Positive
NME 75 VL Nondominant	.215	76.58	19.15	4.28	-3.3 ± 4.5	Likely Positive
NME 100 VL Nondominant	.442	61.77	27.11	11.11	-2.5 ± 5.6	Unclear
NME 125 VL Nondominant	.184	78.80	17.75	3.45	-5.8 ± 7.3	Likely Positive
NME 75 RF Nondominant	.050	94.93	3.87	1.20	-3.3 ± 2.7	Likely Positive
NME 100 RF Nondominant	.045	95.30	3.67	1.04	-3.4 ± 2.7	Very Likely Positive
NME 125 RF Nondominant	.245	79.21	14.07	6.72	-2.6 ± 3.8	Unclear

*Positive interpretations indicate a greater decrease in neuromuscular economy in the Training group

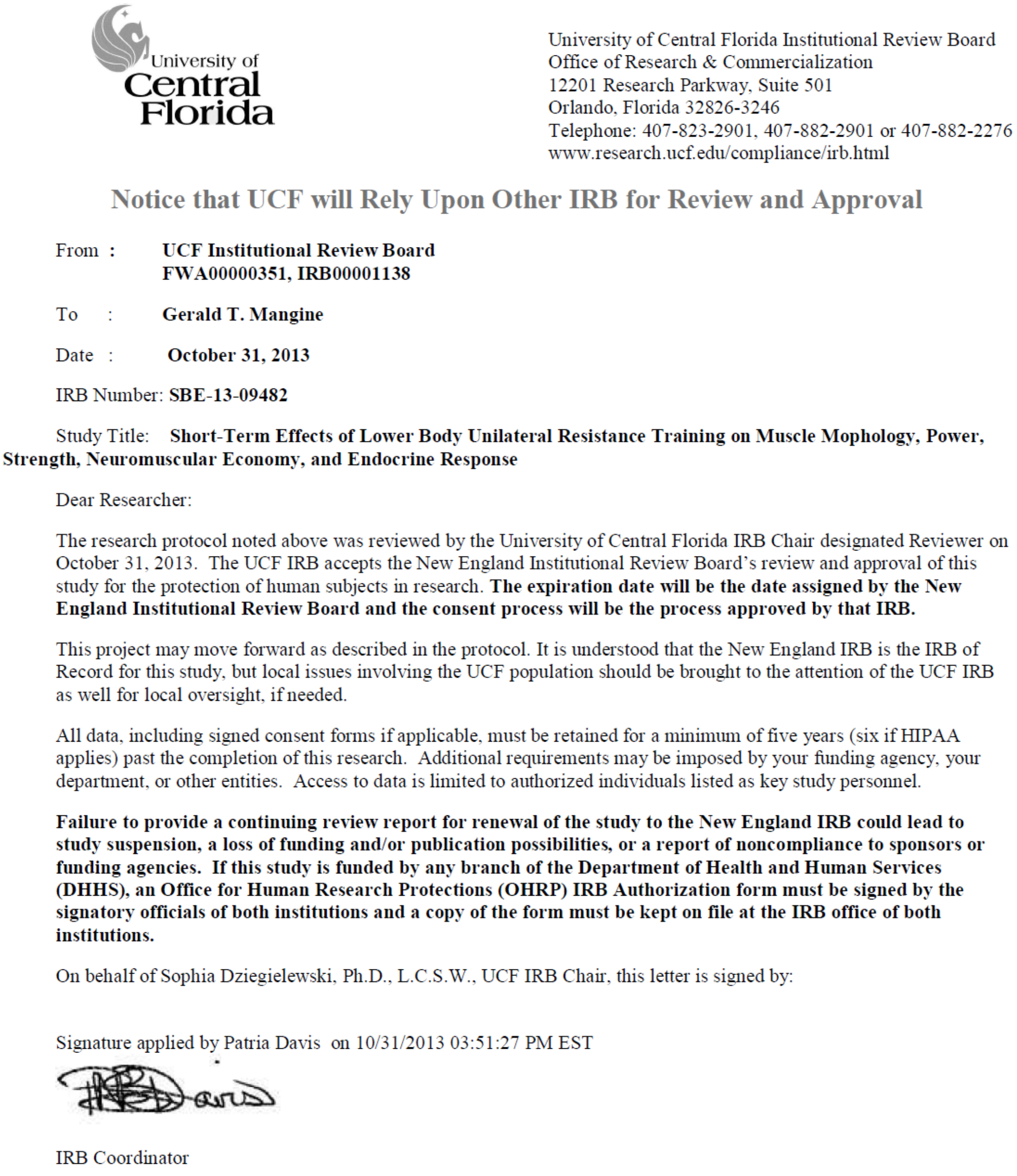
Table 13: Magnitude-Based Inferences comparing the changes in neuromuscular economy slope values between Control and Training groups.



	p values	Positive	Percent Trivial	Negative	Mean Difference	Interpretation
NME Slope VL Dominant	.125	89.62	7.17	3.21	-0.1 ± 0.11	Likely Positive
NME Slope RF Dominant	.280	75.43	14.78	9.79	-0.02 ± 0.034	Unclear
NME Slope VL Nondom	.313	63.81	27.84	8.35	-0.04 ± 0.077	Unclear
NME Slope RF Nondom	.634	17.16	37.48	45.36	0.01 ± 0.041	Unclear

*Positive interpretations indicate a greater decrease in neuromuscular economy slope in the Training group

APPENDIX C: IRB APPROVAL



University of Central Florida

University of Central Florida Institutional Review Board
Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901, 407-882-2901 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

Notice that UCF will Rely Upon Other IRB for Review and Approval

From : **UCF Institutional Review Board**
FWA00000351, IRB00001138

To : **Gerald T. Mangine**

Date : **October 31, 2013**

IRB Number: **SBE-13-09482**

Study Title: **Short-Term Effects of Lower Body Unilateral Resistance Training on Muscle Mophology, Power, Strength, Neuromuscular Economy, and Endocrine Response**

Dear Researcher:

The research protocol noted above was reviewed by the University of Central Florida IRB Chair designated Reviewer on October 31, 2013. The UCF IRB accepts the New England Institutional Review Board's review and approval of this study for the protection of human subjects in research. **The expiration date will be the date assigned by the New England Institutional Review Board and the consent process will be the process approved by that IRB.**

This project may move forward as described in the protocol. It is understood that the New England IRB is the IRB of Record for this study, but local issues involving the UCF population should be brought to the attention of the UCF IRB as well for local oversight, if needed.

All data, including signed consent forms if applicable, must be retained for a minimum of five years (six if HIPAA applies) past the completion of this research. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

Failure to provide a continuing review report for renewal of the study to the New England IRB could lead to study suspension, a loss of funding and/or publication possibilities, or a report of noncompliance to sponsors or funding agencies. If this study is funded by any branch of the Department of Health and Human Services (DHHS), an Office for Human Research Protections (OHRP) IRB Authorization form must be signed by the signatory officials of both institutions and a copy of the form must be kept on file at the IRB office of both institutions.

On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

Signature applied by Patria Davis on 10/31/2013 03:51:27 PM EST

IRB Coordinator

NEIRB
New England Institutional
Review Board

September 13, 2013

Gerald Mangine
University of Central Florida
12494 University Boulevard
Orlando, FL 32816

Re: **NEIRB # 13-266** SBE-13-09482 "Short-Term Effects of Lower Body Unilateral Resistance Training on Muscle Morphology, Power, Strength, Neuromuscular Economy, and Endocrine Response" and Amendment 1 dated September 10, 2013

Date of Amendment Approval: September 13, 2013

Dear Mr. Mangine:

This is to inform you that New England Institutional Review Board (NEIRB), via Expedited Review, Thursday Board, has reviewed **Amendment #1 dated September 10, 2013** for the above-captioned study. The changes to the study have been approved.

Please find the revised Informed Consent document, NEIRB version 2.0 enclosed. You will note that the date at the bottom right hand corner indicates an updated approval date of 9/13/2013. Only NEIRB-approved informed consent documents should be used. It must be signed by each subject who will participate in this study prior to the initiation of any protocol procedures. In addition, each subject must be given a copy of the signed consent form.

New England IRB has determined that all currently active subjects must be re-consented with the revised consent form.

The approval period for the study ends on 8/4/2014. Any additional modifications in the research protocol, study site/ personnel, or consent form during this time period must first be reviewed and approved by NEIRB.

Please feel free to call me if you have any questions.

Sincerely,

Shana R. Ross

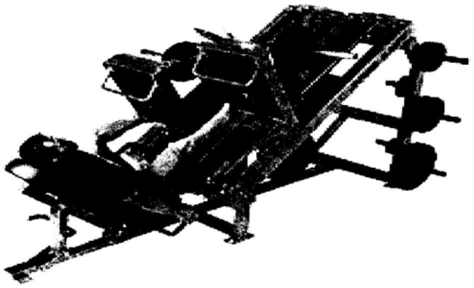
Shana R. Ross, MCJ, CIM, CIP
Lead Administrator

cc: NEIRB Chair

APPENDIX D: RECRUITMENT FLYER

VOLUNTEERS NEEDED FOR RESEARCH STUDY

"Short-Term Effects of Lower Body Unilateral Resistance Training with Colostrum Supplementation on Muscle Morphology, Power, Strength, Neuromuscular Economy, and Endocrine Response"



Description of Project:

We are investigating the effects of unilateral resistance training with and without protein supplementation on the musculature and neuromuscular performance of the leg.

Who is Eligible?

Men between the ages of 18-35 who have not previously engaged in any resistance training

What will you be asked to do?

- Complete 4 testing sessions (2 pre and 2 post)
- Complete 4 weeks of resistance training (3 sessions per week; 30 mins each)
- Ingest a placebo or protein supplement (depending on group) for 28 days

Compensation:

Participants will receive a $100 gift card for completion of the study.

To learn more, contact the principal investigators of the study, Kyle Beyer & Carleigh Boone, at 407-823-4470 or humanperformancelab@ucf.edu.

This research is conducted under the direction of Dr. Jeffrey Stout, Educational and Human Sciences Department, and has been reviewed and approved by the New England Institutional Review Board.

Approved by NEIRB on 9/17/13
As Is [✓] As Revised___ Initials

APPENDIX E: IRB FORM

VOLUNTEER'S STATEMENT:

I agree that I have been given a chance to ask questions about this research study. These questions have been answered to my satisfaction. I may contact Mr. Mangine if I have any more questions about taking part in this study. Mr. Mangine or the company he/she is employed by is being paid by the sponsor for my participation in this study.

My participation in this research project is voluntary. I may quit the study at any time without harming my future medical care or losing any benefits to which I might be entitled. The investigator in charge of this study may decide at any time that I should no longer participate in this study.

If I have questions about my rights as a research subject, other concerns about the research, or I am unable to reach the investigator, I can contact:

New England Institutional Review Board

Telephone: 1-800-232-9570

By signing this form, I have not waived any of my legal rights.

I agree to participate in this study. I will be given a copy of this signed and dated form for my own records.

______________________________ Study Participant (signature)	________ Date
______________________________ Print Participant's Name	
______________________________ Person who explained this study (signature)	________ Date

Approved by NEIRB on 9/13/2013
NEIRB ICF Version 2.0

APPENDIX F: PHYSICAL ACTIVITY READINESS QUESTIONNAIRE

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO		
☐	☐	**1.**	**Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?**
☐	☐	**2.**	**Do you feel pain in your chest when you do physical activity?**
☐	☐	**3.**	**In the past month, have you had chest pain when you were not doing physical activity?**
☐	☐	**4.**	**Do you lose your balance because of dizziness or do you ever lose consciousness?**
☐	☐	**5.**	**Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?**
☐	☐	**6.**	**Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
☐	☐	**7.**	**Do you know of any other reason why you should not do physical activity?**

If you answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

→

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME ____

SIGNATURE ____

DATE ____

SIGNATURE OF PARENT ____
or GUARDIAN (for participants under the age of majority)

WITNESS ____

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.

CSEP | SCPE

APPENDIX G: MEDICAL AND ACTIVITY HISTORY QUESTIONNAIRE

Human Performance Laboratory
University of Central Florida

Confidential Medical and Activity History Questionnaire

Participant #__________

When was your last physical examination? __________________________________

1. **List any medications, herbals or supplements you currently take or have taken the last month**:

Medication	Reason for medication
________________________	________________________
________________________	________________________
________________________	________________________
________________________	________________________

2. **Are you allergic to any medications? If yes, please list medications and reaction**.

3. **Please list any allergies, including food allergies that you may have?**

4. **Have you ever been hospitalized? If yes, please explain**.

Year of hospitalization	Reason
________________________	________________________
________________________	________________________
________________________	________________________

5. **Illnesses and other Health Issues**

List any chronic (long-term) illnesses that have caused you to seek medical care.

Have you ever had (or do you have now) any of the following. Please circle questions that you do not know the answer to.

Sickle cell anemia	yes	no
Cystic fibrosis	yes	no
Water retention problems	yes	no
Heart pacemaker	yes	no
Epilepsy	yes	no
Convulsions	yes	no
Dizziness/fainting/unconsciousness	yes	no
Asthma	yes	no
Shortness of breath	yes	no
Chronic respiratory disorder	yes	no
Chronic headaches	yes	no
Chronic cough	yes	no
Chronic sinus problem	yes	no
High blood pressure	yes	no
Heart murmur	yes	no
Heart attack	yes	no
High cholesterol	yes	no
Diabetes mellitus or insipidus	yes	no
Rheumatic fever	yes	no
Emphysema	yes	no
Bronchitis	yes	no
Hepatitis	yes	no
Kidney disease	yes	no
Bladder problems	yes	no
Tuberculosis (positive skin test)	yes	no
Yellow jaundice	yes	no
Auto immune deficiency	yes	no
Anemia	yes	no
Endotoxemia	yes	no
Thyroid problems	yes	no
Hyperprolactinemia	yes	no
Anorexia nervosa	yes	no
Bulimia	yes	no
Stomach/intestinal problems	yes	no
Arthritis	yes	no
Back pain	yes	no
Gout	yes	no
Hepatic encephalopathy	yes	no
Mania	yes	no
Hypermania	yes	no
Monosodium glutamate hypersensitivity	yes	no
Seizure disorders	yes	no

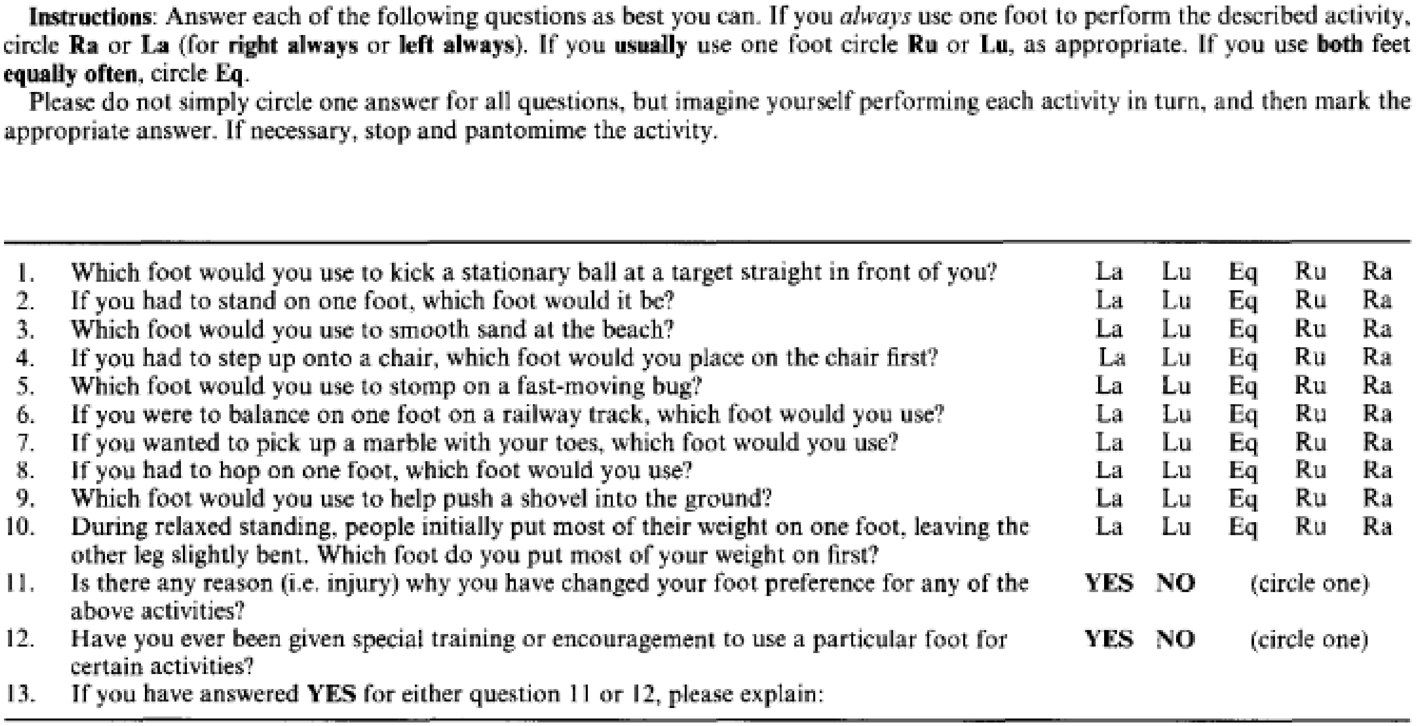
Any others (specify):____
____
____

Do you smoke cigarettes or use any other tobacco products?	yes	no
Do you have a history of drug or alcohol dependency?	yes	no
Do you ever have any pain in your chest?	yes	no
Are you ever bothered by racing of your heart?	yes	no
Do you ever notice abnormal or skipped heartbeats?	yes	no
Do you ever have any arm or jaw discomfort, nausea, Or vomiting associated with cardiac symptoms?	yes	no
Do you ever have difficulty breathing?	yes	no
Do you ever experience shortness of breath?	yes	no
Do you ever become dizzy during exercise?	yes	no
Are you pregnant?	yes	no
Is there a chance that you may be pregnant?	yes	no
Have you ever had any tingling or numbness in your arms or legs?	yes	no
Has a member of your family or close relative died of heart problems or sudden death before the age of 50?	yes	no
Has a health care practitioner ever denied or restricted your participation in sports for any problem	yes	no

If yes, please explain: ____
____

Are you presently taking any nutritional supplements or ergogenic aids? (if yes, please detail. ____
____
____
____
____

APPENDIX H: WATERLOO FOOTEDNESS QUESTIONNAIRE



Instructions: Answer each of the following questions as best you can. If you *always* use one foot to perform the described activity, circle **Ra** or **La** (for **right always** or **left always**). If you **usually** use one foot circle **Ru** or **Lu**, as appropriate. If you use **both** feet **equally often**, circle **Eq**.

Please do not simply circle one answer for all questions, but imagine yourself performing each activity in turn, and then mark the appropriate answer. If necessary, stop and pantomime the activity.

1.	Which foot would you use to kick a stationary ball at a target straight in front of you?	La	Lu	Eq	Ru	Ra
2.	If you had to stand on one foot, which foot would it be?	La	Lu	Eq	Ru	Ra
3.	Which foot would you use to smooth sand at the beach?	La	Lu	Eq	Ru	Ra
4.	If you had to step up onto a chair, which foot would you place on the chair first?	La	Lu	Eq	Ru	Ra
5.	Which foot would you use to stomp on a fast-moving bug?	La	Lu	Eq	Ru	Ra
6.	If you were to balance on one foot on a railway track, which foot would you use?	La	Lu	Eq	Ru	Ra
7.	If you wanted to pick up a marble with your toes, which foot would you use?	La	Lu	Eq	Ru	Ra
8.	If you had to hop on one foot, which foot would you use?	La	Lu	Eq	Ru	Ra
9.	Which foot would you use to help push a shovel into the ground?	La	Lu	Eq	Ru	Ra
10.	During relaxed standing, people initially put most of their weight on one foot, leaving the other leg slightly bent. Which foot do you put most of your weight on first?	La	Lu	Eq	Ru	Ra
11.	Is there any reason (i.e. injury) why you have changed your foot preference for any of the above activities?	**YES**	**NO**		(circle one)	
12.	Have you ever been given special training or encouragement to use a particular foot for certain activities?	**YES**	**NO**		(circle one)	
13.	If you have answered **YES** for either question 11 or 12, please explain:					

APPENDIX I: DIETARY RECALL

Food Record Sheet

Subj#:_______________ **Date:**___________

Day 1

Time	**FOOD/BEVERAGE DESCRIPTION**	**AMOUNT**	**Total kcal** *(from label)*

Day 2

Time	**FOOD/BEVERAGE DESCRIPTION**	**AMOUNT**	**Total kcal** *(from label)*

Day 3

Time	**FOOD/BEVERAGE DESCRIPTION**	**AMOUNT**	**Total kcal** *(from label)*

APPENDIX J: DATA COLLECTION SHEET

Unilateral Resistance Training Data Collection Sheet

Subject #:		**Date:**		**Time:**		**Testing Session:**	PRE	POST
Group:		**Height:**	cm	**Weight:**	kg	**Dom Leg:**	L	R

MVC	Left Leg			Right Leg		
	T1	T2	T3	T1	T2	T3
Peak Torque						

EMG & Neuromuscular Economy

CH5: CH6: CH9: CH10: Bike Trial Order:

		Left		Right	
		Vastus Lateralis	Rectus Femoris	Vastus Lateralis	Rectus Femoris
Max Trial 1	**File**				
Max Trial 2	**File**				
Max Trial 3	**File**				
75 Watts	**File**				
100 Watts	**File**				
125 Watts	**File**				
NME75					
NME100					
NME125					

Comments:

1 Repetition Maximum

	Right				**Left**				**Upper Body**			
	Leg Press		Leg Extension		Leg Press		Leg Extension		Chest Press		Low Row	
Set	Load	Reps	Load	Reps	Load	Reps	Load	Reps	Load	Reps	Load	Reps
1												
2												
3												
4												
5												
6												
1RM												

APPENDIX K: TRAINING LOG

Subject #: ____________ Dominant Leg: _________ Week #: ____________

1 Repetition Maximums

Leg Press: Chest Press: Leg Extension: Low Row:

80% 1RM

Leg Press: Chest Press: Leg Extension: Low Row:

Date: ________________ Trainer: ____________

	Set 1 (80% X 8-10 Reps)	Set 2 (80% X 8-10 Reps)	Set 3 (80% X 8-10 Reps)
Unilateral Leg Press	X	X	X
Chest Press	X	X	X
Unilateral Leg Extension	X	X	X
Low Row	X	X	X
Single Leg Jumps			

90 Seconds Rest

NOTES:

Date: ________________ Trainer: ____________

	Set 1 (80% X 8-10 Reps)	Set 2 (80% X 8-10 Reps)	Set 3 (80% X 8-10 Reps)
Unilateral Leg Press	X	X	X
Chest Press	X	X	X
Unilateral Leg Extension	X	X	X
Low Row	X	X	X
Single Leg Jumps			

90 Seconds Rest

NOTES:

Date: ________________ Trainer: ____________

	Set 1 (80% X 8-10 Reps)	Set 2 (80% X 8-10 Reps)	Set 3 (80% X 8-10 Reps)
Unilateral Leg Press	X	X	X
Chest Press	X	X	X
Unilateral Leg Extension	X	X	X
Low Row	X	X	X
Single Leg Jumps			

90 Seconds Rest

NOTES:

REFERENCES

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, S. P., Halkjaer-Kristensen, J., & Dyhre-Poulsen, P. (2000). Neural inhibition during maximal eccentric and concentric quadriceps contraction: Effects of resistance training. *Journal of Applied Physiology (Bethesda, Md.: 1985), 89*(6), 2249-2257.

Bryden, Lorin J Elias MP. (1998). Footedness is a better predictor of language lateralisation than handedness. *Laterality: Asymmetries of Body, Brain and Cognition, 3*(1), 41-52.

Cadore, E. L., Izquierdo, M., Pinto, S. S., Alberton, C. L., Pinto, R. S., Baroni, B. M., . . . González-Izal, M. (2012). Neuromuscular adaptations to concurrent training in the elderly: Effects of intrasession exercise sequence. *Age,* , 1-13.

Cadore, E. L., Pinto, R. S., Pinto, S. S., Alberton, C. L., Correa, C. S., Tartaruga, M. P., . . . Kruel, L. F. (2011a). Effects of strength, endurance, and concurrent training on aerobic power and dynamic neuromuscular economy in elderly men. *The Journal of Strength & Conditioning Research, 25*(3), 758-766.

Cadore, E. L., Pinto, R. S., Alberton, C. L., Pinto, S. S., Lhullier, F. L. R., Tartaruga, M. P., . . . Laitano, O. (2011b). Neuromuscular economy, strength, and endurance in healthy elderly men. *The Journal of Strength & Conditioning Research, 25*(4), 997.

Cadore, E. L., Pinto, R., Lhullier, F., Correa, C., Alberton, C., Pinto, S., . . . Kruel, L. (2010). Physiological effects of concurrent training in elderly men. *International Journal of Sports Medicine, 31*(10), 689.

Carolan, B., & Cafarelli, E. (1992). Adaptations in coactivation after isometric resistance training. *Journal of Applied Physiology, 73*(3), 911-917.

Carroll, T. J., Herbert, R. D., Munn, J., Lee, M., & Gandevia, S. C. (2006). Contralateral effects of unilateral strength training: Evidence and possible mechanisms. *Journal of Applied Physiology, 101*(5), 1514-1522.

Coburn, J. W., Housh, D. J., Housh, T. J., Malek, M. H., Beck, T. W., Cramer, J. T., . . . Donlin, P. E. (2006). Effects of leucine and whey protein supplementation during eight weeks of unilateral resistance training. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 20*(2), 284-291. doi:R-17925 [pii]

Dudley, G. A., Tesch, P. A., Miller, B. J., & Buchanan, P. (1991). Importance of eccentric actions in performance adaptations to resistance training. *Aviation, Space, and Environmental Medicine, 62*(6), 543-550.

Evetovich, T. K., Housh, T. J., Housh, D. J., Johnson, G. O., Smith, D. B., & Ebersole, K. T. (2001). The effect of concentric isokinetic strength training of the quadriceps femoris on electromyography and muscle strength in the trained and untrained limb. *The Journal of Strength & Conditioning Research, 15*(4), 439-445.

Farthing, J. P. (2009). Cross-education of strength depends on limb dominance: Implications for theory and application. *Exercise and Sport Sciences Reviews, 37*(4), 179-187.

Farthing, J. P., Borowsky, R., Chilibeck, P. D., Binsted, G., & Sarty, G. E. (2007). Neuro-physiological adaptations associated with cross-education of strength. *Brain Topography, 20*(2), 77-88.

Farthing, J. P., Chilibeck, P. D., & Binsted, G. (2005). Cross-education of arm muscular strength is unidirectional in right-handed individuals. *Medicine and Science in Sports and Exercise, 37*(9), 1594.

Farthing, J. P., Krentz, J. R., Magnus, C. R., Barss, T. S., Lanovaz, J. L., Cummine, J., . . . Borowsky, R. (2011). Changes in functional magnetic resonance imaging cortical activation with cross education to an immobilized limb. *Med Sci Sports Exerc, 43*(8), 1394-1405.

Fimland, M. S., Helgerud, J., Solstad, G. M., Iversen, V. M., Leivseth, G., & Hoff, J. (2009). Neural adaptations underlying cross-education after unilateral strength training. *European Journal of Applied Physiology, 107*(6), 723-730.

Gabriel, D. A., Kamen, G., & Frost, G. (2006). Neural adaptations to resistive exercise. *Sports Medicine, 36*(2), 133-149.

Garfinkel, S., & Cafarelli, E. (1992). Relative changes in maximal force, EMG, and muscle cross-sectional area after isometric training. *Medicine and Science in Sports and Exercise, 24*(11), 1220-1227.

Häkkinen, K., & Komi, P. V. (1982). Electromyographic changes during strength training and detraining. *Medicine and Science in Sports and Exercise, 15*(6), 455-460.

Hermens, H. J., Freriks, B., Merletti, R., Stegeman, D., Blok, J., Rau, G., . . . Hägg, G. (1999). *European recommendations for surface electromyography* Roessingh Research and Development The Netherlands.

Hoffman, J. R., Wendell, M., Cooper, J., & Kang, J. (2003). Comparison between linear and nonlinear in-season training programs in freshman football players. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 17*(3), 561-565.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise, 41*(1), 3.

Hortobagyi, T., Scott, K., Lambert, J., Hamilton, G., & Tracy, J. (1999). Cross-education of muscle strength is greater with stimulated than voluntary contractions. *Motor Control, 3*(2), 205.

Hortobagyi, T., Lambert, N. J., & Hill, J. P. (1997). Greater cross education following training with muscle lengthening than shortening. *Medicine and Science in Sports and Exercise, 29*, 107-112.

Houston, M., Froese, E., St P, V., Green, H., & Ranney, D. (1983). Muscle performance, morphology and metabolic capacity during strength training and detraining: A one leg model. *European Journal of Applied Physiology and Occupational Physiology, 51*(1), 25-35.

Kamen, G., & Knight, C. A. (2004). Training-related adaptations in motor unit discharge rate in young and older adults. *The Journals of Gerontology.Series A, Biological Sciences and Medical Sciences, 59*(12), 1334-1338. doi:59/12/1334 [pii]

Kannus, P., Alosa, D., Cook, L., Johnson, R., Renström, P., Pope, M., . . . Kaplan, M. (1992). Effect of one-legged exercise on the strength, power and endurance of the contralateral leg. *European Journal of Applied Physiology and Occupational Physiology, 64*(2), 117-126.

Khouw, W., & Herbert, R. (1998). Optimisation of isometric strength training intensity. *The Australian Journal of Physiotherapy, 44*(1), 43-46.

Knight, C., & Kamen, G. (2001). Adaptations in muscular activation of the knee extensor muscles with strength training in young and older adults. *Journal of Electromyography and Kinesiology, 11*(6), 405-412.

Komi, P., Viitasalo, J., Rauramaa, R., & Vihko, V. (1978). Effect of isometric strength training on mechanical, electrical, and metabolic aspects of muscle function. *European Journal of Applied Physiology and Occupational Physiology, 40*(1), 45-55.

Lee, M., & Carroll, T. J. (2007). Cross education. *Sports Medicine, 37*(1), 1-14.

Lee, M., Gandevia, S. C., & Carroll, T. J. (2009). Unilateral strength training increases voluntary activation of the opposite untrained limb. *Clinical Neurophysiology, 120*(4), 802-808.

Milner-Brown, H., & Lee, R. (1975). Synchronization of human motor units: Possible roles of exercise and supraspinal reflexes. *Electroencephalography and Clinical Neurophysiology, 38*(3), 245-254.

Moritani, T. (1979). Neural factors versus hypertrophy in the time course of muscle strength gain. *American Journal of Physical Medicine & Rehabilitation, 58*(3), 115-130.

Morrissey, M. C., Harman, E. A., & Johnson, M. J. (1995). Resistance training modes: Specificity and effectiveness. *Medicine and Science in Sports and Exercise, 27*(5), 648-660.

Munn, J., Herbert, R. D., Hancock, M. J., & Gandevia, S. C. (2005). Training with unilateral resistance exercise increases contralateral strength. *Journal of Applied Physiology, 99*(5), 1880-1884.

Nardone, A., Romano, C., & Schieppati, M. (1989). Selective recruitment of high-threshold human motor units during voluntary isotonic lengthening of active muscles. *The Journal of Physiology, 409*, 451-471.

Narici, M., Roi, G., Landoni, L., Minetti, A., & Cerretelli, P. (1989). Changes in force, cross-sectional area and neural activation during strength training and detraining of the human quadriceps. *European Journal of Applied Physiology and Occupational Physiology, 59*(4), 310-319.

Ploutz, L. L., Tesch, P. A., Biro, R. L., & Dudley, G. A. (1994). Effect of resistance training on muscle use during exercise. *Journal of Applied Physiology, 76*(4), 1675-1681.

Shaver, L. G. (1970). Effects of training on relative muscular endurance in ipsilateral and contralateral arms. *Med Sci Sports, 2*, 165-171.

Shaver, L., G. (1975). Cross transfer effects of conditioning and deconditioning on muscular strength. *Ergonomics, 18*(1), 9-16.

Shima, N., Ishida, K., Katayama, K., Morotome, Y., Sato, Y., & Miyamura, M. (2002). Cross education of muscular strength during unilateral resistance training and detraining. *European Journal of Applied Physiology, 86*(4), 287-294.

Tillin, N. A., Pain, M. T., & Folland, J. P. (2011). Short-term unilateral resistance training affects the agonist–antagonist but not the force–agonist activation relationship. *Muscle & Nerve, 43*(3), 375-384.

Tracy, B., Ivey, F., Hurlbut, D., Martel, G., Lemmer, J., Siegel, E., . . . Hurley, B. (1999). Muscle quality. II. effects of strength training in 65-to 75-yr-old men and women. *Journal of Applied Physiology, 86*(1), 195-201.

Yue, G., & Cole, K. J. (1992). Strength increases from the motor program: Comparison of training with maximal voluntary and imagined muscle contractions. *Journal of Neurophysiology, 67*(5), 1114-1123.

Zhou, S., Oakman, A., & Davie, A. J. (2002). Effects of unilateral voluntary and electromyostimulation training on muscular strength on the contralateral limb. *School of Health and Human Sciences Papers,* , 455.

Zijdewind, I., & Kernell, D. (2001). Bilateral interactions during contractions of intrinsic hand muscles. *Journal of Neurophysiology, 85*(5), 1907-1913.