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Bilateral deficit: A comparison between upper-body and lower-body maximal strength

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Bilateral Deficit: A Comparison Between Upper-Body and Lower-Body Maximal Strength

by

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Dedication

I would like to dedicate this thesis to my amazing family. First, to my beautiful wife, Zena, who has provided me the love and support that I needed to help me get through the difficult obstacles that I had to overcome during this project. Next, I wish to dedicate this to project to my family members who I lost during the course of this project. Although you are gone, you will forever be in my heart and your important life lessons will live on.

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Structured Abstract

Purpose: The study's primary purpose was to determine if maximal unilateral strength is greater than maximal bilateral strength for the leg press and vertical dumbbell press exercises. The secondary purpose was to determine if blood glucose levels differ between the unilateral and bilateral conditions for the leg press exercise. Methods: Thirty college-aged volunteers reported on two separate occasions, 72 hours apart, for maximal strength testing. Blood glucose was obtained before and after strength testing for the leg press exercise. A paired samples t-test was conducted to determine significance ($p < .05$). Results: Participants were significantly stronger for the bilateral leg press; however, no significant differences were observed for the vertical dumbbell press exercise. No significant differences were observed in plasma blood glucose for the leg press exercise. Conclusion: Participants did not display a bilateral lateral deficit, which may have been a result of their resistance training prior to the study.

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Chapter 1: Introduction

In order for athletes to realize their maximum potential for their particular sport, it is important that their resistance training (RT) program elicits the greatest adaptations. However, there are questions regarding which training methods are most effective in order to elicit the necessary adaptations (Nijem & Galpin, 2014). Recently, unilateral training (ULT), or the use of one limb at a time, has been suggested by some strength and conditioning professionals to be a superior method for eliciting strength gains. This suggestion is based on a limited number of studies that have demonstrated a bilateral deficit (BLD). Simply stated, the BLD is a phenomenon in which the maximal voluntary strength of both limbs contracting simultaneously is less than the sum of the weight lifted by the left and right limbs contracting in isolation (Costa, Moreira, Cavalcanti, Krinski, & Aoki, 2015). However, training recommendations to improve sports performance based on the BLD are not currently possible because the effect of this particular phenomenon on athletics is not well understood (Škarabot, Cronin, Strojnik, & Avela, 2016).

Overview of the Problem

The National Strength and Conditioning Association (NSCA) defines resistance training (RT) as a "specialized form of conditioning involving the progressive use of a wide range of resistive loads and a variety of training modalities designed to enhance health, fitness, and sports performance" (Faigenbaum et al., 2009, p. 60). With that being said, RT is frequently utilized by strength and conditioning professionals because of its effectiveness for improving athletic performance. Specifically, the improvements in performance that athletes experience as a result of the adaptations following RT include increases in: muscular strength, power and speed, hypertrophy, local muscular endurance, motor performance, balance, and coordination (Kraemer & Ratamess, 2004).

Two desirable adaptations for athletes that result from RT are increased strength and power. Strength can be defined as the ability of the neuromuscular system to generate maximal force (May, Cipriani, & Lorenz, 2010). Meanwhile, power can be defined as the ability of the neuromuscular system to produce the greatest possible impulse in a given period of time (Flessas, Koumpoula, Tsopani, & Oikonomou, 2008). Regardless of the sport, strength lays the foundation for the development of power, which is a necessity in the vast majority of athletic competitions (Kanehisa, & Miyashita, 1983). Simply stated, increases in athletes' maximal strength will increase their maximal power outputs, which can result in improved performances. Furthermore, the importance of power for competitive athletes has been well-established in the scholarly literature. For example, research has demonstrated that developing lower-body power is critically important for improving athletic performance in sporting activities that require any of the following: sprinting, swinging, kicking, explosively changing direction, and running (May et al., 2010). Thus, properly designed RT programs are of critical importance for athletic success.

When designing a RT program for athletes, it is important that strength and conditioning coaches select exercises that will elicit the greatest adaptations (Harries et al., 2012). However, at this point in time, there is some debate regarding which RT exercises and methods should be incorporated into RT programs in order to elicit these adaptations (McCurdy, Langford, Doscher, Wiley, & Mallard, 2005). Another important decision that must be made when choosing exercises for a RT program is whether or not a particular exercise is biomechanically relevant to an athlete’s particular sport (McCurdy et al., 2005). In other words, exercise selection should be based on whether or not it resembles the physical demands that are placed on the athlete in competition. Hence, the coaching staff needs to determine the requirements of the individual athletes before selecting exercises for his/her RT program. This ensures that those exercises best address those particular athletes’ competitive needs. For example, if the athlete has a deficiency in lower-body power, then exercises that elicit the greatest adaptations in that particular region in order to correct that specific weakness should be utilized (Harries et al., 2012; May et al., 2010).

Although there is no universal agreement as to which methods of RT are superior for athletes to maximize performance, unilateral training, or the use of one limb at a time, has recently received much attention among strength and conditioning professionals (Nijem & Galpin, 2014). This recent attention is the result of a limited number of studies demonstrating that participants absolute weight lifted while RT is less when training bilaterally compared to unilaterally, which is referred to as the bilateral deficit. While some unilateral exercises, such as step ups and lunges, are utilized in many RT programs, they are only implemented as assistance exercises and are not commonly used as the primary exercises for eliciting adaptations (McCurdy et al., 2005). Furthermore, single-legged squats have provided insight into the kinematics during higher-load activities, such as running and explosive change of direction movements, which may have implications for RT programs for preventing athletic-related injuries (Dawson & Herrington, 2015). Because there is no available research comparing the adaptations that result from unilaterally resistance training (ULRT) with bilateral resistance training (BLRT), there are questions regarding how ULRT should be incorporated into an athlete's training program. Thus, research is necessary in order to determine whether ULRT or

BLRT are the most beneficial for enhancing athletic performance.

Due to the fact that the vast majority of movements that occur in sports require an athlete to move explosively with one limb at a time, there is speculation that unilateral training may be beneficial to competitive athletes. However, there is currently insufficient data from scholarly investigations examining this assumption. Most scholarly research examining the BLD has demonstrated that unilateral exercises produce greater maximal strength compared to bilateral performances (Costa et al., 2015). A limited amount of research has reported a bilateral facilitation, which occurs when the sum of the unilateral strength is less compared to the sum of the bilateral strength (Teixeira, Narciso, Taroco, & Salomão, 2013). It is also important to note that most of the available scholarly research examining the BLD has used measures of strength that are not frequently utilized in RT programs for athletes, such as isokinetic and isometric measures (Škarabot et al., 2016). Due to the fact that the strength measurements used in most studies to identify the BLD do not reflect the types of exercises found in RT programs for athletes, future studies using RT exercises that are common in athletes' RT programs are necessary.

Another important consideration for athletic training programs is the effects that a strength and conditioning program has on plasma glucose levels in the body. This is an important consideration because plasma glucose is one of the most tightly regulated homeostatic variables in the body (Boron & Boulpaep, 2012). Research has demonstrated that plasma glucose levels do not change dramatically during resistance training (Fleck & Kraemer, 2014). Thus, during a single resistance training session, carbohydrate availability for the anaerobic energy system does not appear to be a limiting factor for performance. Having said that, these studies were few in number, which warrants additional investigations to confirm the previous findings.

However, it is important to note that consistently motoring plasma glucose levels during RT is critical for some special populations. For example, individuals with diabetes must check their plasma glucose levels before, sometimes during, and immediately after exercise (Swank, 2009). This careful monitoring is important in order to determine the effects of exercise, which may require compensation with either appropriate dietary and/or medication regimen changes (Swank, 2009). Because much of the current research focuses on the effects of RT on plasma glucose levels for diabetics, this study is necessary because it will provide additional information regarding the plasma glucose responses to RT for non-diabetic individuals.

Need for the Study

This study is necessary to determine if the BLD is typical expression for individuals with at least 1 year of previous RT experience for an upper-body and a lower-body movement. In addition, to the author’s best knowledge, there are no scholarly investigations examining the effects of BLRT and ULRT on plasma blood glucose levels. If the results of this study can substantiate the existence of a bilateral deficit, this could lead to additional research that may result in the discovery of new information that is beneficial to athletes. Specifically, future studies could provide answers for the following queries: whether or not unilateral training elicits greater adaptations compared to bilateral training, if unilateral exercises can be used to prevent injury, and how strength and conditioning professionals should incorporate unilateral exercises into an athlete’s RT program (Nijem & Galpin, 2014). Thus, the knowledge acquired from future investigations of unilateral training could potentially provide strength and conditioning professionals with information that will enable them to design RT programs that result in greater adaptations and fewer injuries. In addition, the information gained could provide insight into whether or not plasma glucose levels respond differently to unilateral and bilateral RT exercises.

Statement of the Problem

The primary purpose of this study was to determine whether or not a bilateral deficit was present when performing the dumbbell vertical press exercise and the dynamic leg press exercise, which are two exercises commonly utilized in strength and conditioning programs. A secondary purpose was to determine if blood plasma glucose levels significantly differ between the unilateral and bilateral conditions for the dynamic leg press exercise.

Research Questions and Hypotheses

Question 1: Is there a significant difference between maximal voluntary contraction strength from a unilateral and a bilateral contraction for the vertical dumbbell press and dynamic leg press exercises?

Hypothesis 1: The maximal voluntary contraction strength for the unilateral contractions will be greater than the maximal voluntary contraction strength of the bilateral contraction for the vertical dumbbell shoulder press and leg press exercises.

Question 2: Is there a significant difference between pre-exercise and post-exercise plasma glucose following the dynamic leg press exercise during the unilateral and bilateral exercises?

Hypothesis 2: The post exercise plasma glucose levels will not significantly differ compared to the pre-exercise plasma glucose levels.

Definition of Terms

Bilateral Deficit—a reduction in performance during bilateral contractions when compared to the sum of identical unilateral contractions (McCurdy et al., 2005).

Bilateral Facilitation—stronger contractions when making simultaneous efforts with both limbs (Gillen, 2014).

Bilateral Training—simultaneous contraction of the same muscles in contralateral limbs (Nijem & Galpin, 2014).

Power—the ability of the neuromuscular system to produce the greatest possible impulse in a given period of time (Flessas et al., 2008).

Resistance Training—a form of strength training in which each effort is performed against a specific opposing force generated by resistance (Fleck & Kraemer, 2014).

Unilateral Training—exercises that restrict contraction to one limb individually (Nijem & Galpin, 2014).

Assumptions

- The participants selected are healthy and free of any physical (e.g., neurological impairment, muscular disorder) ailments that might influence the results of the study.
- Participants were familiar with the vertical dumbbell press and dynamic leg press exercises.

Limitations

- Small sample size.
- A complete training history detailing the manner in which the participants performed their RT exercises (i.e.., bilaterally or unilaterally) for the dynamic leg press and vertical dumbbell press prior to the study was not collected.
- No electromyogram (EMG) recordings in order to compare muscle activation patterns.
- Diet was not controlled.

Delimitations

- Selection of college-aged students 18–24 years of age.

Chapter 2: Review of Literature

The earliest research demonstrating the bilateral deficit (BLD) dates back nearly five decades when Henry and Smith (1961) initially described the phenomenon. In this particular study, the authors reported that the maximal force generated during simultaneous hand-grip contractions was significantly less compared to the sum of the forces produced single-handedly (Henry & Smith, 1961). Since then, this particular phenomenon has been observed in a wide variety of populations. Having said that, the scientific literature has demonstrated the BLD in trained and untrained, adolescent and elderly, and male and female populations (Costa, Moreira, Cavalcanti, Krinski, & Aoki, 2015). The evidence collected thus far suggests that the BLD is a naturally occurring phenomenon that is restricted to twin synchronous movements (e.g., simultaneous flexion), but, not simultaneous flexion and extension (Ohtsuki, 1983). In addition, the published research indicates that this particular phenomenon is restricted to contractions of homonymous limbs (Herbert & Gandevia, 1996; Howard & Enoka, 1991). The BLD has also been reported to occur during a wide variety of contraction types. For example, this particular phenomenon has been observed during isometric, concentric, and eccentric contractions (Costa et al., 2015). However, at this point in time, researchers are uncertain if there are significant differences between unilateral and bilateral contractions during close (e.g., combined hip and knee extension) versus open kinetic chain resistance training exercises (e.g., bench press; Škarabot et al., 2016). It is also important to note that the BLD has been observed during a broad range of exercises. That said, this phenomenon has been observed in upper-body (i.e., shoulder flexion) and lower-body movements (i.e., hip press, leg extension).

Most studies investigating the BLD have utilized the bilateral index as presented by Howard and Enoka (1991) [BI (%) = (100 * (bilateral/(right unilateral + left unilateral)) - 100]. That said, a positive bilateral index score indicates a bilateral facilitation, which occurs when the relative sum of the bilateral forces is greater compared to the sum of the unilateral forces (Howard & Enoka, 1991). In contrast, a negative bilateral index score would demonstrate that a BLD had been observed, which would occur if the sum of the unilateral forces were significantly greater compared to the sum of the bilateral forces (Howard & Enboka, 1991). It is important to note that some published studies have reported a bilateral facilitation. However, there is a sufficient amount of scholarly research that confirms the existence of this particular phenomenon to warrant additional investigations (Škarabot et al., 2016).

Upper Body vs. Lower Body Bilateral Index Scores

Regardless of the type of contraction, the upper-body exercises, on average, exhibited a lower bilateral index scores in comparison to the lower-body movements. Specifically, meta-analysis has reported that the bilateral index scores were -5.8 ± 3.5 for the upper-body and 13.2 ± 10.3 for the lower-body exercises, respectively (Škarabot et al., 2016). It is important to note that the magnitude of the BLD between the upper-body and lower-body limbs dramatically differs among the published studies. Having said that, the magnitude has been reported to be smaller in the upper-body limbs with deficits between 2% and 20% while the reported deficits for the lower-body limbs have ranged between 13% and 25% (Škarabot et al., 2016). Thus, the current research on the BLD demonstrates that there are important distinctions between the upper-body and lower-body limbs, which may have implications for training prescriptions. For example, ULRT may be more appropriate for the lower-body limbs because the scholarly research has reported that the magnitude of the BLD is greater for the lower-body limbs.

Dynamic Contractions

Currently, the published scholarly literature examining the BLD lacks consistency because these studies have used a variety of contraction models and/or exercises when examining this phenomenon. However, a recent meta-analysis of dynamic contractions has reported an average bilateral index of -11.7 ± 9.7 % regardless of the contraction model or exercise used, which included isokinetic, concentric, and eccentric (Škarabot et al., 2016). For these dynamic contractions, the BLD has been consistently reported in multi-articular movements such as the leg press and the vertical jump (Jakobi & Chilibeck, 2001; Škarabot et al., 2016). However, the studies that used the dynamic contraction model and failed to report a BLD are in the minority, and these two studies used the concentric knee extension and the isokinetic bench press (Škarabot et al., 2016). Due to the fact there are many confounding factors that can influence whether or not an individual can produce force, it is difficult to determine the reasons for the aforementioned studies' inability to observe a BLD. However, it is unlikely that differences in subject characteristics are a contributing factor to the inability of some studies to observe a BLD during dynamic contractions because, as previously discussed, the phenomenon has been observed in a broad range of different populations (Costa et al., 2015).

At this point in time, it is difficult to determine the specific underlying mechanisms that are responsible for the BLD during dynamic contractions (Škarabot et al., 2016). However, the following are suggested mechanisms that researchers theorize may contribute to this particular phenomenon during dynamic contractions: whether or not the exercise uses a single or multiple joint, interactions between the actin and myosin filaments, the velocity of the muscular contractions, and the activation and length of the muscles utilized during dynamic contractions (Costa et al., 2015). It is also important to note that the available data have shown that the magnitude of the BLD is different for the various types of dynamic contractions. Having said that, the reported magnitude of the BLD for concentric and eccentric contractions is approximately 10% on average for both contraction models (Škarabot et al., 2016). Interestingly, the isokinetic contractions have a greater range that typically increases as the contraction velocities increase. For example, one particular study used isokinetic combined hip and knee extension at 10 different velocities (Vandervoort, Sale, & Moroz, 1984). Furthermore, this particular study reported a linear increase in the magnitude of the BLD that ranged from 9% during 0°/s up to 49% during 424°/s, respectively (Vandervoort et al., 1984). However, researchers have indicated that additional research is needed to explore the influence that the various types of contractions have on this particular phenomenon as well as how differing velocities and joint angles affect the magnitude of the BLD (Škarabot et al., 2016).

Isometric Contractions

In contrast to dynamic contractions, the results of isometric contractions are far more inconsistent in reporting a BLD, which is due to the fact that some studies observed a BLD while other studies failed to observe the phenomenon (Škarabot et al., 2016). However, it is important to note that Jakobi and Chilibeck (2001) suggest that the isometric contraction model is the most suitable for investigating the underlying mechanisms of this particular phenomenon.

This suggestion is based on the fact that isometric movements are restricted to some degree (Jakobi & Chilibeck, 2001). The relevant BLD articles that used isometric contractions reported a bilateral index score of 8.6 ± 8.5 (Škarabot et al., 2016). With regards to the upper and lower body, the available research has neither reported a dramatic difference in magnitude for these particular contractions (e.g., -9.0 ± 8.0 vs. -8.1± 9.2, respectively) nor has reported a significant difference in consistency of a BLD (e.g., present in 70 or 71% of all published studies; Škarabot et al., 2016).

For isometric measurements used to assess the BLD, the research using knee extension exercises appears to be the most ambiguous, and, according to Škarabot et al. (2016), could have been influenced by the use of varying populations as participants. Simply stated, for this particular study, the dramatic differences in terms of the participants' characteristics very well could have influenced the observed differences in the magnitude of the BLD index scores. One particular BLD study utilized three different populations for the isometric knee extension exercise in order to determine if any significant differences would be observed between the groups. The results of this particular study revealed that while the BLD was observed for the untrained participants, the participants classified as cyclists failed to demonstrate a negative bilateral index scores (Howard & Enoka, 1991). Furthermore, this same study also noted that other groups of athletes failed to demonstrate a BLD. Specifically, the participants classified as weightlifters in the aforementioned study demonstrated a positive bilateral index score, which demonstrated a bilateral facilitation (Howard & Enoka, 1991). Thus, it appears that differences in the characteristics of the participants may influence the magnitude of the BLD, but additional research is needed in order to determine how the individual characteristics of the aforementioned participants influenced this particular phenomenon.

While there is a large amount of ambiguity for the isometric knee extension exercise, BLD investigations using combined hip and knee extension contraction models have consistently demonstrated a negative bilateral index score (Beurskens, Gollhofer, & Muehlbauer, 2015; Donath, Siebert, Faude, & Puta, 2014; MacDonald, Losier, Chester, & Kuruganti, 2014; Schantz, Moritani, & Karlson, 1989; Vandervoort et al., 1984). In other words, the phenomenon has been routinely observed during these types of exercises. Having said that, all of the published studies using these particular contraction models have reported a BLD (Škarabot et al., 2016). Moreover, the results of these studies cannot be attributed to differences in populations used due to the fact that this particular phenomenon has been studied in a broad range of participants (Škarabot et al., 2016). However, possible explanations for the consistency demonstrated during combined hip and knee isometric exercises could be a result of the following: greater postural requirements, synergistic contributions during combined hip and knee contractions, and the ability of participants to counterbalance during BLD assessments (Škarabot et al., 2016).

Differences in joint knee angles among the various studies is another important factor that further adds ambiguity to the BLD literature on the isometric knee extension (Škarabot et al., 2016). Studies have reported significant differences with regard to the BLD at different angles during isometric contractions. For instance, while one study reported a BLD at 45 degrees during isometric contractions, the phenomenon was not observed during isometric contractions at either 0 or 90 degrees (Kuruganti, Tiernan, & Pardy, 2011). In contrast, other research has demonstrated the BLD at a variety of joint angles. Matkowski, Martin, and Lepers (2011) used a joint angle of 70 degrees of knee flexion in order to test if participants displayed a BLD. This particular joint angle is of particular importance because research has indicated that 70 degrees of knee flexion is close to the optimal muscle length that allows for maximal force production (Kubo, Tsunoda, Kanehisa, & Fukunaga., 2004). It is possible that postural stability requirements and the ability to counterbalance are insufficient for a BLD to be observed during the knee extension exercise and that these requirements are different for each joint angle (Škarabot et al., 2016). Interestingly, other BLD research reported similar trends for isometric contractions of the upper-body limb as well. Specifically, Drury and Mason (2004) observed a BLD at elbow flexion of 45 and 90 degrees; however, no BLD was observed at an elbow flexion of 135 degrees.

With regard to the upper-body limbs, the BLD has been observed during shoulder flexion, thumb adduction, finger abduction, and elbow flexion and extension, respectively (Škarabot et al., 2016). However, at this point in time, there is some ambiguity in the scholarly literature examining this particular phenomenon during handgrip exercises. While the vast majority of the research that utilized handgrip exercises reported a BLD, there are some studies that did not report such findings (Škarabot et al., 2016). According to Škarabot et al. (2016), it is possible that different positioning of the participants during testing between the various studies may have resulted in different results because the various positions used during testing may have resulted in different lengths of the hand flexors. The body positioning of participants during testing is a likely explanation for the aforementioned high variability between the results of the different studies. Magnus and Farthing (2008) and Taniguchi (1997) measured force while the participant’s elbows were extended and did not report a BLD during handgrip exercises. In contrast, most of the BLD reported using handgrip exercises measured force while the participants had their elbows flexed at a 90-degree angle (Škarabot et al., 2016).

Ballistic and Explosive Movements

Research has demonstrated that the BLD is also present when the participants performed ballistic types of movements, such as ballistic jumps and other similar explosive types of movements. Overall, research has demonstrated that the sum of unilateral legged jumping (e.g., one-legged jumping) heights are greater compared to the heights of bilateral jumps for the countermovement jump, drop jumps, and the squat jump. Van Soest et al. (1985) reported that the jumping height for well-trained male volleyball players during one-legged jumps was 58.5% compared to the height reached when the same participants performed two-legged jumps for the vertical countermovement jump. Furthermore, an investigation examining the countermovement jump performance for elite sprinters reported a phenomenon similar to the BLD. Specifically, Bračič et al. (2010) reported that elite sprinters with higher BLD values were not able to produce high peak forces equally on the blocks at the start of a sprint. As a consequence, these sprinters produced lower total impulse of force on the blocks, which resulted in lower block velocity (Bračič et al., 2010). In short, these findings are important because these values are strongly correlated with performance. Specifically, total impulse of force on the blocks and block velocity are related to overall 60 meter and 100 meter sprint performances (Harland & Steele, 1997; Mero, Komi, & Gregor 1990). It appears that both one-legged and two-legged drop jumps are influenced by the participants’ athletic background. Research has demonstrated that power athletes have greater BLD scores for the drop jump test, which Pain (2014) suggested could be a result of the fact that power athletes have a greater number of fast twitch muscle fibers. For this particular study, the BLD was observed during the drop jumps by the measurement of peak concentric force as well as peak power (Pain, 2014). Likewise, one-legged squat jumps also reported a BLD as well. Specifically, one published study reported that the height jump performed with one leg was 58.1% of the height that when the jump was performed bilaterally (Bobbert, de Graaf, Jonk, & Casius, 2006). However, it has been suggested that jumping height may not be the best performance measure to assess the BLD. That said, these questions revolve around whether or not jumping height is normalized to the height of the participant in the standing position (Škarabot et al., 2016). Thus, the ability of jumping height to serve as a measure to determine whether or not a BLD was observed depends if the jumping height is normalized to the heights in the upright standing position or to the participant's height at takeoff (Škarabot et al., 2016). Despite these questions, Hay, de Souza, and Fukashiro (2006) reported a BLD of 13% during leg press jumps, which were measured by recording the resultant ground reaction impulses.

Differences in the force-velocity curves between unilateral and bilateral contractions may explain the observed BLD during ballistic actions such as jumping and/or explosive dynamic contractions. According to Bobbert et al. (2006), these differences in the force-velocity curves have been suggested even though there is a tendency for electromyogram (EMG) activity to be coupled with the BLD in force. As previously mentioned, van Soest et al. (1985) reported a BLD during human jumping, which the authors attributed to to differences in the force-velocity relationships. Differences in the center of mass have been suggested as potential mechanisms for these observed differences in human jump heights. Škarabot et al. (2016) suggested that because the velocity of the center of mass was greater for the two-legged jumps, the extensor muscles must have shortened at greater velocities during two-legged jumps that resulted in less force and less work done. Likewise, it is also important to consider body positioning and how a participant's weight is distributed prior to jumping. Specifically, as long as a participant does not shift his/her mass more to one side than the other, the weight of the human body is equally distributed between both legs during a two-legged jump. Moreover, such situations result in a reduced active state of the leg muscles because the body positioning at the start of the jump results in a reduced active state in the initial position of equilibrium (Škarabot et al., 2016). In other words, the authors suggest that the leg muscles are not fully activated during the initial range of motion. According to Bobbert et al. (2006), this consideration is important during the squat jumps because they do not require a preparatory countermovement that activates the extensor muscles. Moreover, the muscular shortening velocities may be able to explain the BLD during these types of contractions. Specifically, musculoskeletal model simulations have demonstrated that as much as 75% of the BLD can be explained by greater shortening velocities during two-legged jumps, which indicates that the aforementioned differences in the force-velocity curves are probable underlying mechanisms for this particular phenomenon (Bobbert et al., 2006). The available evidence also suggests that other velocity-based differences may explain this particular phenomenon. For instance, the average push-off time is longer in duration during the unilateral jumps compared to bilateral jumps, which may be a result of differences in the weighted load between these conditions (Škarabot et al., 2016).

Muscle Contraction Differences

Observed differences between unilateral and bilateral muscular contractions have been proposed as an explanation for the BLD. For example, the extensor muscles are required to shorten at much greater velocities during two-legged jumps than one-legged jumps, and they produce less force and ultimately less work as a result (Bobbert, de Graaf, Jonk, & Casius, 2006). It stands to reason that unless an individual shifts their body weight more to one side compared to the other during a two-legged jump, that their weight will be evenly distributed between both legs during the jump. The implications of this equal distribution of body weight prior to performing a two-legged jump are significant because it results in a reduced active state during the initial equilibrium position. (Bobbert et al., 2006). This is important because it is believed that this reduction of active state results in submaximally activation of the muscles during the initial movement of a bilateral jump (Škarabot et al., 2016). However, the magnitude of activation may be more significant for some movements compared to others. For example, the aforementioned submaximal activation appears to play a more significant role during squat jumps, which do not require any preparatory countermovement (Bobbert et al., 2006). Moreover, Bobbert et al. (2006) suggested that greater shortening velocities of contracting muscles can explain 75% of the observed BLD, which indicates that the underlying mechanisms of the BLD may potentially be the result of differences in the force-velocity relationship.

Although the vast majority of investigations report a BLD during explosive/ballistic contractions, a bilateral facilitation (BLF), or stronger during the simultaneous contraction of both limbs, has been reported by a few studies. For example, Ebben et al. (2009) reported a

BLF during jumping for participants with backgrounds in track and field. Although the authors of this particular study suggested that the findings are a result of the participants competing in different track and field events, other scholars have suggested that such reasoning is difficult to accept due to the fact that throwing events are not completely bilateral in nature (Škarabot et al., 2016). However, additionally research is needed to substantiate these findings.

At this point in time, most of the research examining the BLD has focused on the maximal force that a contracting muscle or muscle group can produce. However, one recent study did demonstrate that the BLD was present when testing the participants' total volume of load lifted (Costa et al., 2015). Although previous research that has focused on the maximal force produced by a muscle has helped researchers identify potential underlying mechanisms of the BLD, maximal force is not what determines performance in many athletic or daily activities (Dickin et al., 2011). More specifically, the ability of a muscle group to generate the greatest muscular power (i.e., force x velocity) is far more important in athletics than the ability of a muscle group to generate a high maximum force at a slower speed of movement (Dickin et al., 2011). Numerous studies have shown that a muscle can generate the greatest amount of power during a submaximal load (Kawamori & Haff, 2004). Maximal muscular power is imperative in any situation during which an individual is trying to prevent themselves from slipping and falling, and during activities that involve jumping, sprinting, and throwing (Dickin et al., 2011). Analysis of sporting activities reveals that there are many situations in which an athlete is required to generate maximal instantaneous power during bilateral contractions of identical muscles on the opposite sides of their body (Dickin et al., 2011). Thus, future studies are needed to address factors other than maximal force when examining this particular phenomenon.

Joint Angle Influences

An important factor that appears to influence whether or not a BLD is observed during isometric contractions is the joint angle that is utilized in the various studies. For example, Owings and Grabiner (1998) reported a BLD at joint angles of 45° and 90° for isokinetic knee extension, which was observed before and after a fatigue protocol performed at 30° and 150°. In contrast, results from a similar study found that although participants denominated a BLD for 45° isometric knee extension exercises, this particular phenomenon was not observed at either 0° or 90°, respectively (Kuruganti, Murphy, & Pardy, 2011). Thus, research indicates that there may be an optimal angle in order to observe a BLD. With that being said, Matkowski et al. (2011) reported a BLD during isometric knee extensions at 70° of knee flexion, which is a joint angle that was selected because it is close to the optimal muscle length for a muscle to produce maximal force. Overall, meta-analysis indicates that the BLD is more prevalent in knee extension exercises at intermediate muscle lengths (Škarabot et al., 2016). Additional research examining the impact that various joint angles have on the BLD has suggested that the angle in fact does influence whether or not the BLD is observed during elbow flexion exercises. Specifically, Drury et al. (2004) reported that although the BLD was present at 45° and 90° during elbow flexion exercises, researchers failed to observe the phenomenon when participants performed the same exercises at 135°.

Currently, the mechanisms responsible for the observed BLD during isometric contractions cannot be confirmed with any certainty. Having said that, the lack of explanation for the origins of this particular phenomenon may be due to the fact that it has not been observed in all experimental conditions (Magnus & Farthing, 2008). To further complicate the understanding of the BLD, some research has shown that this particular phenomenon can be overcome through specific training protocols. Specifically, research has shown that the BLD can be reduced and/or reversed through training protocols that utilize simultaneous bilateral contracts of the limbs (Dickin et al., 2011). However, it is likely that the complexity in identifying the causes responsible for the manifestation of the BLD is a result of multiple mechanisms at play during a given set of circumstances (Škarabot et al., 2016).

Control Limitation

Although the BLD is an unstable phenomenon, establishing its existence with absolute certainty is important because it may represent a control limitation of the neuromuscular system (Jakobi & Chilibeck, 2001; Rejc et al., 2015). However, this particular phenomenon appears to be adaptable as a result of training due to the fact that some studies have reported a BLF (Škarabot et al., 2016). If such a control limitation exists, then there is the potential that it could be overridden for a variety of different types of athletes. For example, the establishment of a BLD, and the potential to override this control limitation, would be a special concern for athletes who perform bilateral contractions exclusively (e.g., powerlifters, rowers, ski jumpers),–as well as athletes whose performance is limited by the ability to generate force unilaterally (e.g., throwers in track and field, both high and long jumpers; Jakobi & Chilibeck, 2001). Although there has been speculation by strength and conditioning coaches, the potential impact that the BLD may have on athletic performance has not yet been determined by the available scholarly research (Jakobi & Chilibeck, 2001). However, the BLD research that has been in the published scholarly literature is significant enough to be considered a potentially limiting athletic performance factor.

At this point in time, the effects of the BLD on athletic performance are unknown. In other words, scholars are uncertain if this particular phenomenon helps or if it hinders athletic performance (Škarabot et al., 2016). It is important to note that the vast majority of sports require locomotion, or a "reciprocal" movement pattern, during which forces are predominantly unilateral, especially for ground-based sport (Archontides & Fazey, 1993). In other words, most sports require athletes to explosively move and change direction, which requires one limb at a time producing the necessary force for explosive-athletic movements. However, at this point in time, strength and conditioning professionals are unsure if training limbs in isolation is the most appropriate method for eliciting desired performance gains. According to Santana (2001), the question remains on whether or not bilateral jumping and BLRT should be replaced with their unilateral variations for improving athletic performance.

General Populations

Although the BLD may constitute an important performance-limiting factor for athletes, this phenomenon appears to have important applications for general populations as well. For example, some researchers have suggested that the BLD also has implications for elderly individuals when rising from a chair (Rejc et al., 2015). However, there is some uncertainty as to whether or not the BLD exists, or is prevalent, among older populations. Having said that, some research suggests that the BLD may be the result of an inhibition of the fast-twitch motor unit recruitment (Janzen, Chilibeck, & Davison, 2006). The impact that any potential inhibition of these particular motor units has on the BLD is relevant because research has demonstrated that older individuals have a reduced number and smaller sized fast-twitch muscle fibers (Kawakami et al., 1998; Vandervoort et al., 1984). Specifically, research has confirmed quantitative changes in the muscle in terms of a reduction of size associated with age, which is especially evident when comparing those 20–30 years of age with those 70 years and older (Mitchell et al., 2015). Thus, it stands to reason that an observed BLD would be less pronounced in older participants than younger participants.

Overall, the findings of studies examining the BLD in older populations are mixed (Janzen et al., 2006). Specifically, both Owings and Grabiner (1998) and Kuruganti et al. (2005) reported a BLD for both knee extension and knee flexion exercises for participants between 55 and 75 years of age. Similarly, Hernandez et al. (2003) reported a BLD for older participants (73.3 ± 4.4 years) with elbow flexion exercises. In contrast, some BLD research using older participants failed to find any significant results to confirm the existence of this phenomenon. For example, four studies conducted by the same research group in a close proximity of time failed to observe a BLD for older participants between the ages 62 and 75 during knee extension exercises (Hakkinen et al., 1995; Hakkinen et al., 1996a; Hakkinen et al., 1996b;, Hakkinen et al., 1997). Based on the available research, it has been suggested that changes to the neuromuscular system associated with age are the most likely explanation for the aforementioned failure to observe a BLD for older participants (Janzen et al., 2006).

Psychological Influences

Perceived exertion. According to Jakobi and Chilibeck (2001), the BLD may simply be a result of differences in perceived exertion, which can be defined as the subjective intensity of effort and/or fatigue that an individual may feel during exercise. The aforementioned differences appear to be greater in studies that involve contractions of the lower limbs than contractions of the upper limbs (Škarabot et al., 2016). Sekie and Ohtuski (1990) suggested that the BLD may be because of participants' failure to exert themselves to the same degree during bilateral contractions as during unilateral contractions. Likewise Vint and McLean (1999) suggested that the greater perceived exertions during bilateral actions may be the result of perceptual differences between unilateral-resistance training (ULRT) and bilateral-resistance training (BLRT), which significantly influences the magnitude of the observed BLD (Škarabot et al., 2016). Furthermore, the aforementioned results were reproduced by Hernandez et al. (2003) during isometric contractions of the elbow flexors. Hernandez et al. (2003) supported Vint and Mclean (1999) results by reporting a near constant 11% BLD for perceived exertions of 25%, 50%, and 75%.

Participant naivete. Interestingly, Secher et al. (1988) reported that when subjects were given incorrect information, such as that the bilateral forces would be greater compared to the total of unilateral forces, the observed BLD was reduced. Thus, in some instances, it appears that the BLD may in fact be the result of an awareness of this particular phenomenon, or it potentially may be a result of a lack of awareness of it (Škarabot et al., 2016). In contrast, Koh et al. (1993) reported that correct information had no influence on bilateral index scores during ramp isometric contractions. Donath et al. (2014) conducted a study in order to determine whether or not pre-information conditions would influence the manifestation of the BLD during isometric leg press exercises for trained adult males. In this particular study, all participants completed maximal isometric strength tests with the following conditions: no pre-information, false pre-information, and correct pre-information (Donath et al., 2014). Interestingly, the authors indicated that the cognitive-volitional influences seemed to have a negligible influence on the BLD (Donath et al., 2014). In other words, the authors did not find any evidence that pre-exercise information had any effect whatsoever on whether or not this particular phenomenon was observed.

Division of attention. Based on the theory of division of attention, there is a reduction of force when two remote parts of the body generate force simultaneously (Škarabot et al., 2016). Furthermore, this theory is based on the dual task theory from the field of cognitive psychology that proposes that because attention is a limited resource, it may in fact limit performance (Takebayashi et al., 2009). Some researchers have suggested that this particular phenomenon plays a significant role in whether or not the BLD is observed. For instance, Vandervoort et al. (1984) suggested that during the bilateral leg exercises, there is a division of contraction between the two limbs that results in a reduction of motoneuron pool excitability. However, there is evidence that directly contradicts this assertion. Specifically, Škarabot et al. (2016) stated that because the BLD is restricted to twin synchronous movements and contraction of homonymous limbs, the attention demands of exercise are unlikely contributors to this particular phenomenon.

Influence of Postural Adjustments

Herbert and Gandevia (1996) were the first researchers to suggest that the BLD may be limited by participants' ability to make adjustments to their posture. The authors for the aforementioned study also speculated that the postural adjustments influence the bilateral index scores, which may be more important for large muscle groups. That said, Janzen et al. (2006) reported a BLD when the participants performed multi-joint exercises; however, the phenomenon was not present for single-joint exercises. For this particular study, the authors suggested that the multi-joint exercises require greater postural stability compared to single-joint exercises, which is why the BLD was present for the former exercises and not the latter (Janzen et al., 2006). Additional research has been conducted to determine the potential influence that adjustments to posture may have on the BLD. Magnus and Farthing (2008) examined how postural stability may contribute to the BLD by comparing the bilateral index scores of the leg press, which has greater posture stability requirements, with those of handgrip exercises, which have less posture stability requirements. Because a BLD was present only during leg press exercises and not the handgrip exercises, the hypothesis that postural stability has a direct effect on the BLD was substantiated (Magnus & Farthing, 2008). However, it is important to note that while the handgrip exercise is an isometric contraction, the leg press is a dynamic exercise, which may explain the observed difference (Škarabot et al., 2016).

Counter Balance. Simoneau-Buessinger, Leteneur, and Toumi (2015) research further supports the theory that the BLD may be a result from the participants' ability to counterbalance while performing the exercise. In other words, the supposed physiological phenomenon of BLD may be a result of the addition of torque that is produced from participants adjusting their bodies. For example, research has demonstrated that when measured with a dynamometer, which measures trunk torsion to the contralateral side of the body, there is an increased net torque when participants perform unilateral contractions (Škarabot et al., 2016). According to researchers, this increased net torque likely influences the expression of the BLD (Škarabot et al., 2016). Thus, the currently available research demonstrates that, in some situations, postural stability appears to influence whether or not the BLD is observed.

In contrast to the aforementioned studies that demonstrate how postural stability influences the BLD, some exercises have postural requirements that do not allow for the creation of additional torque. For example, the knee extension is an exercise that is quite limited because of low postural stability requirements, which results in a reduced ability to counterbalance (Škarabot et al., 2016). As a result, future investigations of this particular phenomenon should attempt to control postural stabilization requirements in order to prevent participants from counterbalancing during testing conditions. Researchers have suggested that additional studies should report the specific positioning of participants during the various testing conditions based on the evidence gathered thus far that suggests that counterbalancing affects the expression of the BLD (Škarabot et al., 2016).

Joint Stability

It has been suggested that joint stability may also influence the expression of the BLD. That said, joint stability closely relates to postural stability requirements because excursion of the hip and knee joints requires greater activity of synergists that act as joint stabilizers compared to the much smaller carpo-phalangeal joints (Škarabot et al., 2016). As a result, these differences in joint activation likely influence the expression of this particular phenomenon (Škarabot et al., 2016). However, additional research is necessary in order to determine how various joints of the body and the differences in joint activation impact the BLD.

Limb Dominance

Research has indicated that limb dominance is a significant factor with regards to the BLD. Having said that, the currently available research indicates that the BLD is more prevalent in upper-body exercises than lower-body exercises (Škarabot et al., 2016). The reason for the greater prevalence during upper-body exercises may be a result in differences in the levels of physical activity between the upper body and lower body in activities of daily living (Škarabot et al., 2016). This notion is based on research that has demonstrated differences in the levels of activity for the dominant and non-dominant upper-body limbs, but not for the lower body limbs (Jakobi & Chilibeck, 2001). Because left-handed participants have consistently demonstrated less discrepancy between the dominant and non-dominant limbs in terms of strength, it has been suggested that the effect of limb dominance on the BLD may be limited to right-handed participants (Škarabot et al., 2016). However, not all of the published research investigating the BLD supports the notion that the BLD is limited to right-handed individuals. Specifically, Cornwell et al. (2012) conducted the only study that directly investigated the impact that limb dominance has on the BLD and reported that only the left-handed group demonstrated a significant reduction in the amount of force generated during contractions that were performed bilaterally (Cornwell et al., 2012). Thus, the effects that limb dominance have on this particular phenomenon may be limited to only left-handed individuals. However, additional research studies are needed to confirm these findings due to the fact that the magnitude of the observed BLD in this study was small compared to other studies. Specifically, Cornwell et al. (2012) reported a BLD that was only 1.3%, which is relatively small compared to other studies that report a deficit between 5 and 22% (Škarabot et al., 2016).

Physiological Factors

Antagonist Activation. Research has indicated that antagonist activation is not significantly different during bilateral contractions than unilateral contractions, which suggests that these activations do not appear to have any influence on the BLD (Škarabot et al., 2016). In addition, other studies have revealed that antagonist activation is even greater during unilateral contractions than bilateral contractions, which supports the notion that antagonist activation does not influence the BLD (Simoneau-Buessinger et al., 2015). With regards to antagonist activation, Cresswell and Overdal (2002) reported a burst of hamstring EMG activity in the contralateral leg while participants performed unilateral knee extension exercises. However, during this study, none of the participants were given any instructions regarding what to do with the non-active leg, and the non-active leg was not fixed in place to prevent movement (Škarabot et al., 2016). It is worthy to note that activation of the non-contracted leg has a significant impact on the magnitude of this particular phenomenon, and other researchers have reported similar results of EMG bursts of activity as well when the participants performed unilateral isometric contractions (Škarabot et al., 2016). Howard and Enoka (1991) reported that that the BLD for participants who activated the hamstring muscles in the contralateral leg exhibited a BLD of 21%. In contrast, participants who did not activate the hamstrings in the contralateral leg had a BLD of 14% (Howard & Enoka, 1991). According to Cresswell & Overdal (2002), "afferent feedback produced by the contralateral hamstrings activation may interact in a faciliatory manner with the descending command to the quadriceps muscle performing unilateral extension, thereby increasing the force production of the antagonist muscles". Furthermore, Howard and Enoka (1991) suggested that the contralateral muscular activation may result in increased torque produced by unilateral contractions when compared to bilateral contractions.

Core muscle activation. At this point in time, there is only one investigation that assessed the contribution of core muscles to the BLD (Škarabot et al., 2016). That said, Magnus and Farthing (2008) demonstrated that the core musculature was activated to a much greater extent during the leg press exercise than the handgrip exercise. However, the aforementioned study did not find any differences in the activation of the core muscles between the bilateral contractions and the unilateral contractions for the leg press and handgrip exercises (Škarabot et al., 2016). According to Magnus and Farthing (2008), the similar core activation may have resulted in a disadvantage for the bilateral contractions as a result of smaller inputs to postural stability because the ground reaction forces were higher during the bilateral contractions. With that being said, future research should examine the potential differences that core musculature activation patterns have on this particular phenomenon because the aforementioned research has indicated that it may affect the overall net force production.

Co-activation of synergist musculature. Currently, there is very little research that considers the co-activation of synergist muscles as an underlying mechanism of the BLD. That said, McCurdy et al. (2010) is the only published study examining the effects of the co-activation of synergist musculature. For this investigation, the aforementioned authors reported that gluteus medius activation was much greater during a single-leg squat compared to the traditional bilateral squat (McCurdy et al., 2010). As a result, it has been suggested that the greater synergist contribution leads to greater net torque, which may explain why a BLD has observed during BLRT (Škarabot et al., 2016). Future research should consider recording the activity of synergistic muscle groups during single joint and multijoint exercises in order to determine how synergy influences the expression of this particular phenomenon. In addition, it has been suggested that that recording the activity of the synergist muscles may potentially provide a way to control for or monitor participants counterbalancing during BLD assessments (Škarabot et al., 2016).

Muscular contraction velocity. A number of studies have reported that the BLD increases in magnitude as the speed of the muscular contractions increases. Vandervoort, Sale, and Moroz (1987) noted that by increasing the velocity of concentric contractions during leg extensions, the magnitude of the BLD significantly increased. Likewise, another study that investigated the effects of contraction velocity in maximal concentric and eccentric actions reported that the magnitude of the BLD significantly increased as the contraction velocities increased (Dickin & Too, 2006). The authors concluded that as velocity increased, there was a more significant d decrease, or an incomplete activation, of the fast twitch muscle fibers during bilateral muscular contractions compared to unilateral contractions (Dickin & Too, 2006). However, other research has failed to report an increase in the magnitude of the BLD as velocity increases. For example, one particular study examined the rate of force development (RFD) over consecutive 50 ms periods (0-50, 50-100 and 100-150 ms) and, while there was a BLD for the 50-100ms, no other periods demonstrated a BLD (Buckthorpe et al., 2013). It has been suggested that the BLD may be a result of the inhibition of type II muscle fibers, which are utilized to a greater degree during rapid muscle contractions (Howard & Enoka, 1991). It is important to note that the aforementioned velocities are much slower than the velocities that athletes display during maximal physical performances (i.e., sprinking; Škarabot et al., 2016).

Motor Unit Recruitment Patterns

As previously mentioned, the magnitude of the BLD increases as the contraction velocity increases. It is also worthy to note the impact that type II muscle fibers have on this particular phenomenon. Because type II muscle fibers contribute more to force production at higher contraction velocities, some scholars have suggested that the BLD may be a result of the inhibition of these particular muscle fibers during explosive contractions (Škarabot et al., 2016). Furthermore, the manner in which muscle fibers are contracted appear to significantly influence the magnitude of the BLD. For example, Koh et al. (1993) reported that the BLD was greater when force was produced rapidly during step and ramp contractions compared to contractions that resulted in a linear increase of force. The significance of these findings indicate that the BLD could be explained by the inhibition of fast-twitch muscle fibers (e.g., type II muscle fibers; Koh et al., 1993).

Research has shown that type II muscle fibers exhibit a substantial decrease in force as a response to repeated electrical stimulation, which is why they are classified as fatigue sensitive (Rubin & Strayer, 2011). The low resistance to fatigue for these particular fibers is very important for researchers investigating the BLD. Having said that, studies have examined the impact of muscle fiber fatigue on BLD in order to determine the role that fiber type and/or recruitment patterns of motor units have on this particular phenomenon (Škarabot et al., 2016). Interestingly, the recruitment patterns of motor units may help provide insight into understanding the BLD. For instance, one particular study reported that there was a smaller decline in bilateral force compared to unilateral force during concentric combined hip and knee extension during a fatigue test (Vandervoort et al., 1984). Due to the fact that high-threshold motor units fatigue at a faster rate, it was hypothesized that the observed smaller decline in bilateral force may have been the result of a reduction in the recruitment of the high-threshold motor units during bilateral contractions (Škarabot et al., 2016). However, the same authors conducted a similar investigation and reported evidence that the bilateral actions were more susceptible to fatigue, which conflicted with their previous study. With that being said, Vandervoort et al. (1987) reported that the bilateral movements fatigue more quickly compared to the unilateral contractions for the bench press exercise. The authors of these two studies suggested that the observed differences between the studies were likely the result of the following: differences in participants' levels of muscular training, familiarity with the exercises used during the investigations, and/or differences in the participants muscle fiber composition (Vandervoort et al., 1987). However, there are other important considerations (e.g., confounding factors) that must be made when interpreting these results. Škarabot et al. (2016) suggested that systemic influences associated with fatigue (e.g., so-called non-local muscle fatigue), which are neurological and biochemical, are difficult to account for as potential confounders. Furthermore, there is a lack of understanding regarding how non-local muscle fatigue affects unilateral and bilateral exercises and whether or not there are significant differences between the two methods of resistance training (Škarabot et al., 2016). Moreover, there may be differences between unilateral and bilateral contractions with regards to synergist muscle contributions that may result in potentiation because of repeated contractions in a short period of time (Škarabot et al., 2016).

Other testing procedures have been utilized in order to determine the significance of muscle fiber type and their contraction velocities on the BLD. Research has utilized this phenomenon using explosive force, rate of force development, and maximal voluntary contraction (Škarabot et al., 2016). As previously mentioned, Buckthorpe et al. (2013) reported that the BLD was limited during explosive force occurring during the first 100 ms with no observed differences in EMG activity reported. In contrast, Owings and Grabiner (1998) reported that the magnitude of the BLD was identical regardless of contraction velocity, which they used isokinetic knee extensions at 30°/s and 150°/s. Thus, the increased speed of contraction did not influence the magnitude of the phenomenon. In contrast to Owings and Grabiner (1998), other research did confirm that changes in contraction velocity influenced whether or not a BLD was observed. For instance, Brown et al. (1994) demonstrated that the magnitude of the BLD decreased as the speed of isokinetic contractions increased from 30°/s and 150°/s. However, other research using similar contraction velocities failed to report BLD's of the same magnitudes (Škarabot et al., 2016). On the other hand, other research has reported that the magnitude of the BLD decreased as the isokinetic contractions increased in speed from 60°/s to 240°/s, and in direct contrast to other studies, the BLD was not detected at 360°/s (Škarabot et al., 2016).

Neurophysiological factors

EMG and force. In many investigations comparing the differences between unilateral and bilateral muscular contractions, surface muscle activity (EMG) has been applied simultaneously with the force readings (Farina, Merletti, & Anoka, 2014). However, there is much ambiguity in the scholarly literature with regard to the parallelism between EMG and force, which some studies reported that the BLD follows the trend in EMG activity, but others have failed to report such a coupling (Škarabot et al., 2016). Scholars have noted that the force-EMG relationship is curvilinear and that this relationship might only exhibit a linear relationship during high force values (Lawrence & De Luca, 1983). Thus, it is highly unlikely that EMG will be able to detect any small changes in maximum force. In addition, the force-EMG relationship appears to be dependent on other physiological factors. That said, motor unit recruitment, relative amounts and the location of various motor unit types, viscoelastic properties, crosstalk from adjacent muscles, and rate coding properties also appear to influence the force-EMG relationship. Research has also suggested that the aforementioned discrepancy could be the result of different contributions of the antagonists and/or synergists that could influence the magnitude of EMG activity (Herbert & Gandevia 1996; Post, van Duinen, Steens, & Renken, 2007).

Spinal mechanisms. Spinal mechanisms have also been suggested as contributing factors to the BLD. Research has suggested that there is a shared neural network between the contralateral limbs, which is evidenced by cross-extensor reflexes and the cross-education phenomenon (Škarabot et al., 2016). In addition, it has been suggested that the aforementioned shared neural network may also contribute to the non-local effects of fatigue and stretching (Škarabot et al., 2016). Ohtsuki (1993) proposed that the peripheral reflex systems may be partially responsible for the existence of the BLD. Furthermore, some research has demonstrated that an effect of the Ia afferents is a contributing factor to the BLD. Specifically, Delwaide et al. (1988) showed that the degree of reciprocal inhibition is increased by the activation of the contralateral limb, which suggests that the Ia afferents have an effect on the contralateral limb. Similarly, one particular study indicated that H-reflex amplitude was dependent on whether or not the contraction was unilateral or bilateral. Specifically, the authors showed that the H-reflex amplitude was smaller during the maximal voluntary contraction (MVC) condition, which was a result of a reduction in motor neuron excitability (Kawakami et al., 1988). Moreover, the authors of the aforementioned study suggested that unilateral contractions resulted in sensory input to the spinal cord that could result in the inhibition of motor neurons in the contralateral leg (Kawakami et al., 1988). However, other research contradicted the aforementioned theory of spinal reflexes. That said, Howard and Enoka (1991) reported that electrical stimulation during unilateral contractions resulted in facilitation of the contralateral limb. One particular study reported a BLD in force and EMG activity during reflexively evoked contractions, but the researchers were unsuccessful in demonstrating a BLD during MVC (Khodiguian, 2003). As a result, the spinal reflex contributions to this particular phenomenon are difficult to interpret. According to some researchers, the modulation of the reflexively evoked and MVC may in fact be different, which would make comparisons difficult to interpret (Škarabot et al., 2016).

Based on the available research, it appears that corticospinal and interhemispheric control of the hand and leg muscles are different (Škarabot et al., 2016). Moreover, researchers have suggested that these differences may affect the expression of this particular phenomenon (Brouwer & Ashby, 1990; Luft et al., 2002; Volz et al., 2015). It also appears that there are significant neurological differences between the upper-body and lower-body limbs that may explain observed differences between the two regions of the body. Specifically, research suggests that spinal cord circuits may have a greater effect on lower-limb movements compared to upper-limb movements (Danner et al., 2015). Furthermore, the size of the lower-body limbs appears to directly affect lower-limb movements as well. Because the muscles of the lower-body limbs are much greater in size compared to the upper-body limbs, they may be more difficult to fully activate in order to produce greater force than the smaller muscles of hand grip exercises (Škarabot et al., 2016). As a result, it is quite possible that the larger mass of the lower-body limbs affects the expression of the BLD because the larger muscles affect neural drive (Škarabot et al., 2016).

Neural inhibition. Ohtsuki (1983) was the first researcher to suggest that the BLD may be the result of interhemispheric inhibition. Interestingly, differences in the reaction times for bilateral contractions and unilateral contractions were observed decades before Ohtsuki's published

research. For instance, Gazzaniga and Sperry (1966) reported that the reaction times for unilateral contractions were shorter compared to the reaction times for the bilateral contractions. However, there was no observed differences when the test subjects had both hemispheres of their brains surgically sectioned (Gazzaniga & Sperry, 1966). Some research indicates that there are differences between voluntary control of bilateral and unilateral contractions. Oda and Moritani (1995) demonstrated that during unilateral contractions, the movement-related cortical potentials were more pronounced in the contralateral hemisphere of the brain. Furthermore, the authors also reported that for the bilateral contractions that the cortical potentials were of a lower amplitude, which was confirmed in a similar study performed by the same researchers (Oda & Moritani, 1996). The authors' research also demonstrated that the motor cortices share a common drive for the modulation of maximal bilateral contractions
(Oda & Moritani, 1996). Thus, the aforementioned research indicates that inhibition of the primary motor cortex is the underlying mechanism of the BLD. Oda and Moritani (1996) research also suggested a significant difference between the upper and lower body with regards to the BLD. Specifically, the authors reported that the cortical activity deficit was greater in the non-dominant (left) arm, and that there was a greater deficit in both force and EMG activity for the dominant arm (right) during bilateral handgrip exercises (Oda & Moritanti, 1996). As a result, Oda (1997) suggested that the aforementioned discrepancy demonstrates that the cortical activity changes in the right hemisphere are smaller compared to the effects of change in the left hemisphere. Lastly, Oda (1997) stated that decreased neural input to the motor cortices and/or inhibitory mechanisms in other brainstem pathways need to be thoroughly studied as a potential

mechanism that is responsible for the BLD.

It is important that future studies control for confounding factors that may have influenced the expression of the BLD among the various studies. Surprisingly, many of the published scholarly investigation if this particular phenomenon failed to use randomization of either the unilateral or bilateral conditioning (Škarabot et al., 2016). Based on this information, it is highly probable that either fatigue and/or potentiation may have affected the results (Jakobi & Chilibeck, 2001). To further complicate the interpretation of the currently available BLD investigations, it has been reported that large variability between participants is frequently observed (Škarabot et al., 2016). That said, it has been suggested that the inability to adequately reproduce dynamic tests may in fact be a result of the aforementioned variability among participants, which it is surprising that only a few studies have reported when dramatic differences exist between the participants tested (Taniguchi, 1997; Vandervoort et al., 1984; Vandervoort et al., 1987).

Summary

Although the BLD was first observed nearly five decades ago (Henry & Smith, 1961), this particular phenomenon is not well understood Specifically, the currently available research has not been able to adequately explain the observed differences of the BLD between the upper body and lower body or how joint angle influences the expression of this particular phenomenon. That said, there are a variety of proposed mechanisms underlying the BLD, such as muscle fiber type, perceived exertion, pre-exercise information, and participants’ ability to make postural adjustments, limb dominance, contraction velocity, spinal mechanisms, and increases in reciprocal inhibition in the contralateral limb (Škarabot et al., 2016). However, none of the aforementioned suggested mechanisms adequately explain the differing expressions of this particular phenomenon.

This study is important because it could possibly identify a control limitation for the BLD that can potentially be overridden, which could lead to improved athletic performances. The information gathered from this study can also lead to further research, such as how the BLD can be used to predict athletic injuries. Thus, the knowledge acquired from this study could influence future investigations that may be able to provide strength and conditioning professionals with valuable information that will enable them to design RT programs that result in greater adaptations and fewer injuries.

Chapter 3: Methodology

Participants

The study population consisted of both male and female participants at least 18 years of age with at least one year of resistance training experience. Each participant was required to have incorporated vertical dumbbell pressing movements and leg press exercises into their resistance training program for at least 1 year. Additional inclusion criteria included the ability to demonstrate proper technique for the aforementioned exercises for all training conditions during the screening session, which was supervised and assessed by the principal investigator. All participants were required to fill out the Physical Activity Readiness Questionnaire (PAR-Q) and a health history questionnaire in order to determine whether or not they were free from any neurological and/or neuromuscular conditions that could have affected their safety (Adams, 1999). Exclusion criteria also included any previous and/or current injuries that can compromise the participants' health. The sample size required was 30 participants (19 male, 11 female) as determined by the rule of thumb method. The principal investigator gained IRB approval for the use of human subjects in research prior to the study as well (see Appendix A) and all participants completed an informed consent prior to any data collection (see Appendix A). Furthermore, left-handed individuals were excluded from the study because of previously mentioned research that indicates that it is a potential cofounder. In short, research indicates that left-handed individuals display less grip strength differences, which may be a result of performing more physical activity with their non-dominant hand during activities of daily living that are designed for right-handed individuals (Cornwell et al., 2011).

Procedures

Subject recruitment. Participants were recruited from undergraduate and graduate classes in a sample of convenience at Eastern Michigan University. The principal investigator contacted professors within the Health Promotion and Human Performance (HPHP) department in order to gain approval to make an announcement prior to the start of class time. After the announcement, the principal investigator provided a contact email address for those interested in participating in the study.

Consent/screening session. Prior to the study, all participants were informed of the experimental risks and the potential benefits of the study. During this period of time, participants received detailed information regarding what will be expected of them during each of the two training sessions. Afterwards, sufficient time was allotted to answer any and all questions that the participants might have. Each participant was given an institutionally approved informed consent to sign, and the informed consent was thoroughly explained for those who were still interested in participating.

Anthropometric data. During the screening process, which occurred on Day 1, all participants' anthropometric parameters were assessed once their signed informed consents were completed. Body height was measured in centimeters and body weight in kilograms as per the Center for Disease Control (CDC, 2016). Afterwards, body mass index (BMI) was calculated with the following formula: person's weight in kilograms divided by the square of height in meters (kg/m^2; CDC, 2016). The aforementioned data were measured with a Seca electronic scale for weight and triplicate measures were taken and averaged for all participants to ensure accuracy and height was measured with a stadiometer.

After the anthropometric measurements were recorded, each participant completed a brief familiarization session. During this session, the principal investigator and trained research assistants explained and demonstrated the correct posture that should be maintained during the execution of each exercise protocol, the proper range of motion, and the necessary contraction velocity for each of the training sessions. After each training protocol was demonstrated, the participants performed a supervised movement screening process of the dumbbell vertical press and the leg press exercises both bilaterally and unilaterally. In order to ensure privacy, each participant performed the movement screening process individually. For these screening movements, participants used submaximal weight (30–50% of their self-reported maximal repetition) for a single set of 8–10 repetitions. To ensure safety, trained research assistants were positioned on both sides of all participants for each resistance training session. Successful demonstration of these movements in a biomechanically correct manner was required for each participant in order to participate in the study.

Experimental Design

This study utilized a randomized crossover design in which all participants involved completed the various bilateral and unilateral resistance training exercise protocols on separate days, which allowed participants to act as their own controls. Participants reported to the Eastern Michigan University Running Science Laboratory on three separate occasions on non-consecutive days with Days 1, 2, and 3 being approximately 72 hours apart to allow for muscular recovery. Day 1 consisted of the aforementioned instructional session while Days 2 and 3 consisted of the various training conditions randomly assigned. Each of these training days consisted of either bilateral or unilateral conditions for both the vertical press and the leg press exercises. Participants were tested individually at the Eastern Michigan University Rec/IM in order to ensure privacy. Lastly, all participants were instructed to avoid any strenuous physical activity, such as RT or aerobic exercise, 72 hours prior to testing.

Protocols

Warm up/cool down. Prior to any of the resistance training sessions, each participant was required to warm up for approximately 5 minutes on a treadmill at a comfortable self-selected walking speed between 2 and 4.5 mph at a grade of 0% in order to prepare for physical exertion. This low-intensity warm up was utilized in order to increase heart rate, blood flow, deep muscle temperature, and respiration rate, which prepared the participants for physical exertion (Adelsberger & Tröster, 2014). Following each of the testing sessions, the participants used a similar cool down method to transition from exercise back to a steady state of rest and to reduce delayed onset muscle soreness (Olsen, Sjøhaug, Van Beekvelt, & Mork, 2012).

Maximal bilateral resistance training (RT) sessions. Participants performed both the dumbbell vertical press and the leg press exercises on the same day for both the bilateral and unilateral conditions with the leg press exercise performed first to ensure consistency. A single repetition to failure protocol was utilized for all maximal effort training sessions in which the weight was increased after each successful attempt for both the vertical press and the leg press exercises. Although ULRT and BLRT order was randomized by a computer generator, for each lifting session participants trained the leg press followed by the dumbbell vertical press to ensure consistent relative exertion (e.g., physical effort) between each RT session. Prior to maximal attempts for both sessions, participants began by warming up with 50% of their self-reported one repetition maximum (1RM) for 6–10 repetitions. Afterwards, participants rested 3 minutes and then performed a single repetition at 70% of their self-reported 1RM. The time of rest between each submaximal effort leading up to the participant's maximal effort was exactly 3 minutes. This rest period was measured by a graduate assistant with a stopwatch. Afterwards, the amount of weight lifted was increased by 10% between each successful submaximal lift to ensure standardization among the participants. This process continued for participants until they could no longer increase weight for either exercise. For all trials, participants were instructed to use maximal effort and maximal velocity for each testing condition, and only the repetitions that utilized a full-range of motion were recorded. All data were recorded in an excel spreadsheet, and an additional copy was written onto a printed excel spreadsheet in order to prevent the loss of data. Each participant was assigned a randomly generated numerical identifier, which was matched on a name list stored in a secure location to ensure privacy.

Maximal unilateral resistance training (RT) sessions. For the maximal unilateral RT training sessions, participants performed both the dumbbell vertical press and the leg press with one limb at time. For the unilateral resistance training, participants began by warming up with 50% of their self-reported one repetition maximum (1RM) for 6-10 repetitions. Next, participants rested 3 minutes and then performed a single repetition at 70% of their self-reported 1RM. The weight for the dumbbell vertical press was the same as the weight used in the aforementioned bilateral RT, but only one limb at a time was used. However, for the leg press, the weight was approximately 50% of the weight used by the participants for the bilateral leg press. As was the case for the bilateral resistance training, participants increased the weight utilized by 10% with a 3–minute rest period between breaks to ensure consistency. This process continued for participants until they could no longer increase weight for either exercise. Afterwards, the maximal unilateral lifts for the left and right limbs were summed together to determine the total amount of weight lifted.

Blood Testing Procedures

All participants had their blood glucose concentrations tested just prior to warming up on the treadmill and immediately following the last successful lift for both the bilateral and unilateral dynamic leg press exercises. The finger stick method was utilized to assess pre-exercise and post-exercise blood glucose in order to determine if there are any significant changes. Two of the 30 participants chose not to provide blood samples. Three measures were taken on all participants to ensure accurate measurements. The two values closest in value were averaged and recorded while the third value was discarded.

Statistical Analysis

The mean and standard deviation were calculated for the participants' descriptive characteristics. After the data were collected, the results for each participant were analyzed using paired samples t-tests to examine the difference between unilateral and bilateral vertical dumbbell press and unilateral and bilateral leg press exercises. For the unilateral testing conditions, the sums of the left and right limbs were summed together to compare to the bilateral testing conditions. Need to specify the analysis method for comparing pre- and post-exercise blood glucose concentrations. Data were analyzed with IMB SPSS Statistics 21.0 software.

Chapter 4: Results

The participants' demographic information for the present study was analyzed and is presented in Table 1. As listed below, the total sample (*N*=30) consisted of 11 females and 19 males.

Table 1
Descriptive Statistics of Participants

	N	Minimum	Maximum	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
Height (cm)	30	147.00	185.00	170.13	9.30	-.443	.427	.600	.833
Weight (kg)	30	58.00	99.00	73.73	11.50	.325	.427	-.832	.833
Age (years)	30	19.00	37.00	22.96	3.72	2.399	.427	6.941	.833
Valid N (listwise)	30								

Paired samples t-tests were used to examine the difference between unilateral and bilateral vertical dumbbell shoulder press and unilateral and bilateral dynamic leg press exercises. Results for all four testing conditions are found in Table 2.

Table 2
Differences Between Bilateral and Unilateral Testing Conditions

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1	bi-leg press - uni-leg press	107.516	96.5975	17.6362	71.4466	143.5868	6.096	29	.000
Pair 2	bi-vertical press - uni-vertical press	.667	13.113	2.394	-4.230	5.563	.278	29	.783

The analysis of the data as presented in Table 2 above and Figure 1 below failed to support Hypothesis 1 that the maximal muscular strength would be greater during the ULRT condition for the leg press exercise. Although the results demonstrated a significant difference between the two training condition for the leg press exercise ($\bar{x}$ = 107.516, *SD* = 96.5975) and (t(29) = 6.096, *p* = .000) the maximal muscular contraction strength was greater for the BLRT condition ($\bar{x}$ = 495.23, S = 209.17) rather than the ULRT condition ($\bar{x}$ = 387.72, S = 209.49). Overall, 28 participants displayed a BLF while two displayed a BLD.

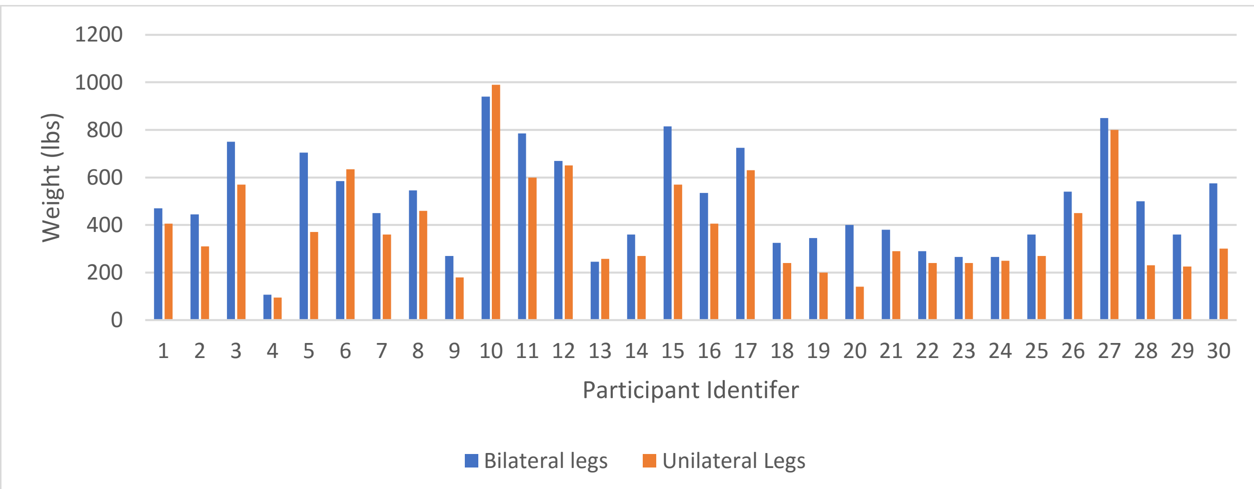

Figure 1. Bilateral vs. unilateral maximal strength values for dynamic leg press.

It was hypothesized that participants would be stronger for the ULRT condition than the BLRT condition for the vertical dumbbell shoulder press exercise. However, as found in Table 2 above and Figure 2 below, the data analysis did not reveal a significant difference between either the BLRT condition ($\bar{x}$ = 99, S = 36.42) or the ULRT condition ($\bar{x}$ = 98.33, S = 32.76) for the vertical dumbbell shoulder press exercise (Mean difference = .667, S = 13.113) and (t(29) =.278, *p* = .783). Fifteen participants displayed a BLD, 14 participants displayed a bilateral facilitation (e.g., stronger during bilateral lifts), and one participant was equally strong during both training conditions. Thus, the results of this particular study failed to the support hypothesis that the maximal muscular strength displayed would be greater for the ULRT condition for this particular exercise.

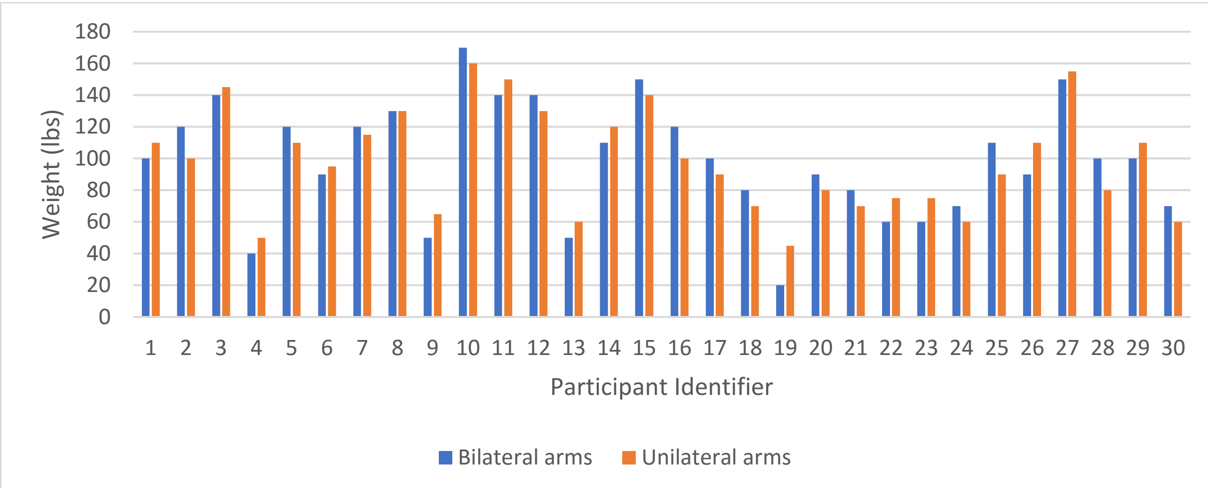

Figure 2: Bilateral vs. Unilateral Maximal Strength Values for Vertical Dumbbell Press

Table 3.
Descriptive Statistics of Plasma Blood Glucose Values

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	pre-bi-leg-glucose - post-bi-leg-glucose	-.714	14.060	2.657	-6.166	4.738	-.269	27	.790
Pair 2	pre-uni-leg-glucose - post-uni-leg-gluc	-2.250	9.644	1.823	-5.990	1.490	-1.235	27	.228

It was hypothesized that no significant difference would be observed in plasma blood glucose levels between the BLRT condition and the ULRT conditions for the dynamic leg press exericse. The following values were observed for the plasma blood glucose for the dynamic leg press exercise: BLRT condition (pre-exercise $\bar{x}$ = 98.96, S = 13.84; post-exercise $\bar{x}$ = 99.68, S =

16.57) and ULRT condition (pre-exercise $\overline{x}$ = 98.54, S = 10.98; post-exercise $\overline{x}$ = 100.79 S = 12.15). The results for changes in plasma blood glucose between the two testing conditions, as listed in Table 3 above and displayed in Figure 3,– below, did not reach significance for neither the unilateral condition ($\overline{x}$ = -2.250, *SD* = 9.644) and (t(27) = -1.235, *p* = .228) nor the bilateral condition ($\overline{x}$ = -.714, *SD* = 14.060) and (t(27) = -.269, *p* =.790). Thus, the analysis of data supported the hypothesis that no significant changes in plasma blood glucose would be observed between the two conditions.

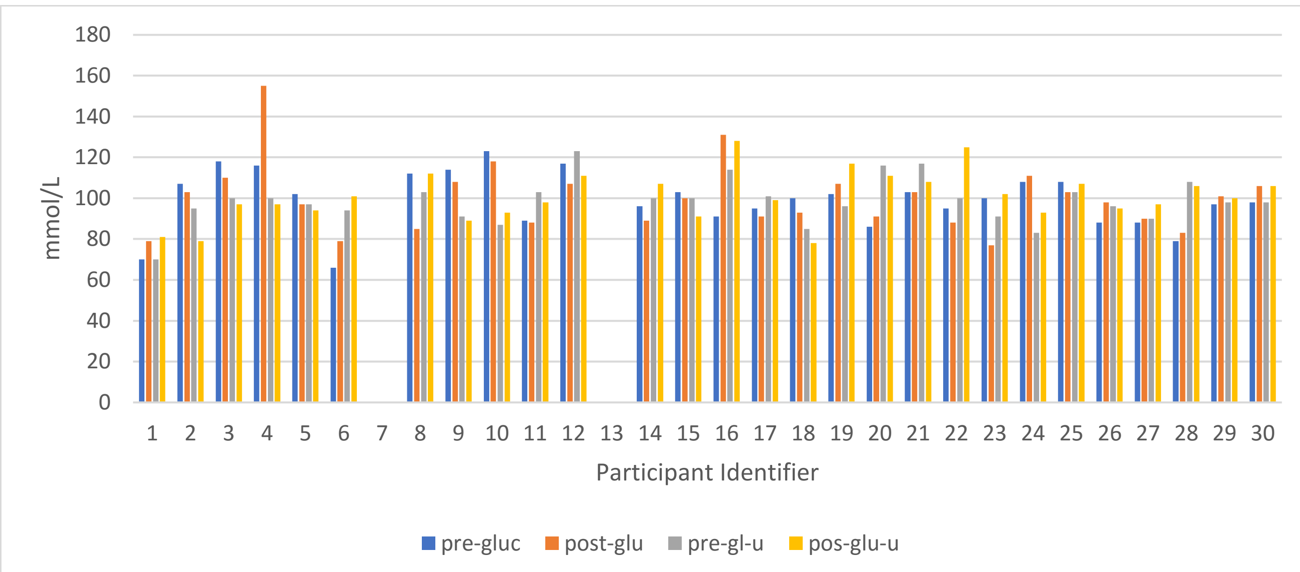

Figure 3. Pre-exercise and post-exercise plasma blood glucose values.

Chapter 5: Discussion

The purpose of the current project was twofold. First, to determine if significant differences existed between maximal muscular strength between ULRT and BLRT for the dynamic leg press and vertical dumbbell press exercises. Second, to determine whether or not plasma blood glucose levels would significantly differ between the two experimental conditions. Although there was a significant difference between the bilateral and unilateral testing condition for the dynamic leg press exercise, participants were stronger during the BLRT condition rather than the expected ULRT condition. While it was hypothesized that participants would be stronger during the ULRT condition, there was no significant difference between the bilateral and unilateral testing condition for the vertical dumbbell shoulder press exercise. The hypothesis that no significant differences in plasma blood glucose levels would be observed between the BLRT and ULRT condition was supported by the analysis of data.

Previous BLD Research

As previously discussed, although the vast majority of research studies reported a BLD, there are some published studies that have reported a BLF (Behm et al., 2003; Buckthorpe et al., 2013; Häkkinen et al., 1993; Häkkinen et al., 1996; Jakobi et al., 1998; Herbert et al. 1996; Khodiguian et al., 2003; Magnus et al., 2008; MacDonald et al., 2014; Schantz et al., 1998; Secher et al., 1975; Secher et al., 1998; Taniguchi et al., 1997; Vandervoort et al., 1987; Veliekas et al., 2013). While these 15 scholarly investigations have failed to report a BLD, the vast majority of the published studies have established the existence of this particular phenomenon. Specifically, 62 of the 77 BLD investigations that have been published to date have reported to have observed a BLD (Škarabot et al., 2016). Thus, there is sufficient data to establish the existence of this particular phenomenon.

Types of Muscular Contractions

It is important to note that relatively few of the scholarly investigations of this phenomenon used contraction models that were relevant to the present study. Of the available 77 BLD investigations, most of the studies utilized isometric contractions while only nine used dynamic contraction models (one eccentric, eight concentric contractions; Škarabot et al., 2016). As a result, there is a tremendous gap in the scholarly literature examining the BLD effects on contraction models frequently utilized in typical RT programs. Most of the BLD investigations available that used the leg press exercise utilized isometric strength measures, which dramatically differ from the dynamic leg press exercise used in the present study. Specifically, motor units within the muscles are activated in different manners during the lengthening and shortening phases of eccentric and concentric movements (i.e., full range of motion exercises) for dynamic movements compared to isometric movements (i.e., static exercise; Gardiner, 2011). Simply stated, most of the BLD investigations used exercise models that dramatically differ compared to exercises that are typically used by athletes and general populations.

Previous Dynamic Leg Press Investigations

To the author's best knowledge, there are only two published peer-reviewed studies that assessed the BLD with the dynamic leg press exercise. With that being said, the results of the present study are in contrast to the two currently available studies that reported a greater maximal muscular strength during ULRT when compared to BLRT for the dynamic leg press exercise. Specifically, Hay et al. (2006) and Magnus et al. (2008) reported that the maximal muscular strength was significantly greater for participants when performing the dynamic leg press exercise during the ULRT condition. It is important to note that the aforementioned studies had relatively small sample sizes of five and eight participants, respectively, and while the participants' training history for Hay et al. (2006) was not defined, Magnus et al. (2008) selected participants not currently involved in formal strength training programs. As a result, it is questionable whether or not these two studies are generalizable to other populations (e.g., highly-trained populations). Due to the lack of data using the dynamic leg press in BLD research, it is difficult to make inferences based on previous studies as to why the participants in the present study overwhelmingly displayed a BLF during the leg press exercise (i.e., 28 BLF, 2 BLD).

Effects of Previous Training History

It is worth mentioning that all of the participants for the present study self-reported the twice-weekly use of a bilateral exercise, the back squat, in their strength training programs. Having said that, one plausible explanation for why a BLF was overwhelmingly observed may be the result of the participants' training history prior to the study. Thus, the chronic bilateral stimulus of the back squat may have resulted in the prominence of the BLF for the leg press exercise during the present study. This is an important point because the limited amount of data available indicates that chronic and/or high-intensity training may decrease or possibly reverse the BLD (Nijem & Galpin, 2014). This assertion is based on previously discussed cross-sectional research indicating that the prevalence and magnitude of the BLD may be dramatically influenced by the participants' sport and exercise training history (Nijem & Galpin, 2014). For instance, Secher et al. (1988) reported that elite level rowers (i.e., world-class rowers) demonstrated a BLF. In contrast, the same study also found that the participants classified as non-elite rowers (i.e., club rowers) demonstrated a BLD (Secher et al., 1988). There is one other available peer-reviewed article examining the BLD, and it also compared highly trained participants with those who were not considered highly trained. Specifically, Howard and Enoka (1985) demonstrated that, while highly trained weight lifters and cyclists displayed a BLF, sedentary participants displayed a BLD. Taken together, these two studies indicate that the expression of this particular phenomenon may in fact depend on the participants' exercise and sport history. However, there is an insufficient amount of data examining the differences between highly trained and those not classified as such to determine how training history affects whether a BLD or BLF is observed. The major limitation of the present study is that a complete training history of the participants was not collected. This is an important point due to the fact that a limited number of published studies have reported that BLRT reduced the BLD while ULRT increases the magnitude of the BLD (Nijem & Galpin, 2014).

The research presented by Secher et al. (1988) and Howard and Enoka (1985) is relevant to the current study because, as previously mentioned, all of the participants for the present study had at least 1 year of RT. However, conclusions regarding the data collected during this present study must be interpreted with caution because the effects of previous training history on this particular phenomenon are not entirely understood at this time. Although a limited number of studies suggest that training history may influence whether or not a BLD is observed, the number of studies investigating how training influences this particular phenomenon are few (Škarabot et al., 2016). Thus, additional studies are necessary to determine how various RT protocols affect the magnitude of the BLD. This lack of understanding is also due to the fact that there are few BLD investigations that used dynamic contractions and the number of participants used were relatively small; thus, definite conclusions regarding how training history affected the results of the present study are not possible at this time.

A few longitudinal studies provide further evidence of how the BLD can be affected by training history. For instance, Kuruganti and Seaman (2006) noted that a short-term BLRT regimen (6 weeks) dramatically reduced the BLD equally in young/middle-aged (18–35) as well as old (55–75) males and females. However, the aforementioned study did not use participants who would be considered highly trained. Interestingly, there is one long-term RT study available that examined how training with the leg press exercise affects this phenomenon. Chilibeck et al. (2006) reported that a 26-week long training program performed 3 times a week resulted in a significant reduction of the BLD by the BLRT group while the ULRT did not reduce their BLD measures. Based on these results, the authors concluded that BLRT is the preferred method of training for activities and sports that require the contraction of both limbs simultaneously (Chilibeck et al., 2006). In addition, the authors suggested that the BLD was inversely related to a participant's measured BLD prior to the study (Chilibeck et al., 2006). In other words, participants with a larger BLD could more easily reduce their BLD through BLRT.

Currently, there is very little research that examines how ULRT impacts this particular phenomenon. That said, one scholarly article reported that ULRT dramatically changed the BLD in a relatively short period of time. Specifically, Taniguchi et al. (1997) noted that ULRT increased the BLD rather than reducing it. An impressive feature regarding this study is that the authors repeated the experimental testing conditions 3 times with different participants and with varying contraction models and reached the same general conclusions (Taniguchi et al., 1997). Although there is a paucity of data regarding how BLRT and ULRT affect the BLD, these few studies suggest that the modality of training utilized may affect this phenomenon. However, there are only a handful of studies and additional research is needed to confirm the aforementioned findings before any inferences can be made with certainty.

Although all of the participants in the present study self-reported routinely utilizing the leg press exercise in their RT programs, it is unknown whether or not participants performed this particular exercise bilaterally or unilaterally leading up to the study. Likewise, neither information regarding other lower body exercises used by the participants in their training programs nor the manner in which such exercises were performed was collected (e.g., lunges, leg extensions, leg curls). Based on the aforementioned studies that examined how training history affects the BLD, it stands to reason that if bilateral exercises reduce the BLD and unilateral exercises increase the BLD, that the volume of exercise and the manner in which they are performed (i.e., BLRT, ULRT) will contribute to whether or not this particular phenomenon is observed. This lack of information gathered prior to the present study is critically important because, as already mentioned, a limited number of published studies indicate that training methodology can decrease or even reverse the BLD (Najem & Galpin, 2014). Not collecting this information was a limitation that future studies need to address.

Because of the dearth of data, the current body of research does not provide enough information to say with any certainty whether or not a BLD is a typical outcome during the vertical dumbbell shoulder press. It is important to note that the one published article examining the BLD for the vertical dumbbell shoulder press measured muscular endurance during testing conditions (Costa et al., 2015), which significantly differs from maximal muscular strength (Škarabot et al., 2016). Furthermore, the only other published research study examining the BLD and the shoulder joint examined shoulder flexion with a cable pulley contraption, which also significantly differs in terms of muscle fiber recruitment compared to the shoulder press exercise used in the present study (Aune, Aune, Ettema, & Vereijken, 2013). This is an important point due to the dramatic differences between free weight and machine exercises. With that being said, it is well established that free weight exercises increase the stabilization requirements for a particular joint of the body compared to machine exercises that replicate the same movement patterns (McCaw & Friday, 1994).

Core Musculature Activation Patterns

There are important differences with regards to the activation patterns of various muscle groups between unilateral and bilateral vertical shoulder press exercise. Saeterbakken et al. (2012) reported unilateral vertical shoulder press resulted in greater neuromuscular activation of the core musculature compared to bilateral vertical shoulder press. Moreover, the aforementioned research examining EMG activation demonstrated a twofold activation of the rectus abdominis during the unilateral contraction compared to the bilateral contraction for the vertical dumbbell press testing condition (Saeterbakken et al., 2012). The authors concluded that this increased activation of the core region was a result of the destabilizing torque from performing the exercise unilaterally compared to bilaterally (Saeterbakken et al., 2012). Thus, there are dramatic differences between ULRT and BLRT for the vertical dumbbell press exercise that may have influenced the results of the present study. To the author's best knowledge, the present study is the only BLD investigation that has compared the maximal muscular strength between the bilateral and unilateral conditions for the vertical dumbbell shoulder press during a full range of motion.

Effects of Core Activation Patterns

Previous research has shown that, in some circumstances, core activation can influence the BLD, which may be another reason why prior training history could have influenced the results of the current study. For example, for training conditions that result in greater core activation, the absolute weight lifted could be greater if a participant's previous training focused on developing strength and power in the core region. In other words, a participant who developed strength and power for the core region would be able to generate more torque compared to a participant with weak core musculature. It is well established that maximal strength and power of the core muscles can be developed through the use of weight loads (e.g., dumbbells, weighted plates, resistance bands, medicine ball work) through multiple planes of motion (Willardson, 2007). Once again, previous research has shown that, in some circumstances, core activation can influence the expression and magnitude of particular phenomenon. Because the effects of core musculature action and how it affects this phenomenon during various exercises is not currently well understood, and the strength and power development of the participants' core region is unknown, comparing the results from this particular study to other scholarly BLD research is difficult at best.

Effects of Upper-Body Training Protocols

It is possible that individual differences in upper-body-resistance-training methodology prior to the present study (i.e., BLRT or ULRT) may have influenced whether or not a participant was stronger unilaterally or bilaterally for the vertical dumbbell shoulder press testing. As previously discussed, Kuruganti and Seaman (2006) reported that a 6-week training intervention of BLRT significantly reduced the magnitude of the BLD. Not only were the aforementioned results consistent for the lower-body exercises, but they also held for the upper body exercises as well (i.e., lat pulldown, biceps curl, shoulder press, and bench press). Thus, it appears that a short-term training intervention can potentially alter this particular phenomenon for both the upper body and lower body in a variety of exercises. However, many of these exercises were machine weights rather than free weights that have differing postural requirements and muscle recruitment patterns (e.g., stabilizing muscles). Similarly, Botton et al. (2015) reported that ULRT potentiated unilateral specific strength for recreationally active young females. Based on the information collected from these relatively few studies, it stands to reason that whether or not a BLD or BLF is observed for this particular exercise may also depend on training methodology. Thus, the lack of significant difference between the ULRT and BLRT for the vertical dumbbell shoulder press in the present study may be the result of whether or not participants performed this exercise unilaterally or bilaterally prior to their participation in the present study. However, it is important to note that prior to testing, all participants confirmed that they used this particular exercise, not the manner in which it was performed. Although the results for this particular exercise may have been influenced to some degree by specific training conditions (i.e., ULRT vs BLRT) prior to the study, definite conclusions cannot be made with any certainty due to a lack of information regarding the participants' training history.

As previously mentioned, the limited data available suggests that chronic high-intensity training and/or training volume performed bilaterally decreases or even eliminates the BLD (Nijem & Galpin, 2014). Although the results for the leg press exercise may potentially align with this research because each participant utilized a popular bilateral exercise (i.e., the back squat), it is much more difficult to explain the present study findings for the vertical dumbbell shoulder press. In other words, definite conclusions are not possible regarding why the number of BLD and BLF among the current participants was nearly evenly split for the vertical dumbbell shoulder press (15 BLF, 14 BLD, and 1 equally strong in both conditions). Despite a few available studies indicating that training influences this complex phenomenon, no information other than the regular use of the vertical dumbbell shoulder press by the participants was gathered. However, it stands to reason that the ability to counterbalance while performing this particular exercise may have impacted the results of the present study. Research has demonstrated that additional torque can be produced when postural adjustments are made while performing resistance training exercises, and the vertical dumbbell shoulder press allows for greater opportunities to counterbalance than the leg press in order to generate additional torque (Škarabot et al., 2016). Thus, a possible explanation for the dramatic difference in data for the vertical dumbbell shoulder press compared to the leg press is that the stability requirements during the heavier loads affected the participants differently, resulting in differing postural adjustments to generate torque. Similarly, although there is little research, antagonist activation may have influenced the present study results for the vertical dumbbell shoulder press. For example, Creswell et al. (2002) demonstrated that a burst of EMG activity in contralateral limb during ULRT. Thus, there is the potential that during ULRT, that some of the participants may have elicited a burst of muscle activity in the contralateral limb that can increase torque. However, because EMG activity was not measured during testing for this study, any speculation regarding the aforementioned effects of torque and how it influenced the data collected for the aforementioned exercises is not possible.

Plasma Blood Glucose

As listed in Table 3, there were no significant differences in plasma blood glucose levels between the BLRT and ULRT conditions. Although to the author's best knowledge there are no currently published studies examining the differences between these conditions, these results align with the present understanding of human physiology. The concept of homeostasis indicates that a bodily mechanism is responsible for maintaining internal milieu (Merrill, 2008). In addition, it is important to note that plasma glucose levels are one of the most tightly controlled physiological parameters within the body at all times (Boron & Boulpaep, 2012). The results of this particular study are in accordance with the available research because plasma glucose levels did not significantly differ between the two training conditions. This was expected because, as previously discussed, plasma glucose levels do not dramatically change during a single bout of resistance training for healthy, well-fed individuals (Fleck & Kraemer, 2014). It is also important to note that, to the author's best knowledge, there is no published study at this time that compares the effects of BLRT and ULRT on plasma blood glucose levels.

Strengths and Limitations

An important strength of the current study is that all of the participants had at least 1 year of RT. Thus, it is highly unlikely that the observed differences between the two testing conditions were the result of the participants being inexperienced with regards to RT (i.e., neuromuscular learning). Another strength of the present study is that participants' body positioning was standardized for all participants in order to prevent differing biomechanical movement patterns. For instance, for the leg press exercise, all participants placed their feet shoulder width apart at the center of the point of contact on the leg press machine to ensure standardization. Likewise, for the vertical dumbbell shoulder press, participants sat on a weight bench without a back support with their feet shoulder width apart and their legs bent at 90 degree angles. These body positions were used for both the BLRT and ULRT for this particular study. The use of a full range of motion for the exercises used in the present study was another important strength of the present study. This is an important feature because, as previously mentioned, most of the available BLD studies used isometric contractions, and athletes and general populations almost always utilize a full range of motion while performing RT exercises.

A limitation of the present study was that a complete training history was not collected for the participants, which may have provided valuable information to help better understand how recent RT influences whether or not a BLF or BLD is observed. As a result, it is imperative that future studies obtain complete training histories of all participants to better understand how BLRT and ULRT prior to the start of a study influence the expression of the BLD. In addition, more intervention studies are necessary to better understand how both BLRT and ULRT influence this complex phenomenon. Although research indicates that chronic BLRT and ULRT influence the expression of the BLD (Howard & Enoka, 1985; Khodiguia.n et al, 2005; Kuruganti, Parker, Rickards, Tingley, & Sexsmith, 2005; Janzen et al., 2006; Secher, 1975), these studies are few in number, and further investigations are necessary to confirm the findings of the few intervention studies examining the BLD (Škarabot et al., 2016). Another important limitation of the present study is no EMG recordings were taken during this study in order to compare muscular activation patterns during the two testing conditions. As previously discussed, research has demonstrated that there exist significant differences in muscular activation patterns between BLRT and ULRT (Škarabot et al., 2016). As a result, inferences regarding how different musculature activation (e.g., rectus abdominis, spinae rectus) as a result of counter balancing, antagonist activation, or synergist musculature cannot be made with any certainty. Because of this, it is important that future research utilize EMG assessments during BLRT and ULRT to better understand how postural adjustments, antagonist activation, coactivation of synergist muscles, and varying core muscular activation patterns differ between the aforementioned testing conditions and their influence on the BLD. However, the vast majority of the published studies that did record EMG used isometric measures, which as previously mentioned, dramatically differ from exercises that are performed in a full range of motion. Lastly, diet was not controlled for any participants at any point during the study. Thus, there is the potential that participants' baseline plasma glucose levels were not consistent between Testing Session 1 and Testing Session 2. For future investigations, it is important that diet is controlled to ensure standardization.

Conclusions

This study sought to determine if a BLD would be observed for participants with at least one year of previous RT experience for the vertical dumbbell press and the dynamic leg press exercises, and if significant differences would be observed in plasma blood glucose between the BLRT and ULRT conditions. Analysis of data did not reveal a BLD for the vertical dumbbell press. Although a significant difference was observed for the dynamic leg press exercises, it was for the bilateral condition and not the hypothesized unilateral condition. Thus, the first hypothesis was not supported by the analysis of the data collected. However, the second hypothesis was supported due to the fact that no significant difference was observed in plasma blood glucose levels between the BLRT and the ULRT conditions for the dynamic leg press exercise.

Recommendations for Future Research and Actions

At this point in time, the relationship between the BLD and physical performance is largely unknown due to a lack of information. Furthermore, more research is needed to understand whether or not this complex phenomenon influences sports-related injuries. In conclusion, the BLD is a complex phenomenon that is not well understood, and because of the limited amount of relevant data available, recommendations regarding BLRT and ULRT for athletics and general populations cannot be made with any certainty at this point in time.

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Appendix A: Permission Letter

Hello James,

This email serves as confirmation that your study, entitled "A comparison between upper-body and lower-body maximal strength," was approved under Expedited review by the EMU Human Subjects Review Committee on February 15, 2017.

Please let me know if you need anything else.

Best,

Sonia

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Appendix B Consent Form

RESEARCH @ EMU

Informed Consent Form

The person in charge of this study is James Lee Ramsey and is a graduate student at Eastern Michigan University. His faculty adviser is Dr. Moore. Throughout this form, James Lee Ramsey will be referred to as the "investigator."

Purpose of the study

The purpose of this research study is twofold: first, this study will attempt to determine whether or not the use of one limb at a time while performing the vertical dumbbell press and leg press exercises results in greater muscular strength outputs compared to the identical movement patterns performed with both limbs simultaneously. Second, this study will evaluate whether or not plasma glucose concentrations significantly differ between the one limb at a time and the both limbs simultaneously training conditions.

What will happen if I participate in this study?

Participants will report to the Eastern Michigan University exercise physiology laboratory on three separate occasions on non-consecutive days with a 72 hour rest period separating all visits to allow for complete muscular recovery. During visit 1, the purpose of the study will be explained, health history forms will be completed, height and weight will be measured to calculate body mass index (BMI), and any and all questions will be thoroughly answered. Next, participants will perform the movement screening process using submaximal weight for aforementioned exercises with one limb at a time and both limbs simultaneously for an assessment of proper technique. The testing conditions for the maximal strength for the one limb at a time and both limbs simultaneously for both these exercises will occur during visits 2 and 3.

Before each resistance training session, participants will sufficiently warm up on a treadmill for five minutes at a comfortable self-selected pace. All participants will be tested for maximal muscular strength for the leg press and the vertical dumbbell press with one limb at a time and both limbs simultaneously during both visit 2 and visit 3. After properly warming up, all participants will progressively increase the amount of weight lifted following a three minute rest period until they can no longer perform a repetition. Plasma glucose samples will be collected for all participants following the leg press exercises for all training conditions via the finger stick method.

Following the treadmill warm up, participants will perform 6-10 repetitions with 50% of their self-reported one repetition maximum (1RM). Afterwards, participants will perform a single repetition at 70% of their self-reported 1RM. The time of rest between all resistance training efforts will be exactly 3 minutes. Afterwards, the amount of weight lifted will be increased by 10% between each successful submaximal and this process will continue for participants until they can no longer increase weight for either exercise.

All data will be recorded in an Excel spreadsheet, and an additional copy will be written onto a printed out Excel spreadsheet in order to prevent the loss of data. Each participant will be randomly assigned a randomly computer generated number, which will be matched on a name list stored in a secure location to ensure privacy.

Participants will perform both maximal leg press and the vertical dumbbell press exercises with one limb at time. For the unilateral vertical dumbbell press, participants will begin by warming up with 50% of their self-reported one repetition maximum (1RM) for 6-10 repetitions, which will be the same weight that will be used during the maximal bilateral resistance training session, however, only one limb will be used in isolation. Next, participants will rest 3 minutes and then will perform a single repetition at 70% of their self-reported 1RM. The increases in weight for the unilateral vertical dumbbell press will be 10% between each successful attempt as was used in the aforementioned bilateral resistance training. For both the leg press and vertical dumbbell press exercises, all participants will complete all of the required repetitions for the dominant limb first, then, all of the required repetitions for the non-dominant limb. However, for the unilateral leg press, the weight will be approximately 50% of the weight used by the participants for the bilateral leg press until repetition maximum is achieved.

All participants will have their plasma glucose concentrations tested 15 minutes prior to the aforementioned treadmill warm up and 15 minutes following the last successful repetition for the leg press press exercise. The finger stick method will be utilized to assess pre and post exercise plasma glucose concentrations during visits 2 and 3 in order to determine if there are significant differences between the bilateral and unilateral leg press conditions. 3 measures will be taken for all participants to ensure accuracy.

What are the anticipated risks for participation?

There are no anticipated significant risks associated with this particular study. However, participants may experience mild delayed onset muscular soreness as a result of participation. Participants might also experience slight discomfort because blood samples will be collected via the finger stick method, which will require a slight prick of the fingertip in order to obtain a small sample of blood.

Are there any benefits to participating?

The potential benefits from participating in this study include learning more effective strength and conditioning methods that can result in greater improvements in maximal muscular strength and muscular power outputs.

What are the alternatives to participation?

The alternative is not to participate.

How will my information be kept confidential?

We will keep your information confidential by collecting all of your data individually and storing this information on a password protected Excel spreadsheet on a password protected laptop. All data will be deidentified. Furthermore, neither your name nor any personal identifiers will be associated with the data collected from you. Only the principal investigator and the thesis chair will have access to the data.

We will make every effort to keep your information confidential, however, we cannot guarantee confidentiality. There may be instances where federal or state law requires disclosure of your records.

Other groups may have access to your research information for quality control or safety purposes. These groups include the University Human Subjects Review Committee, the Office of Research Development, the sponsor of the research, or federal and state agencies that oversee the review of research. The University Human Subjects Review Committee is responsible for the safety and protection of people who participate in research studies.

We may share your information with other researchers outside of Eastern Michigan University. If we share your information, we will remove any and all identifiable information so that you cannot reasonably be identified.

The results of this research may be published or used for teaching. Identifiable information will not be used for these purposes.

Storing study information for future use

We would like to store your information from this study for future use related to bilateral deficit in the field of strength and conditioning. Your information will be labeled with a code and not your name. Your information will be stored in a password-protected or locked file. Your de-identified information may also be shared with researchers outside of Eastern Michigan University. Please initial below whether or not you allow us to store your information:

__________Yes   ___________No

Are there any costs to participation?

Participation will not cost you anything.

You will be responsible for your transportation costs to and from the study.

Will I be paid for participation?

You will not be paid to participate in this research study.

Study contact information

If you have any questions about the research, you can contact the Principal Investigator, James Lee Ramsey, at jramsey9@emich.edu or by phone at 734-717-1603. You can also contact Becca Moore at rmoore41@emich.edu or by phone at 734.487.2824

For questions about your rights as a research subject, contact the Eastern Michigan University Human Subjects Review Committee at human.subjects@emich.edu or by phone at 734-487-3090.

Voluntary participation

Participation in this research study is your choice. You may refuse to participate at any time, even after signing this form, with no penalty or loss of benefits to which you are otherwise entitled. You may choose to leave the study at any time with no loss of benefits to which you are otherwise entitled. If you leave the study, the information you provided will be kept confidential. You may request, in writing, that your identifiable information be destroyed. However, we cannot destroy any information that has already been published.

Statement of Consent

I have read this form. I have had an opportunity to ask questions and am satisfied with the answers I received. I give my consent to participate in this research study.

Signatures

____
Name of Subject

____ _____________________

Signature of Subject Date

I have explained the research to the subject and answered all his/her questions. I will give a copy of the signed consent form to the subject.

____

Name of Person Obtaining Consent

____

Signature of Person Obtaining Consent Date