The effects of training status and exercise intensity on plyometric exercise volume

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The Effects of Training Status and Exercise Intensity on Plyometric Exercise Volume

A thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

Kevin J. Cronin
June 2010
MASTER’S THESIS

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Kevin J Cronin
June 25th, 2010
ABSTRACT

The purpose of the present study was to examine the effect of training status and exercise intensity on the volume of repetitions completed before propulsive force output decreases below 90 percent of maximum force output. We also examined the effect of training status and exercise intensity on the change in eccentric rate of force development (E-RFD) and contact time (CT) across exercise repetitions (depicted as the slope of the regression line relating the E-RFD and repetitions, and the slope relating CT for each repetition completed). Thirty subjects were recruited from the university population (15 plyometrically trained and 15 recreationally trained). Testing took place on two separate days. On day one of testing subjects completed a dynamic warm up, jump assessment, 1RM leg press, and six maximal effort jumps. On day two of testing subjects completed a dynamic warm up along with continuous low (counter movement jumps) and moderate (box jumps at 25% of subjects height) intensity plyometric exercises that were randomly assigned. A regression analysis of E-RFD and CT was used to observe the trends across all repetitions for both intensities in both subject groups. Repetitions completed in each condition were broken into quartiles for each subject, and mean quartiles were analyzed for E-RFD and CT to observe the trends between the two groups at each intensity. The statistical analysis used within the present study were two three-way mixed factors analyses of variance (ANOVA) to evaluate the effect of exercise intensity, repetition quartile, and training status on E-RFD and CT. The results of the regression analysis for E-RFD and CT for the CMJ and box jumps revealed that there was a great deal of variability between the recreationally trained and the plyometrically trained subjects when looking that the positive and negative slopes of the regression lines. The quartile analysis for E-RFD and CT revealed difference in the rate of decline in E-RFD
and CT between the plyometrically and recreationally trained subjects across the four quartiles. The statistical quartile analysis for E-RFD revealed a significant exercise by quartile interaction ($p = .03$) with the simple effects revealing a significant difference in E-RFD between quartile 3 ($p = .01$) and quartile 4 ($p < .001$). The statistical quartile analysis for CT revealed a significant quartile by group interaction ($p = .009$) with the simple effects revealing a significant effect of quartile on contact time ($p = .002$) in the recreationally trained group. A significant exercise by group interaction ($p = .047$) was also revealed with the simple effects showing a significant difference in contact time between exercises in both the plyometrically trained ($p = .021$) and recreationally trained ($p < .001$) groups. These findings indicate that there were differences in E-RFD and CT when comparing regression and quartile analysis of the trained and recreationally trained groups at the two different intensities of plyometric exercises. Although, in some instances it was observed that the plyometrically trained subjects ‘performed’ better than their recreationally trained counterparts, the results of the present study reveal a applicable difference in E-RFD and CT between the third and fourth quartiles among the two groups.
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Chapter I
The Problem and Its Scope

Introduction

Plyometric exercises and training programs have been used for many years by coaches and athletes to increase performance in strength and power-related sports. These exercises, which include explosive jumping, bounding, and throwing, attempt to link strength with speed of movement in order to optimize performance (Chu, 1998). Plyometric exercise can be defined as a quick, powerful movement using a pre-stretch, or countermovement, that involves the stretch shortening cycle (SSC) (Wilk, et al., 1993). These types of movements are used to train muscles to optimally use the SSC to produce maximal force in as short amount of time as possible. Training programs that use plyometric movements have been shown to be extremely beneficial for sports performance, as indicated through the improvement of force production, improved running economy, decreased sprint times, increased jump height, and increased in peak power (Brown, Mayhew, & Boleach, 1986; Gehri, Ricard, Kleiner, & Kirkendall, 1998; Luebbers et al., 2003; Ronnestad, Kvamme, Sunde, & Raastad, 2008; Turner, Owings, & Schwane, 2003; Villarreal, Gonzalez-Badillo, & Izquierdo, 2008). It has also been observed that previously recreationally trained males experienced an increase in muscle cross-sectional area, peak power, and countermovement jump height, and strength improvements after a 12-week plyometric training program (Vissing, et al., 2008). These exercises can be accomplished using different types of jumps (in place and standing), hops (multiple or single), bounds, as well as shock movements (box jumps or depth jumps) and all have been used to activate the SSC during a plyometric movement (Chu, 1998; Baechle & Earle, 2000). There is strong evidence supporting the benefits of plyometric training programs in individuals with various training backgrounds,
but this is not the case when it comes to the optimal manipulation of the training variables within these programs. The plyometric programs used to elicit these benefits are mainly based on anecdotal evidence, and are not necessarily supported by research.

In accordance with the National Strength and Conditioning Association’s (NSCA) position statement on explosive training and numerous SSC fatigue studies, plyometric exercises need to be done when the individual is not fatigued, physiologically or neuromuscularly, in order to obtain the highest power output during each repetition. As the number of repetitions increase during a set of plyometric movements, power output decreases below maximum power output. Likely due to fatigue, this may alter technique and lead to counterproductive training and a possible increase risk for injury. The manipulation of acute program design variables such as duration, frequency, rest periods, volume, and intensity provide practitioners with various avenues for individualizing training programs for athletes. Although limited research is available regarding these variables, practitioners who are knowledgeable about various program design parameters related to resistance training, endurance training, agility training, and speed training can use this knowledge and apply it to plyometric training. Ideally, there should be clear research based guidelines that can be used to initiate adaptation through plyometric training. Specifically, there is little research on the recommended training volume of repetitions for plyometric training. Volume for plyometric training programs is a vital component that needs to be clarified for practitioners. With more information on training volume, practitioners can monitor training to prevent overtraining and plateaus in development, and promote optimal training outcomes due to the improved knowledge of volume of repetitions completed before power output decreases. The present study was undertaken to allow for a more accurate and adequate way to equate volume for
plyometric training program design and progression. The purpose of the present study was to evaluate volume of repetitions related to power output completed at two different intensities between trained and recreationally trained subjects. In identifying the volume of repetitions completed at two intensities, it is our hope that this information can provide strength and conditioning practitioners research based information with regards to the manipulation of volume among this subject population. Although research is lacking with regards to the manipulation of training variables, there are some techniques, guidelines, and characteristics involved that need to be understood before the implementation of a plyometric training program.

**Purpose of the Study**

The purpose of the present study was two-fold. First, we set out to examine the effect of training status and exercise intensity on the volume of repetitions completed before propulsive force output decreases below 90 percent maximum force output. Second, we examined the effect of training status and exercise intensity on the change in eccentric rate of force development (E-RFD) and contact time (CT) across exercise repetitions (depicted as the slope of the regression line relating the E-RFD and each repetition completed and the regression line relating CT and each repetition completed).

**Hypothesis**

We hypothesized that the plyometrically trained subjects would complete a greater number of repetitions than the recreationally trained subjects before propulsive force decreased during low and moderate intensity plyometric exercises. We also hypothesized that both groups will complete a greater number of repetitions at the low intensity exercise than at the moderate intensity exercise.
Finally, we hypothesized that there would be a significant difference in the rate of decline in performance of eccentric rate of force development (E-RFD) and there would also be an increase in contact time (CT) for the low and moderate (lE-RFD, and mE-RFD, respectively; lCT, and mCT, respectively) intensity plyometric exercise when plyometrically trained and recreationally trained individuals performed low (CMJ) and moderate (box jumps) intensity plyometric exercises.

**Significance of the study**

Studies have looked at the benefits of plyometric training and the resulting enhancement of performance, but there has been little research done on the manipulation of corresponding program design variables. The present study was undertaken to provide practitioners with more information on plyometric training volume and how they might manipulate repetition volume to create an environment that maximizes physiological and neuromuscular adaptation. By examining different training intensities and repetitions for both plyometrically trained and recreationally trained participants, more specific training protocols might result. The eventual goal of the present study was to give strength and conditioning practitioners a better understanding of training volume and in turn allow for a better utilization of this training variable in plyometric training programs.

**Limitations of the study**

A possible limitation of the present study is the lack of intensity within the plyometric exercises used. This may be a limitation because low and moderate intensity plyometric exercises may not be effective in eliciting differences between the two groups, plyometrically trained and recreationally trained. Along with inadequate intensity, another limitation may be the variability in the groups. In other words, the definition of membership in the groups
may be too similar such that the group differences are not present because the groups are too alike in their physical status. Another limitation of the present study is the size of the force platform. The reason for this is twofold; first, the subjects that participate in the study may have a difficult time completing numerous repetitions while still landing on the force platform during continuous repetitions. Second, individuals may also not have ‘optimal’ jump positioning on the platform during the acquisition process due to the size of the platform which could contribute to the limitation of the study. Some final limitations that need to be considered in the present investigation are the lack of control over level of exercise prior to testing, the injury status of individuals, the possible lack of familiarity with the testing that is required through this investigations, possible differences in effort level across repetitions, and the type of training that is being done within both subject samples.

**Definition of terms:**

Concentric Muscle Action – a muscle action that consists of the muscle fibers shortening.

(Baechle & Earle, 2000)

Contact time (CT) – was measured by taking the first peak (onset of landing) of the GRF and subtracting it from the take off peak.

Contact time Box Jump (bxj-CT) – was measured by taking the first peak (onset of landing) of the GRF and subtracting it from the take off peak.

Contact time (vj-CT) – was measured by taking the first peak (onset of landing) of the GRF and subtracting it from the take off peak.

Contractile Element (CE) – Contractile element exerts active force during shortening and is considered to be a function of the formation of cross-bridges between the thick and thin myosin and actin filaments. (Hill, 1938)
Delayed Onset Muscle Soreness (DOMS) – normally occurs within 24-72 hours post exercise. The muscle induced muscle damage followed by an inflammation induced increase in fluid in the muscle probably causes the muscle discomfort. Normally DOMS is associated with a decrease in muscle strength and may also have an effect on the muscles ability to generate adenosine triphosphate (ATP). (Baechle & Earle, 2000)

DorsiFlexion – decrease in the angle between the shank and the foot (decrease in ankle angle). (Baechle & Earle, 2000)

Eccentric Muscle Action – a muscle action that consists of the muscle fibers lengthening while contracting. (Baechle & Earle, 2000)

Eccentric Rate of Force Development (E-RFD) – will be measured for each intensity and will be done by taking the first peak of GRF divided by the time from onset of landing force to the first peak of GRF. (Jensen & Ebben, 2007)

Elastic Energy - is the capacity of a body to do work during reformation. (Enoka, 2002)

Fatigue - failure to maintain the required force and failure to continue at a given intensity. (Edwards, 1981)

Intensity - the amount of stress placed on involved muscles and connective tissue and joints, and the type of exercise that is being preformed dictates the intensity. (Baechle & Earle, 2000)

Length Tension Relationship - the amount of force that a muscle can exert is related to its length. If the muscle fiber is greater or less than resting length the force production capabilities in the muscle fiber will be compromised. (Enoka, 2002)

E-RFD – the rate or speed at which force can be produced or decreased (in the case of eccentric actions as related to plyometrics) during the low intensity exercises.
Low intensity – in relation to a specific plyometric exercise, Squat Jumps. This exercise is deemed ‘low intensity’ by the National Strength and Conditioning Association. (Baechle & Earle, 2000)

Macrocycles – the year long planned periodization. Typically an entire training year but may also be a period of many months up to four years (for Olympic athletes). (Baechle & Earle, 2000)

mBxJ-GRF - the average of the peak box jump ground reaction force during the box jumps maximal testing. This data will be used to analyze the volume of repetitions completed at the two intensities on the second day of testing.

mE-RFD - the rate or speed at which force can be produced or decreased (in the case of eccentric actions as related to plyometrics) during the moderate intensity exercises.

Mesocycles - Two or more cycles within the macrocycle, each lasting several weeks to several months. (Baechle & Earle, 2000)

Microcycles – Typically one week long but could last for up to four weeks, depending on the program. (Baechle & Earle, 2000)

Moderate intensity - in relation to a specific plyometric exercise, Box Jumps. This exercise is deemed ‘moderate intensity’ by the National Strength and Conditioning Association. (Baechle & Earle, 2000)

Motor Unit – a motor neuron and the muscle fibers it innervate. (Enoka, 2002)

Motor Unit Recruitment- a way for achieving greater force production due to the increased number of active motor units. (Enoka, 2002)

Muscle Spindle – are a proprioceptive organ that is sensitive to the rate and magnitude of a stretch. (Baechle & Earle, 2000)
mVJ-GRF – the average of the peak vertical jump ground reaction force during the vertical jump maximal testing. This data will be used to analyze the volume of repetitions completed at the two intensities on the second day of testing.

Overload - placing greater than normal demands on the exercising musculature which elicits training adaptation to the involved musculature. (Baechle & Earle, 2000)

Parallel Elastic Component (PEC) – stores elastic energy in parallel to the contractile component of a muscle. PEC is composed mainly of the connective tissue surrounding and binding muscle tissue. (Hill, 1938)

Plantarflexion – increase in the angle between the shank and the foot (increase in ankle angle). (Baechle & Earle, 2000)

Plyometrics - a rapid powerful movement that is preceded by a preloading countermovement that utilizing a SSC in the muscle. (Wilk, et al., 1993)

Program Duration – the length of the training program that usually consists of a macrocycles broken down into mesocycles and microcycles. (Baechle & Earle, 2000)

Rate of Force Development - is a function of strength and the time at which it takes an individual to develop that strength. (Van Soest, 1985)

Rest-Periods – the amount of time between repetitions and sets that allows that athlete to recover from the stimuli that was placed on it. (Baechle & Earle, 2000)

Series Elastic Component (SEC) – serves to store and later release elastic energy. The SEC has been thought of as lying within the tendonius tissue but a recent model suggests that the SEC also lies within the muscle fibers. (Hill, 1938)

Stiffness - the property of a system to resist an applied stretch. (Enoka, 2002)

Strength to Weight Ratio – strength divided by body weight. (Chu, 1998)
Stretch Reflex – is the body’s involuntary response to an external stimulus that stretches the muscles, involved with increase in motor unit firing rates. (Baechle & Earle, 2000)

Stretch Shortening Cycle (SSC) - is when a muscle tissue is stretched to cause eccentric tension immediately before concentric contraction. (Wilson, Elliott, & Wood, 1991)

Volume - is the amount of ‘touches’, ‘distance’ or ‘throws’ completed by an individual through a plyometric training session. (Baechle & Earle, 2000)

Volume of Repetitions – the number of repetitions completed during a designated exercise. (Baechle & Earle, 2000)

Work-to-Rest Ratio – a ratio that puts the amount of time the athlete exerts themselves to the amount of rest that is required. The work to rest ratio is specific to what energy system is being trained. With regards to plyometric training the work to rest ration can be between 1:5 and 1:10. This allows for maximal effort during each repetition. (Baechle & Earle, 2000)
Chapter II  
Review of Literature

Introduction

Plyometric training has been used by athletes and coaches alike to increase sport performance for decades. The present body of research surrounding the benefits of plyometric training has supported the improvement of force production, improved running economy, decreased sprint times, increased jump height, and an increased peak power. The SSC occurs when a muscle tissue is stretched to cause eccentric tension immediately before a concentric contraction (Wilson & Flanagan, 2008). The following review will provide insight on components of plyometric training, performance enhancements seen with plyometric training, the numerous mechanisms involved with plyometric movements, fatigue and its association with decreased performance during SSC activities, and the manipulation of training variables with regards to plyometric programming.

Components of Plyometric Training

In most athletic events muscles need the ability to exert force in a short period of time and in most cases an athlete’s success in their respective endeavors depends on the speed at which they can generate force. Wilk and colleagues (1993) explain the theoretical basis of SSC exercise and present a philosophy for utilizing the stretch reflex to produce an explosive reaction in the upper extremity. With regards to plyometric movements, if an eccentric contraction immediately proceeds a concentric contraction there will be a significant increase in the force generated concentrically as a result of the storage of elastic energy (Radcliffe & Farentinos, 1990) and due to the activation of the stretch reflex. The SSC employs the stimulation of the body’s muscle spindle mechanoreceptors to facilitate an increase in muscle
recruitment over a minimal amount of time. Wilk discusses the phases of a stretch shortening exercise. The movement is broken up into three distinct phases. The first phase of the movement is the setting or eccentric phase (preloading period). Within this phase the athlete mentally prepares for the activity and preloads the active muscle. The second phase of the movement is called the amortization phase. This phase is the time between undergoing the yielding eccentric contraction and the initiation of a concentric force. If the amortization phase is slow the stored elastic energy dissipates as heat and the stretch reflex is not activated. The more quickly the individual transitions from the eccentric phase to the concentric phase, the more powerful the response. The third stage of a plyometric movement is the concentric phase.

Specific techniques involved with plyometric training are used in order to keep participants safe and to make sure that the exercises are being executed in a proper manner. Due to the lack of research that designates specific techniques that can improve performance and decrease the likelihood of injury the techniques that follow are recommended through the work of Radcliffe and Farentinos (1999). In a plyometric jump, they recommend landing with the ankle locked in dorsiflexion with full-mid-forefoot contact upon landing, keeping the knees and hips up during the explosive phase (concentric phase) of the plyometric movement (this promotes maximum knee drive and hip extension), keeping the heels up during the jump to allow further projection of the hips and body flight by reducing the arc and rate of the swing leg, and keeping the thumbs up in order to keep upper body posture and facilitate increased force production. Radcliffe and Farentinos (1999) also suggest that athletes should use proper breathing techniques during plyometric activity in order to assist in structural support and exertions. Proper breathing techniques can allow for increased
rigidity within the spinal column, which aids in structural support. Upon landing they recommend again that the athlete should maintain a locked ankle, dorsiflex the foot/ankle, and maintain two thirds full foot contact with the ground in order to allow for the exertion of maximal effort after the eccentric phase of the movement. The technique recommendations of Radcliffe and Farentinos (1999) provide suggestions for technique and hopefully provide recommendations for injury free participation.

There are published guidelines for plyometric training programs for practitioners working with athletes to improve athletic performance. The guidelines offer information on programming, and also provide precautionary measures. One example is the National Strength and Conditioning Association’s (NSCA) position statement on explosive/plyometric exercises. The NSCA position statement suggests that a plyometric training program should begin with a thorough set of warm up exercises, the program should be sports specific, training should not be performed when an athlete is fatigued, and footwear/landing surfaces used in plyometric drills should have good shock absorbing capabilities (NSCA Position Statement Explosive/ Plyometric Exercise, 2009). Additionally, it is recommended that individuals who have already achieved a high level of strength through an already established resistance training program should engage in plyometric exercise. The NSCA also recommends that depth jumps should only be used by a small number of athletes who are engaged in a plyometric training program and as a rule; athletes who weigh over 220 lbs should not participate in depth jumps from platforms higher than 18cm. In order to minimize injury risk, the NSCA recommends that plyometric exercise that affect a particular muscle/joint should not be performed on consecutive days, and plyometric training programs should progress from less demanding drills to more complex/ intense drills.
Bobbert (1990) also suggests that individuals who cannot squat 1.5 times their body weight in a 1RM squat test should not participate in high intensity/shock plyometric training programs. In order to have an adequate base of strength conditioning, Chu (1998), recommends that individuals take part in a resistance training program for a minimum of 2-4 weeks, or until individuals strength ratio is adequate (squat 1.5 times body weight), before taking part in a plyometric training program. These guidelines are set forth to provide the best chance for individuals to perform plyometric training safely and effectively to bring about maximum gains.

Plyometric movements are very complex and involve numerous characteristics that determine their effectiveness in bringing about physiological adaptations. These characteristics include the different phases of a plyometric movement, storage and reutilization of elastic energy, stiffness, stretch reflex/muscle spindle activation, time to develop force, rate of force development, length-tension relationship within muscle fibers, motor unit recruitment, fatigue, and delayed onset muscle soreness. These characteristics will be discussed briefly below.

The SSC is an integral component of plyometric exercise and is involved with most natural and athletic movements. The SSC occurs when a muscle tissue is stretched to cause eccentric tension immediately before a concentric action (Wilson & Flanagan, 2008). It has been suggested that there are three components involved with a SSC. According to Komi (1997), in order for a proper SSC to occur, the muscle must be pre-activated before beginning the eccentric phase, the eccentric phase must be short and fast, and there must be an immediate transition (short amortization phase) between stretch (eccentric) and shortening (concentric) phases. The advantage of the SSC is that a muscle can perform more
positive work if it is actively stretched before being allowed to shorten (Cavagna, Dusman, & Margaria, 1968). This increase in positive work after a pre-stretch of the muscle is the main function of a plyometric movement and one of the reasons why it is used so widely to develop power. The SSC is influenced by the rate and magnitude of the stretch, the level of activation resulting in stiffness of the muscle tendon prior to the concentric phase, the change in muscle length during the stretch, and the time lag between the completion of the stretch and the initiation of the concentric contraction (Wilk, et al., 1993). These characteristics of the SSC are extremely important to keep in mind when implementing a plyometric program because if the SSC is not performed correctly, the exercises become counterproductive. For example, if an athlete is allowed to spend an increased amount of time during the amortization phase of the exercise the SSC will not be utilized to the fullest extent and the specificity of the exercise will not be met. The increase in positive work with an SSC has also been attributed to the storage and reutilization of elastic energy.

Elastic energy is the capacity of a body to do work during reformation (Enoka, 2002). Storage of elastic energy plays a role in shock absorption, while the reutilization of elastic energy is important in the generation of peak power outputs in explosive actions and is especially important for movements involving repetitive SSCs (Van Ingen Schenau, 1997). A three part model has been used to explain elastic energy in human movement, consisting of the contractile element (CE), series elastic component (SEC), and parallel elastic component (PEC) (Hill, 1938). The contractile element consists of the sarcomere, which develops active force during shortening and is considered to be a function of the formation of cross-bridges between the thick and thin myosin and actin filaments (Enoka, 2002). The series elastic component serves to store and later release elastic energy. The parallel elastic component
stores elastic energy in parallel to the contractile component of a muscle (Enoka, 2002). The SEC has traditionally been thought to lie within the tendinous tissue, but a recent model suggests that the SEC also lies within the muscle fibers (Herzog, 1997). The PEC is composed mainly of the connective tissue surrounding and binding muscle tissue (Enoka, 2002). It has been said that an increase in power output after a SSC can be attributed to the storage and subsequent release of elastic energy (Wilson & Flanagan, 2008) derived from these components of the musculoskeletal system, as well as activation of the stretch reflex. A study by Cavagna, Dusman, and Margaria (1968) revealed that the effect of stretching a muscle immediately before concentric action increased muscle fiber work output significantly more than that of a muscle that was not stretched prior to a concentric action.

Although the reutilization of stored elastic energy plays a role in increase power output or force production, the mechanism responsible for the enhancement of this increase is disputed. Some individuals believe that the positive work done is due to the release of elastic energy stored within the elastic components of the musculoskeletal system, while others suggest that the non-elastic mechanism plays a more important role in the positive work done. The disputed characteristics of increased power output are: the time it takes a muscle to develop force, the neuromuscular reflex mechanism, and the potential of the contractile machinery (Van Ingen Schenau, 1997). Although there has been some debate as to the direct cause of this increase in power output or positive work after a muscle has been stretched, Cavagna, Dusman, and Margaria, (1968), Komi and Bosco (1978), and Bobbert (2001) agree that stored elastic energy is a strong contributor to the increase in power output and positive work. Along with the reutilization of stored energy, the degree of stiffness within the
musculoskeletal system can help determine the amount of elastic energy stored, as well as the increase in concentric force production during plyometric movements.

Stiffness within the musculoskeletal system is an important characteristic of plyometric movements and exercises due to its relationship with elasticity of the musculotendinous junction. Stiffness can be defined as the property of a system to resist an applied stretch (Enoka, 2002). Leg spring stiffness represents an integration of the stiffness of all lower limb musculoskeletal structures (including muscles, tendons, and ligaments acting across joints) during locomotion and describes those structures ability to interact in unison in spring like fashion (Dalleau, 1998). Arampatzis (2001) had participants perform depth jumps at three different heights (20, 40, and 60 cm) and after each jump participants were told to jump as high as possible and to do it in a faster manner than the previous jump. The authors reported that as ground contact time decreased, leg and ankle stiffness increased. Although the stiffness within the musculoskeletal system may be a contributor to decrease contact times, it can also be noted that a decreased hip, knee, and ankle flexion can contribute to the decrease in contact time. Increased stiffness uses the tension that is developed during the eccentric phase of the movement to return or react in the original direction of the movement with greater force (Radcliffe & Farentinios, 1999). The stiffness observed allows for the ability of the musculoskeletal system to absorb the energy within the range that the system works, and once the load is released, the tissue returns to its original shape, allowing for the release of that stored energy (Radcliffe & Farentinios, 1999). It has also been seen that an increase in 1a afferent activity, resulting from preactivation, is associated with increased stiffness of the musculature and this has been shown to improve recoil ability (Aura & Komi, 1986). This improved recoil ability can be extremely important during the
amortization phase of plyometric movements. Stiffness within the musculoskeletal system allows for better recoil ability and can help the athlete decrease contact time during the amortization phase of the movement. Another of the contributing factors to prestretch power augmentation is the activation of the stretch reflex through the activity of the muscle spindle (Van Ingen Schenau, 1997).

The two main functions of muscle are to generate power and to react to perturbation (Enoka, 2002). Muscle needs to be spring like in order to react appropriately and the stretch reflex helps the muscle achieve this capability (Enoka, 2002). The stretch reflex and the muscle spindles involved with this reflex play a vital role in the mechanisms surrounding a plyometric movement. When a muscle experiences a brief, unexpected increase in length, the response is known as the stretch reflex (Enoka, 2002). The stretch reflex is the body’s involuntary response to an external stimulus that stretches the muscle (Enoka, 2002). The muscle spindles (within the intrafusal fibers) detect rapid changes in muscle length and induce increased motor unit firing rates to the parent muscle fibers in order to overcome the increased resistance applied to the given muscle fibers. The muscle spindles are a proprioceptive mechanism that reacts to the rate and magnitude of stretch in an active muscle (Enoka, 2002). The activation of muscle spindles sends an impulse to the central nervous system (CNS - Spinal Cord) via 1a afferent nerve fibers. This impulse then synapses with the alpha motor neuron in the CNS and an excitatory impulse travels to the agonist muscle that was stimulated, causing a reflexive muscle action (Wilk et al., 1993). Plyometric movements induce this response during the eccentric phase due to the rapid stretch and the speed of the stretch (<50ms) (Brindle, Nyland, Shapiro, Cabron, & Stine, 1999). Cavagna and associates (1968) said that if the amortization phase of the movement is too long, then
the stretch reflex will not increase the amount of positive work done in the concentric phase (positive work). In other words, it has been advised to keep the amortization phase short in order to consider the movement plyometric and to activate all the mechanisms that can allow for an increase in power output after the pre-stretch of the muscle fibers. The stretch reflex and the muscle spindles play an important role in plyometric movements and allow the system to react to the changes in muscle length through the movement.

Another major component important in maximizing the effect of a plyometric movement is the rate of force development. Time to develop force is a mechanism that has to do with the increased time that the muscle has to become fully activated when there is an initial lengthening contraction. An initial increase in the muscle force at the beginning of the shortening action enhances the positive work that can be done during the concentric action (Enoka, 2002). The time in which an individual loads the agonist muscle in the eccentric phase of the plyometric exercise is vital in the positive work that the individual will be able to accomplish in the shortening or concentric phase of the exercise (Enoka, 2002). Rate of force development is a function of strength and the time in which it takes an individual to develop that strength (Enoka, 2002). An increased rate of force development and consequent decrease in the time it takes a muscle to develop that force can aid an athlete’s performance and allow the athlete to generate force in a rapid manner. If the rate of force development is high, then the individual will likely see the benefits of improved power output. Plyometric exercises are a great way for athletes to improve their rate of force development (Jensen & Ebben, 2007; Vissing, et al., 2008). Program design variables play a vital role in rate of force development during a plyometric training program because if an athlete becomes fatigued due to a volume or intensity that is too high, the athlete will be detrimentally affected and not
be able to develop force as quickly. This decrease in rate of force development will cause the
athlete to increase the amortization phase, defeating the purpose of the plyometric exercise.
Gollhofer, Komi, Fujitsuka, and Miyashita (1987) found that training programs heavily based
on SSC movements can have a detrimental effect on mechanical performance if the program
is not adequately designed. Gollhofer and colleagues used a fatigue study to reveal a
decrease in rate of force development, decrease in force production and increased contact
time when individuals took part in plyometric exercise following a fatigue protocol. Along
with the rate of force development, another mechanism that plays a role in plyometric
movements is the length tension relationship within skeletal muscle.

Efficient motor unit recruitment patterns are important for achieving greater force
production due to the increased number and synchronization of active motor units.
Neuromuscular adaptations (increased motor unit recruitment) that are associated with
plyometrics training enhance the ability of the muscle groups to respond more quickly and
powerfully to changes in the musculoskeletal system (Radcliffe & Farentinos, 1990).
Neuromuscular adaptations that result from plyometric exercise can be associated with an
increase in strength because of this increased neural activation of motor units (Aura & Komi,
1986). The ability of the system to recruit high threshold motor units allows for an increase
in force production (Enoka, 2002). If an activity requires greater force production, the size
principle dictates the range of motor units recruited will start with the smaller low-threshold
motor units and then progress to the high threshold motor units in order to generate enough
force for the activity or movement (Enoka, 2002). As an adaptation to plyometric training,
motor unit recruitment allows for the system to recruit a greater number of motor units to
generate an added amount of force required for movement (Powers & Howley, 2006). The
level of motor units recruited will be based on the intensity of the movement (Enoka, 2002). If an athlete is participating in a high intensity or shock exercises, he or she will likely need to recruit a greater number and a higher threshold of motor units in order to generate enough force to accomplish the movement. In turn, this means that motor unit recruitment is also related to how quickly one is able to recruit high threshold motor units (Baechle & Earle, 2000).

The fatigue associated with plyometric training has the potential to affect the performance of the athlete in a negative manner and can contribute to counter-productiveness of a training session and, therefore, the program. Fatigue has been defined as failure to maintain the required force (Edwards, 1981) and failure to continue at a given intensity (Booth & Thomason, 1991). Peripheral fatigue refers to the decrease in the muscle group’s capacity for exercise (Asmussen, 1979) and can be located distally to the motor neurons in the transmission and or contractile mechanism. The immediate observation with fatigue associated with an increase in the number of repetitions completed during a plyometric exercises is generally a decrease in performance. Gollhofer, Komi, Fujitsuka, and Miyashita, (1987) examined forearm extensors muscles during exhaustive SSC exercise and reported a reduction in maximum force, a decrease in rate of force development, and an increase in contact time with the base of the sledge apparatus (increased amortization phase). This study also revealed that the concentric phase of the SSC exercise was affected more negatively then the eccentric phase of the cycle, as evidenced through the decrease in force production and rate of force development. Fatigue associated with plyometric exercises is typically associated with large acute and delayed changes in muscle mechanics and activation that result in major consequences on joint and muscle stiffness regulation, especially in stretch
shortening-type performance (Komi, 2000). Intense and or unaccustomed eccentric or stretch shortening exercise results in reversible muscle damage that is associated with delayed onset muscle soreness (DOMS), and with proprioceptive and neuromuscular impairments that may last for several days (Nicol, Avela, & Komi, 2006). Fatigue after SSC activity can be attributed to the deteriorated muscle function, reduced tolerance to impact, loss of elastic energy potential, and increased work during the push off phase (Komi, 2000). These aspects of fatigue associated with SSC activity contribute to decreased performance. The research done with regards to fatigue and the SSC are typically done during SSC exhaustive fatigue which requires a large volume of SSC movements to induce these characteristics. The fatigue that can accompany plyometric movements and SSC activities shows the importance of proper program design with regards to rest periods, frequency, and intensity, as well as volume of exercise performed. Proper program design will allow athletes to participate in the training session and prevent exhaustive SSC sessions that will inevitably decrease performance. One of the contributing factors to this decrease in performance is delayed onset muscle soreness, which does not happen within one training session.

Delayed onset muscle soreness associated with eccentric muscle actions during a plyometric exercise can have a detrimental effect on force production, range of motion and comfort level. These detrimental effects are due to the muscle damage and inflammation associated with the muscle action (Hortobagyi, Lambert, & Kroll, 1991), structural damage to the contractile elements of the muscle fiber (Thompson, Nicholas, & Williams, 1999), and impairments of the excitation contraction coupling process (Warren, Ingalls, Lowe, & Armstrong, 2001). Although individuals may experience DOMS and other discomforts after
a plyometric training session, the muscle will likely adapt to the present stimuli and therefore the individual will experience less DOMS after the proceeding sessions and as the program progresses.

Plyometric training has proven to be beneficial for the improvement of athletic performance. The techniques, guidelines, and mechanisms that have been reviewed will allow for an increased understanding of the different components involved in maximizing the benefits of plyometric training.

**Plyometrics and improved performance.** Plyometric training is an important component of many conditioning programs. Through a plyometric training program an athlete is likely to see some performance benefits and improvements in ability. Ronnestad, Kvamme, Sunde, and Raastad (2008) looked at twenty-one Norwegian Professional soccer players who were all training 5-7 days a week. The effects of combined strength and plyometric training with strength training alone on power related skills in these professional soccer players were evaluated over a seven week period. Three groups were evaluated including a strength training group, a combined plyometric and strength training group, and a control group. The control group did not participate in any training other than the training sessions that were required for the team, consisting of six to eight soccer training sessions per week. The strength training group performed heavy strength training twice a week on non-consecutive days in combination with the six to eight soccer training session per week. The strength and plyometric group performed the same strength training program as the strength training group but added a plyometric training program after the strength training session. Training progression occurred through increases in foot contacts with, the number of sets and foot contacts in each drill maintained between 2 sets and 4 foot contacts and 5 sets and
10 foot contacts. The results demonstrated that both training groups, improved in strength, jumping performance, and sprint performance and there were no significant difference between the two training groups. This study revealed that heavy strength training and strength training with plyometrics both significantly increased performance in professional soccer players at both the high force end (1RM and sprint acceleration) and high velocity end (peak sprint velocity and 4 Bounce Test) when the subjects were also performing concurrent explosive soccer training.

Improved sports performance associated with plyometric training has also been shown to be beneficial for endurance runners. Turner, Owings, and Schwane (2003) conducted a study in order to determine if a six-week plyometric training program improved running economy of regular but not highly trained runners. Twenty-one volunteers that were assigned to one of two groups, a control group that was asked to continue with their normal running routine and an experimental group that continued with their running routine and added a moderate intensity plyometric training routine three times a week for six weeks. The results revealed that the average economy of the runners improved with the plyometric training. Running economy (milliliter of oxygen consumed per kilogram of body weight) was tested at 3 different speeds on a horizontal treadmill where VO$_2$ was measured during the last 3 minutes of each 6 minute bout at the various speeds. The results of this investigation showed no differences between the groups in oxygen uptake. In conclusion, it can be said that a six week plyometric training program can improve running economy in regularly trained individuals. A limitation of this study may be the fact that the subject population was not highly trained and this could have played a factor in the improvement in running economy due to the plyometric training program.
In contrast to the previous study, Saunders and associates (2006) examined the effect of a nine-week plyometric training program on running economy in highly trained middle and long distance runners. Fifteen subjects competing at the national or international level (VO₂ max of 71.1 ± 6.0 mL/kg/min) were assigned to a plyometric group that took part in three thirty minute sessions each week for nine weeks and a control group which undertook similar running training as the plyometric group but did not participate in the additional intervention. After a week of familiarization, the plyometric group participated for four weeks of two sessions in the gym and one session on the grass, and the last four weeks consisted of one session in the gym and two sessions on the grass. Gym sessions consisted of back extensions, leg press, hamstring curls, fast feet drills, and squat jumps for maximum height. Grass sessions consisted of alternate leg bounding, high skipping, single leg hopping, double leg jumping over hurdles, and scissors jumps. Running economy was measured at 5 and 9 weeks using treadmill testing to determine sub-maximal VO₂ for four minutes at 3 running speeds (14, 16, and 18 kmh). Ventilation (Ve), heart rate (HR), stride rate (SR) and concentration of blood lactate (Lac) were also measured. GRFs were also measured on a force plate to determine ground reaction forces to determine muscle power characteristics. The authors reported no change in VO₂ at week five and at week nine during the speeds of 14kmh and at 16kmh and there was no difference in the strength and power measures between the two groups. As confirmed in other studies, the addition of a plyometric training program improved running economy at 18kmh by 4.1% in these highly trained runners as compared to the control group. The study also revealed that there was no significant change in sub maximal running economy at the lower speeds. The authors reported an improvement in running economy at 18kmh in the runners who supplemented their regimen with a
plyometric training program. The authors attributed this improvement in running economy at this speed to the elastic mechanism’s influence on stiffness of the spring mechanism during running. Performance benefits have again been seen through a plyometric program intervention and the present study reveals a similar outcome after a plyometric training program and the effect on running economy.

While improvements are consistently reported as a result of involvement in plyometric training programs, improvements have still been shown to continue once an individual experiences a phase of detraining or break in the periodization. Luebbers and colleagues (2003) attempted to determine the effects of a four-week and a seven-week plyometric training program followed by a four-week recovery period of no plyometric training on vertical jump performance and anaerobic power. Thirty-eight physically active young men were broken up into two groups. The participates either took part in a four-week plyometric training program three times per week or a seven-week plyometric training program three times per week. The plyometric training consisted of vertical jumps, bounding, broad jumps, and depth jumps. As the program duration increased, the volume of touches and bounding distance were increased. During the bounding and depth jump exercise the subjects were instructed to minimize the amortization phase of the movement (by decreasing ground contact time). The study controlled for the volume of work done between the two groups in order to make sure the groups did an equal amount of work over the study’s duration. Each group completed 850 vertical jumps, 450m of bounding, 675m of broad jumps, and 240 depth jumps. The results of this study reveal that there was a decrease in vertical jump height observed in both the groups when comparing pre and post testing for vertical jump, and both groups increased in body mass from pre and post measures. Both
The group that took part in the four week plyometric training program saw a 6.5% increase in vertical jump height between the post test and the four week recovery period whereas the group that took part in the plyometric training program for seven weeks increased vertical jump height by 4.4%, post testing to four week recovery period. Overall there was a significant increase in vertical jump height between pre testing and after the four week recovery period. Vertical power decreased significantly between pre- and post-testing in the group that participated in a the four week plyometric training program, whereas there was no change in vertical jump power from pre- to post-testing in the seven week group. Both groups saw a significant increase in vertical jump power between the post-test and the recovery period, with the authors reporting an increase of 3.0% for the four week group, and 2.3% for the seven week group. Both groups also experienced an increase in vertical jump power between pre-testing and post-recovery period. The authors also noted that both training groups showed a significant increase in power output when measured from pre-test to the post-recovery period. This study revealed that when subjects were measured for vertical jump height, vertical jump height power, and anaerobic power immediately after cessation of the training program there was no change observed in the measured variables and in some instances there was a decrease. After the four week recovery period there was an increased observed in vertical jump height, vertical jump height power, and anaerobic power. A four week plyometric training program may be just as effective as a seven week plyometric training program if there is a four week recovery period utilized. Although improvements were seen in all three aspects of testing the true benefits were only seen after
the four week recovery period and this can be very beneficial evidence when prescribing recovery periods prior to the competitive season.

Vertical jump performance is an improvement seen with plyometric training as evident through Luebbers work. Along with Luebber’s work, Brown, Mayhew, and Boleach (1986) attempted to determine the effect of plyometric training on vertical jump ability in 26 male high school basketball players. The average age of the subject population was 15 years ± 1 year. This was a 12-week study where some participants took part in a plyometric training program three times per week and a control group just took part in the regular basketball training. The plyometric training group took part in 34 training sessions over the 12-week span in addition to their regular basketball training. During those 34 training sessions the group performed three sets of ten repetitions per session of depth jumps from 45 cm with 1 minute rest periods between sets. Individuals that took part in the plyometric training program improved their vertical jumping ability by 11.2% when not allowed to use an arm swing during CMJ before jumping and 12.5% when being able to use an arm swing during CMJ before jumping. The control group in this study showed improvements of 5.4% without the arm swing before jumping and 5.9% when allowed to use an arm swing before takeoff. In both cases, it is seems through this study that when individuals are able to use an arm swing during the initiation of a vertical jump they perform better than when not using an arm swing. In the plyometric training group 57% of the vertical jump gain was due to jumping skill improvement, and 43% was due to strength gains according to the author. The authors used an analysis of variance (ANOVA) on the pre- to post-training difference scores for VJNA (vertical jump without arm swing) and VJA (vertical jump with arm swing). The authors concluded that this subject population exhibited an improvement in their vertical
jump ability after a 12-week plyometric training program. The results show that plyometric training has a beneficial effect on vertical jumping ability in young high school basketball players. Plyometric training can, therefore, be used in order to increase jump performance and likely benefit the overall performance of an athlete.

Gehri, Ricard, Kleiner, and Kirkendall (1998) set out to determine whether drop jump training was superior to countermovement jump training for improving vertical jump ability and to determine whether changes in jumping ability could be attributed to positive or negative elastic energy. This study took place over 12 weeks and consisted of a subject population of 14 males and 14 females. These 28 individuals were all of college age and were not participating in any competitive sport or recreational activity that involved jumping. All individuals involved in this study undertook 20-30 minutes of aerobic exercise 3 times per week in order to be included in the present study. The subjects were broken up into three groups: a control group, a countermovement jump (CMJ) group, and a depth jump (DJ) group. All subjects were tested in three different vertical jump categories; the CMJ, the DJ, and the Squat Jump (SJ). The subjects were tested for three maximal jumps in each category. The training DJ and CMJ groups participated in two training session per week. The first two weeks of the intervention consisted of 2 sets of 8 repetitions with five seconds rest between each repetition and 1 minute rest between sets. After the first two weeks of the intervention the remaining ten weeks consisted of 4 sets of 8 repetitions with a five second rest between each repetition and 1 minute rest between sets. The 12-week plyometric training program significantly improved vertical jump height and positive energy production in both the CMJ and DJ groups. The DJ group had higher mean values than the CMJ group when comparing SJ, CMJ, and DJ. The control group’s vertical jump ability improved slightly, but was
extremely inconsistent. The CMJ training program led to significant improvements in positive energy production in both the SJ and CMJ jump conditions but did not produce improvements in positive energy in the DJ. The DJ group improved positive energy production in all three jumps (SJ, CMJ, and DJ). The results of this study also revealed that there were no significant improvements in elastic energy utilization for either group when comparing pre- and post-testing. It should be noted that the subject population that took part in this study had no previous plyometric training experience, and this may have contributed to the larger improvements in vertical jump performance when compared to other studies.

It is evident that plyometric training can induce improvements in jump performance, decrease sprint times, and running economy. Little evidence surrounds the changes in muscle fiber morphologies after a plyometric training program, such as an increase cross sectional area. Vissing and colleagues (2008) compared changes in muscle strength, power, and morphologies induced by plyometric training versus a conventional resistance training program of equal time and effort. The individuals that took part in this study had no prior history of strength training or plyometric training. Sixteen recreationally trained healthy males participated in this 12 week protocol that consisted of 36 training sessions. All the subjects had not participated in resistance training or sports activities involving SSC movement patterns for six months prior to their inclusion in the study. The subjects were randomly assigned to one of two groups. One group participated in the conventional resistance training (CRT) program and the second group participated in the plyometric training (PT) program. The CRT was set up with the aim to improve maximal muscle strength, rate of force development, and hypertrophy in the lower extremity muscle groups. The PT protocol was designed as a typical PT program that progressed in terms of the
number of impacts and individually based height adjustments. The PT program also targeted changes in maximal strength, rate of force development, and hypertrophy of the lower extremities. The CRT program’s various exercises were performed with 3 sets of 4-12 RM. The PT program consisted of countermovement jumps (CMJ), hurdle jumps, and drop jumps. All three exercises were performed with an emphasis on minimizing the amortization phase of the movement and progressed by increasing the height of the hurdles and the height from which individuals dropped. The results revealed no significant difference between groups when evaluating strength in the 1 RM incline bench press and the 3 RM isolated knee extension. With respect to measures of jump height and power, the PT group improved CMJ height whereas the CRT group did not. The results of the ballistic leg press power showed a greater improvement in power output amongst the PT group when compared to the CRT group, indicating improvements of 17% and 4%, respectively. In looking at the changes in cross sectional area of muscle fibers, there was a limited sample size (only four CRT participants and five PT participants) due to difficulties in the biopsy analysis. There was an increase in cross-sectional area of both type I fibers and type II fibers in the CRT group and no change in the PT group. These results suggest that in previously recreationally trained individuals there is a similar performance benefits observed when comparing the CRT group with the PT group. CRT and PT seemed to lead to similar gains in maximal strength, whereas PT induced far greater gains in muscle power. The present study shows that in previously recreationally trained individuals the implementation of a 12 week plyometric training program can have a greater effect on maximal strength and power as compared to a conventional resistance training program.
In contrast to the previous findings, Potteiger and colleagues (1999) examined the effect of plyometric training on leg power output and muscle fiber size of the vastus lateralis. Nineteen physically active men with no previous plyometric training experience participated in an eight-week training regimen. Although the subjects had no previous experience with plyometric training each subject had participated in some sort of resistance training and aerobic activity for at least three months prior to the intervention. Potteiger and colleagues tested the subjects in areas of body composition, vertical jump performance, VO₂ max, and a muscle biopsy of the vastus lateralis both before and after the eight-week intervention. The subjects were broken up into two groups. Group one participated in just the plyometric training for the eight-week period and the second group participated in the plyometric training program along with continuous running at 70% of HRmax. The plyometric group took part in the training program three days a week, consisting of 2-foot vertical jumps, tuck jumps, 2-legged broad jumps, 1-and 2-legged bounding, and depth jumps (completed at 40cm). During the plyometric training sessions, all subjects were instructed to achieve maximum height during jumping activities and were also instructed to minimize contact time when executing bounding and depth jumps. The aerobic exercise that was performed by the second group was accomplished directly following the plyometric training. The results revealed that vertical jump performance improved in both groups from pre-testing to post-testing. Both groups also exhibited an increase in peak and average power during that time. No significant difference was observed in VO₂ max between groups during the eight-week intervention but aerobic power was improved in both groups from pre-testing to post-testing. Both groups did show significant increases in fiber area after the eight week training program. Type I fibers in plyometric training group exhibited an increase of 4.4% and the
plyometric and continuous running group saw an increase of 6.1%. Type II fiber area increased by 7.8% for the plyometric training group and 6.8% for the group that participated in plyometrics and continuous running. The present study revealed that performing an eight-week plyometric training program can improve leg power production and cause an increase in muscle fiber size. The present study also revealed that individuals that are not previously trained can see an increase in muscle fiber characteristics and improvements in performance. Although the subject population is not at an elite level of athletic ability, they still exhibited a benefit from an eight-week plyometric training program.

Plyometric training programs have been shown to improve athletic performance in areas of power, sprint times, running economy, muscle fiber characteristics, and jumping performance. The benefits that accompany a plyometric training program are associated with various physiological characteristics. These characteristics involved with plyometric movements are in direct relation with the improved performance seen from a plyometric training program. The mechanisms that are directly responsible for an increase in force production after a muscle has been stretched are still up for debate but it is evident that there is an increase in force production after a muscle has been stretched. SSC movements allow the system to utilize these characteristics to increase force production during plyometric movements and throughout a training program.

**Mechanism of pre-stretch force augmentation.** Plyometric exercise is a quick, powerful movement using a pre-stretch, or countermovement, that involves an SSC (Wilk, et al., 1993). The purpose of plyometric exercise is to increase the power of subsequent movements by using both the natural elastic components of muscle and tendon, as well as the stretch reflex (Potach & Chu, 2000). Due to the nature of plyometric movements, the
stimulation of the body’s proprioceptors facilitate an increase in muscle recruitment over a minimal amount of time (Potach & Chu, 2000). The various mechanisms involved with plyometric movements are essential and need to be taken into consideration when implementing a plyometric training program.

There are conflicting views about the mechanisms behind improvements in concentric force production after a muscle has developed eccentric tension. A piece of the debate surrounding this mechanism comes from a paper by Van Ingen Schenau (1997). The purpose of this paper was to address the role of storage and reutilization of elastic energy during a SSC movement (which the author refers to as a countermovement) and present a view of the contrasting ideologies surrounding the topic. Van Ingen Schenau explains that it is well-documented that a pre-stretch of a muscle fiber enhances the maximum work output that a muscle can produce during the concentric phase of a movement and the mechanisms behind this enhancement are up for dispute. According to Van Ingen Schenau and others, the time available for force development is said to be the first possible mechanism for the enhancement of maximum work by countermovement (Asmussen & Sorensen, 1971; Bobbert et al. 1996; Chapman & Sanderson, 1990). For instance, if a subject is instructed to execute a movement as fast as possible the author speaks about the fact that it takes time before the muscle force reaches its maximum. Van Ingen Schenau says the second mechanism that is associated with the increased force development during a countermovement is the storage and reutilization of elastic energy. The idea of this storage and release of energy comes from active muscles being pre-stretched and absorbing energy, part of which is temporarily stored in series elastic element and later re-utilized in the phase where muscle acts concentrically (Asmussen & Bonde-Petersen, 1974a; Hull & Hawkins,
Van Ingne Schenau continues to say that the storage and reutilization of elastic energy does not play a significant role in the increase force production after a pre-stretch of a muscle fiber mainly because the dynamics of force development and not the storage and reutilization of elastic energy determine the differences in the amount of work produced. The potentiation of the contractile machinery is the next mechanism that may contribute to the increase in force production after a muscle is pre-stretched. The author suggests that the force produced by an isolated muscle may be enhanced by a stretch to values up to twice the maximum isometric force and this has been also seen in single muscle fibers (Bergel, Brown, Butler, & Zacks, 1972; Cavagna, 1978; Cavagna, Dusman, & Margaria, 1968). This improvement in force is said to be a function of the capacity of the contractile machinery to do work after a fiber has been stretched. The last mechanism, according to Van Ingen Schenau, that may contribute to the pre-stretch force augmentation is the contribution of neuromuscular reflexes (Dietz, Schmidtbleicher, & North, 1978). Van Ingen Schenau questions whether neuromuscular reflexes even play a role in force enhancement during countermovement’s and attributes a possible lack of neuromuscular reflex to the idea that if a muscle absorbs a great deal of mechanical energy there would be no lengthening of the muscle spindles and thus no triggering of the stretch reflexes. Van Ingen Schenau’s paper brings to light the conflicting ideologies surrounding the improvement in force production after a muscle has been stretched prior to a concentric contraction. Van Ingen Schenau concludes his paper by contradicting himself a bit in saying that he is in no way trying to suggest that storage and reutilization of elastic energy are of little importance. Van Ingen Schenau asserts that apart from playing a role in shock absorption (which is a fundamental piece of plyometric movements) and the generation of
high peak power outputs in explosive actions, elastic energy most certainly plays a role in the conservation of mechanical energy. According to the author this is especially important for movements involving repetitive SSCs.

Elastic energy is the capacity of a body to do work during reformation. This ability to do work during reformation is vital to plyometric movements. Hill (1950) examined series elastic component of tendon and virtually pioneered the idea of a 3-component model. This model consists of the series elastic component (SEC), contractile element (CE), and parallel elastic component (PEC) all of which play a vital role in the increased force production after a muscle has been previously stretched. The purpose of the experiment was to determine how much mechanical energy was present in the muscle and its mechanical recording system, due to elastic stretch. The author reported that an important factor in the mechanical behavior of muscle was the passive elastic component in series with the active contractile one. Hill wrote that the passive elastic component acts as a buffer when a muscle passes abruptly from the resting to the active state, and it accumulates mechanical energy that can be used in producing a final force greater than that at which the contractile component itself can shorten. This information is important when it comes to jumping and throwing movements. Hill’s says, it is impossible to evaluate the properties of the series elastic component in a resisting muscle; the contractile component at rest is so extensible that a load is taken almost entirely by the parallel elastic component which in turn means it is necessary to work with an actively contracting muscle in a range/length within which the tension of the parallel elastic component can be neglected. The present study looked at sartori muscles of the English Frog and English Toad. During testing, these muscles had minimal tendon length at the tibial end. A Levin Wyman ergometer was used to evaluate the performance of these muscles. The start
and end of the movements performed were recorded by contacts as slight slickers on the tension record (the tension lever was attached to the muscle through a thin chain). By adjusting the recording system, the tension could be raised, and then the ergometer could be released and a tension-shortening curve recorded exactly as in the muscle experiments. From this, the shortening of the recorded system and its connections could be read off and subtracted from the shortening observed in the muscle experiment between those tensions. In this way the true relation was determined between tension and shortening of the muscle itself, without error due to the elasticity of the recording system and connections. The shortening of the muscle is shown to be made up of two parts; the shortening of the series elastic component and that of the contractile component. The results suggested that when a muscle is stretched during contraction, the tension with which it resists the stretch may be considerably greater than that which it can exert isometrically. The experiment done by Hill gives insight into the ability of a stretched muscle (human or otherwise) to store mechanical elastic energy within the system and subsequently reuse that stored energy.

Although the debate continues regarding the extent to which each mechanism influences the increase in force production after a muscle is stretched prior to a concentric action, the following allows for further insight into the debate. Komi and Gollhofer (1997) explored the benefits of the SSC and the fundamental conditions in which a SSC can take place. Three fundamental conditions are required in order to consider a movement a SSC movement and those are: a well-timed pre-activation of the muscle or muscles before the eccentric phase, a short and fast eccentric phase, and immediate transition (short delay) between stretch (eccentric) and shortening (concentric phase). The evidence in this paper is contradictory to what Van Ingen Schenue considers a SSC movement and to a certain extent
the role of the stretch reflex in a SSC movement. Komi and Gollhofer suggest that the stretch reflex plays a role in the contribution to force output during a SSC movement that was refuted by previous authors Van Ingen Schenau. According to Komi and Gollhofer the stretch reflex plays a significant role in the force generation during the touchdown phase in SSC activities such as hopping and running. The main contributor to the pre-stretch force augmentation increase may not be definitive at this point, but it is evident that there is an increase in power output after a muscle has been stretched.

Herzog (1997) again debated the main contributing mechanism behind the increased power output after a muscle has been previously stretched. Herzog discusses the enhancement of work that is observed after the pre-stretch of a muscle and influence of the series elastic component (SEC). In response to Van Ingen Schenau, Herzog discusses the concept that cross-bridges have an elastic component to their makeup (Ford, Huxley, & Simmons, 1981; Huxley & Simmons, 1971). Recently, it has been shown that there are considerable elastic properties in the thin and possibly the thick filaments of the sarcomere (Higuchi, Yanagida, & Goldman, 1995; Huxley, Stewart, Sosa, & Irving, 1994). Herzog asserts that force production in skeletal muscle occurs via cross-bridge formation of the thick and thin myofilaments which also contain an elastic component in series with the force-producing cross-bridge head (Huxley & Simmons, 1971). While Herzog agrees that cross-bridge formation and the time available for force development play a role in force production, he does not agree with Van Ingen Schenau’s denial of the ability of the elastic energy stored within the system to contribute to force production. In response to Van Ingen Schenau’s stance on the influence of the stretch reflex on the increase in force production, Herzog brings to light the fact that Van Ingen Schenau’s stance questions the fundamental
existence of the SSC. Herzog reacts to Van Ingen Schenau’s paper (reviewed previously) and reveals evidence that the elasticity within the musculoskeletal system plays a role in the increased force production after a SSC-type movement. Herzog supports the belief that the SSC and the stretch reflex play a fundamental role in the enhancement of work done by a muscle after it is stretched, while Van Ingen Schenau does not agree with the stretch reflex playing a fundamental role in the enhancement of work.

The literature reviewed in this section gives insight into the possible contributions to pre-stretch force augmentation seen in SSC movements. Although there is debate as to which mechanism plays the most influential role in pre-stretch force augmentation, it is safe to say that there is an increase in force output after a muscle has been stretched regardless of what mechanism is dominant during the action. All the mechanisms that were previously discussed allow for improvements in athletic performance especially in power related activities when activated in the proper way.

**Use of plyometric movements to evaluate the mechanisms involved.** Aura and Komi (1986) examined the importance of elasticity in human skeletal muscle during locomotion and the mechanical efficiency of positive work and elasticity of the human musculoskeletal system. The positive work and elasticity were investigated on a special sledge apparatus that allowed for a normal SSC to occur. The study consisted of 25 young men with an average age of 24.3 years. The sledge apparatus had a fixed sitting position, a slide on a low friction track, and force plate placed perpendicular to the sliding surface. This sledge was fixed at 20 degrees with respect to the horizontal line. Negative and positive work was measured through a series of SSC exercises. Individuals performed positive work intensity at 60% of their max and the negative work varied depending on the individual. The
sledge was released from a certain distance that corresponded to the specific energy level. The height of the drop was varied between exercises, but held constant within each exercise, being between 20 and 120 percent of maximal concentric exercise. During each trial, the subject resisted the downward movement and immediately after stopping the sledge extended the legs to perform positive work. Through this process the mechanical efficiency of the pure negative and the pure positive work were measured individually for all the subjects. Electrogoniometric measurements were taken along with mechanical work, energy expenditure, electromyographic (EMG) measurements, and mechanical efficiency. The results of this study revealed that mechanical efficiency of the positive work in natural locomotion increased with increasing pre-stretch intensity. The study also revealed that the work done due to elasticity increased with increase in the pre-stretch. The electromyographic (EMG) measurements reveal that the activation changed similarly in all three muscles (vastus lateralis, vastus medialis, and the gastrocnemius) with an increase in the pre-stretch due to changes in drop height. The change in concentric EMG was small and therefore the eccentric/concentric ratio in EMG increased linearly with an increase in pre-stretch loads. The results of this study demonstrate the importance of muscle elasticity in human locomotion and SSC activities.

Komi and Bosco (1978) examined the performance in vertical jump by imposing different stretch loads on activated leg extensor muscles. They hypothesized that the technique used through this study might be of use to investigate the possible differences in the storage and utilization of elastic energy between men and women of comparable physical conditions. Fifty-seven males and females took part in the study. The females were physical education students and some of the male subjects were also physical education students,
while others were players from the Finnish national men’s volleyball team. Subjects were all evaluated for jump performance through a series of vertical jumps (SJ, CMJ, and DJ) on a force platform. During these jumps, all subjects were required to keep their hands on their hips. The male subjects performed drop jump trials from 26 cm to 83 cm whereas the women did drop jump trials from 20 cm to 80 cm. The results suggested that the women subjects had a consistently lower jump height than their male counterparts. In a comparison between jumping conditions it was observed that the SJ was the least efficient condition when compared to the CMJ and the DJ. During the DJ trials the influence of increased height greatly affected the performance of both groups. Females exhibited their highest performance at a DJ height of 47.6 cm. The male physical education students and volleyball players exhibited their highest performances at a height of 63.0 cm and 66.0 cm, respectively. This study also revealed that women were able to utilize most of the energy absorbed in the stretching phase of the CMJ and DJ conditions and males did not. This result would suggest that females can utilize a greater portion of the stored elastic energy than males.

Another mechanism that plays a role in plyometric movement is the amount of stiffness within the musculoskeletal system during these movements. Arampatzis, Schade, Walsh, and Bruggemann (2001) examined the effects of leg stiffness on mechanical power and take off velocity during drop jumps (DJ). The subject population of this study consisted of 15 decathletes whose level of competitive ability was not specified. Subjects performed DJ from three different heights (20 cm, 40 cm, and 60 cm) with their hands on their hips during the jumps. The instructions given to the subjects were “jump as high as you can” and “jump high and a little faster than your previous jump.” After initial testing, the subject population was broken up into five groups. Group one consisted of the individuals with the longest
contact time and group five was made up of the individuals with the shortest contact time. Groups two, three, and four were formed with the individuals that fell between group one and group five. Ground reaction forces during jumps, vertical center of mass velocity, and surface EMG served as dependent variables. The results of this study reveal that all groups had significantly different contact times at the different heights. The leg and ankle stiffness increased with the shorter ground contact times. Vertical ground reaction forces in all cases were lowest in group one and consistently higher in each group with the highest values being found in group five. The EMG analysis revealed that, from a height of 20 cm, there was a significant correlation between leg stiffness and EMG for the gastrocnemius lateralis, gastrocnemius medials, vastus lateralis, and hamstrings. In drop jumps from 40 and 60cm a significant correlation was found between leg stiffness and EMG for the vastus lateralis and hamstrings. These results indicated that it is possible to maximize vertical takeoff velocity through various leg stiffness’s which was seen through the different groups. This study also revealed that there was an optimal leg stiffness value that maximized mechanical power during the positive phase of the drop jump. The results also suggested that stiffness in the lower extremity can be regulated by changing the contact time through the use of different instructions. The results of this study are important due to the fact that performance in many sports is determined by the mechanical power output and the stiffness of the lower extremity during these movements. Maximization of mechanical power was attained through the optimization of leg stiffness and ankle stiffness as well as the optimum amount of activation in the muscle of the lower extremities during the pre-activation phase of the movement.

Previous research has suggested that a countermovement in fast discrete movements can enhance performance and in some cases lead to increased jump heights. Bobbert and
Casius (2005) developed a simulation to determine whether the difference in jump height between CMJs and SJs could be explained by a difference in active state during the propulsion phase. The authors conducted a two-dimensional forward dynamic model of the human musculoskeletal system for the CMJ and SJ consisting of four rigid segments that represented the feet, shanks, thighs, and HAT (head, arms, and trunk). The segments were interconnected by hinge joints that represented the hip, knee, and ankle. In the sub-model there were six major muscle–tendon complexes (MTC) used: hamstring, gluteus maximus, rectus femoris, vasti, gastrocnemius, and soleus. The muscle model followed a Hill type model, which consisted of a series elastic element (SEE), a contractile element (CE), and a parallel elastic element (PEE). The researchers used this model to put the ‘subjects’ in optimal position before commencing the SJ or the CMJ. The simulation compared the different conditions involving a target minimum height of 71, 74, or 77 cm. The authors reported that, regardless of condition, maximum height in the CMJ was greater than the SJ with differences ranging from 0.4 cm at the high condition to about 2.5 cm at the lowest condition. The present study attributed the greater jump height in CMJ to a greater work output of the hamstring and gluteus maximus (0.86 CMJ and 0.87 in SJ), which was determined through the simulation model described previously. The CMJ jump had a total work output of 729J during the propulsion phase and the SJ had a total work output of 710J during the propulsion phase. The surplus of work for the propulsion phase in the CMJ was attributed to a greater force over the first 30% of muscle tendon complex (MTC) shortening in the hip extensors. This study attributes the greater jump height during the CMJ to the fact that there is greater active state development during the preparatory countermovement and the SJ is inevitably developed from the propulsion phase.
During locomotion leg muscles are stretched during the deceleration phase when the foot makes contact with a surface and then the muscles proceed to shorten immediately after, thus giving rise to acceleration of the body upward. Cavagna and colleagues (1968) investigated the extent to which the body can bounce elastically in exercise, such as jumping and running, in which the positive work done by the muscle is preceded by a phase of negative work. The experiment was done on a man’s forearm flexors, on an isolated sartor of a toad, and the gastrocnemius of the frog. The positive work done by the muscles during shortening and the negative work during the stretch phase were measured by an ergometer (which measured the force length of the forearm flexors). The muscles used during this study were immersed in oxygenated ringer solution at 0-2 degrees C. The muscles were fixed to the apparatus that consisted of an ergometer and a piston driven by compressed air. The muscles were dissected and mounted on the lever. The length of the muscle during the actual experiment was determined by the height of the lever and the change in length imposed on the muscle by the movement of the lever (the lever was 3 mm in all experiments). The air pressure moving through the pistons during the study was generally 4 atm (atmospheric pressure), which corresponds to about 40kg. The force pistons on the lever were set at about 10 times the maximal force that could be exerted on it by the subject and was able to confer to the lever and the forearm acceleration such that a constant speed of 10-200cm/sec could be reached in less than five percent of the total length change. The force developed by the flexors was measured at the wrist by a strain gauge transducer fixed to the lever at the height required to connect it to the wrist. The results of this study suggested that an active muscle was able to perform a greater amount of work when shortening occurred immediately after being stretched. Although these results come from a toad sartorius, a frog
gastrocnemius, and on the forearm flexors in a man the greater work performed in an active muscle was still observed after pre-stretch. The results of this experiment demonstrated that greater work was obtained when the muscle is allowed to shorten immediately after being stretch, an observation attributed by the author to the release of elastic energy stored during stretching.

Ishikawa and Komi (2005) designed a study to examine the behavior of fascicle-tendinous tissue interaction during an extremely high intensity load (drop jump exercise) and to clarify the relative contribution of elastic recoil in the tendon during a short contact time drop jump exercise. The researchers hypothesized that the short contact SSC exercise cannot utilize the elastic energy efficiently. Instead, they suggest that the neuromuscular system will rely more on the stretch load intensity but only up to a critical point, beyond which the efficiency of the elastic recoil decreases. The study sample consisted of eleven physically active men and women who all had previous experience in executing drop jumps. The subjects were dropped from different heights to find the drop height that resulted in the best individual height of rise of the center of mass, which was then considered the optimal height for drop. Once the optimal height was identified, three jumps were performed at three separate heights, with subjects dropping directly onto a force platform from an erect stance at different elevations and attempting to rebound upward upon ground contact. The dropping heights included: optimal drop height (OP), optimal height plus 10 cm (High), and optimal height minus 10 cm (low). The drop jumps were recorded on a high speed video camera in order to calculate the joint angles of the lower limb (hip, knee, and ankle). Ground reaction forces and center of pressure were measured by force platform data and electromyographic (EMG) recordings were taken from the medial gastrocnemius and vastus lateralis. The
authors reported that, peak vertical ground reaction forces increased with an increase in drop height or intensity. The ground contact time also increased with increasing drop heights. The EMG data revealed that the pre-activation of the medial gastrocnemius increased more in the OP then the Low and did not show a significant difference between the OP and the High. In the braking phase the medial gastrocnemius, vastus lateralis, and tibialis anterior decreased in EMG activity from Low intensity to High intensity and in the push off phase the EMG activity decreased from Low intensity to OP and increased from OP to High intensity. These results suggest that, regardless of drop height, the conditions for the tendinous tissue recoil were favorable in these short contact drop jumps. The behavior of the fascicle length changed between the medial gastrocnemius and the vastus lateralis. Ultrasound measurement of fascicle length demonstrated that extreme drop heights caused a sudden increase of the fascicle during the braking phase in the medial gastrocnemius muscle but not in the vastus lateralis, which means that less storage of elastic energy occurred at high stretch rates. During these short contact drop jumps, the tendinous tissue underwent lengthening before shortening but the efficiency of the elastic recoil decreased with increasing drop intensity. This finding reveals that the optimal utilization of the elastic recoil was specific to height. If the drop jump height is at optimal height for the individual, then the likelihood of increased utilization of the elastic recoil may be more prevalent. This study is extremely beneficial with regard to plyometric training in the way that it shows strength and conditioning practitioners that increasing the height of the drop jump is not always an optimal solution. The main function of plyometric movements is decreased contact time in order to activate the musculoskeletal/ neuromuscular mechanism to allow for optimal force development and
having a drop jump height that is too high for a given individual cannot accomplish this objective.

The musculoskeletal system is a complex set of structures that rely on many different components to accomplish motor tasks. Bobbert (2001) examined the dependence of SJ performance on the compliance of the tendinous tissue of the triceps surae. Bobbert input kinematic and kinetic data from maximal jump attempts of an experienced male jumper into a two-dimensional forward dynamic simulation. The model calculated internal states and muscle-tendon forces as well as the motion of the body segments corresponding to simulation-time input of the muscles. The segments modeled consisted of the feet, shanks, thighs, and head and trunk (HAT). The simulation model was not tuned to represent individual subjects, but rather, to represent a group of subjects. The simulation completed SJ at different take off velocities (2.89m/s, 2.65m/s, and 2.78m/s), which influenced jump height. The results revealed a good correspondence between the kinematics of the jumps of the model and those of the subject. Through the present study, however, the subject’s jump heights were greater than that of the simulation model at all relevant settings. This can be explained due to the fact that humans do not have completely rigid segments and can generate force through various musculature in order to contribute to the work being done. The outcomes measured in the subject and generated by the model generally did not differ a great deal. It is clear through this analysis that the subject model that used the take off velocity of 2.65m/s had a considerable positive effect on SJ performance: variations in maximum jump height of approximately 9 cm were achieved by changing the compliance of the series elastic element of the triceps surae. The changes in jump height were not only due to the changes in the work output of the muscle-tendon complex, but due to the increased
amount of stored elastic energy. When the series elastic element of the muscle was adjusted for compliance there was a change in performance and in this case, it was an increase in performance. The present study demonstrated that the compliance of the series elastic element of the tricep surae had a considerable effect on the maximum height achieved in an SJ. This increase can be mediated through the changes in work output of both the tricep surae and other muscles along with the changes in efficiency of converting the work. The advantage of series elastic element compliance in squat jumping arises from the temporary storage of energy in the series elastic element and its subsequent release at a high rate.

The timing in activation of the stretch component involved with an increased force production after a muscle has been stretched is vital. Wilson, Elliot, and Wood (1991) examined the reduction in the augmentation derived from prior stretch with increasing pause time during the bench press. They used twelve males all of whom were experienced weight lifters with varying abilities. These lifters performed a bench press exercise that varied in the length of the delay at the end of the eccentric phase of the lift. The lifters performed bench presses that involved 4 different pause durations, consisting of: no pause, short pause, long pause, and movement without a pre-stretch. An experienced lifter determined the pause time subjectively, since, during weight lifting competitions, the judging is done with this same type of system. A clap of the hands indicated the lifter could continue with the movement after the eccentric phase once they heard the clap from the experienced lifter. Each lifter was required to lift 95% of their maximum in the bench press. The results revealed that a 0.1 seconds RBP (rebound bench press) involved a greater rate of performance of work when compared to the other lifts. This was measured through a rigidly mounted force platform where vertical and horizontal forces for each bench press movement were recorded. After
.37 seconds the increase in action was no longer derived from the pre-stretching of the system, this was quantified as (bench press/PCBP impulse)*100%. The authors also noted that a time delay of greater than .45 seconds between the eccentric and concentric phase of the movement did not allow for the benefits of the pre-stretch. Delays during the movement significantly decreased the impulse (force*time) but RBP was still better than pure concentric bench press for impulse. This study revealed the importance of a decrease in amortization phase during a plyometric movement. This is important due to the loss of force production with an increased delay between the eccentric and concentric phases. Although this study was done with the bench press, it illustrates that an increased contact time or delay between the eccentric phase and the concentric phase can influence the power output in the concentric phase of the action.

**Fatigue during plyometric movements.** During physical activity, there is a certain point at which limits are reached and individuals cannot participate at the highest level possible. The various mechanisms that play a role in plyometric movements and the pre-stretch force augmentation can be strongly influenced by fatigue of the system. A review article by Nicol, Avela, and Komi (2006) examined stretch shortening fatigue studies which were performed during human experiments and to show how fatigue can have functional and structural effects on muscle function.

Although there are numerous possible mechanisms contributing to the benefits of pre-stretch force augmentation, it is evident that fatigue affects the way these mechanisms work and in many cases can hinder performance. Komi (2000) explored the effect of fatigue on the performance of the SSC. The main focus of this work was to demonstrate the recoil nature of the SSC and how the stretch reflex plays an important role in force potentiation.
Another objective was to reveal the SSC as a model to introduce fatigue to the system and this fatigue. It has been shown through different avenues that non-fatiguing SSC exercise demonstrates considerable performance enhancement with increased force at a given velocity. Komi discussed the role of the stretch reflex and its contribution to force enhancement during the SSC. According to Komi, the duration of a simple stretch reflex is 40ms long and the maximum delay between initial stretch and the subsequent force potentiation would be around 50-55ms (Mero & Komi, 1985). Komi points out that contact time during a marathon is typically almost 250ms and during sprinting the contact time is typically 90-100ms (Mero & Komi, 1985). These time calculations confirm that stretch reflex could have ample time to be instrumental in force and power enhancement during a SSC. The stretch reflex plays an important role in the SSC and contributes to force generation during the touch-down phase in activities such as running and hopping. Komi also discusses the SSC as a unique model to study neuromuscular fatigue. In SSC, fatigue impact loads are repeated over a certain time period with the exercise taxing all the major elements such as metabolic, mechanical, and neural. Both short and long duration fatigue exercise leads to deterioration in neuromuscular performance. SSC fatigue usually results in reversible muscle damage and has considerable influence on muscle mechanics, joint and muscle stiffness and reflex innervations (Gollhofer, Komi, Fujitsuka, & Miyashita, 1987). Komi reviews numerous studies in this paper that reveal an immediate change in mechanical performance and an inability to tolerate the imposed stretch load when fatigue is present. Effects observed during and after SSC fatigue bouts include: a drop in force after impact, increased contact time in braking and push off phase, and an increase in impact force (Nicol, Avela, & Komi 2006; Horita, Komi, Nicol, & Kyrolainen, 1996; Gollhofer, Komi, Fujitsuka,
& Miyashita, 1987). Komi states that with increased muscle damage a reduction in stretch reflex sensitivity, reduced stiffness regulation, and a deterioration of SSC performance is observed with fatigue.

Horita, Komi, Hamlalainen, and Avela (2002) aimed to investigate the fatigue mechanism of exhaustive SSC exercise on concentric muscle function. Ten healthy male volunteers participated in the study. Fatigue was induced by exhausting SSC exercise on the sledge apparatus inclined at 23 degrees from the horizontal and equipped with a force platform which was perpendicular to the plane of sliding. The subjects performed a series of bilateral sub-maximal rebound jumps along the gliding track of the sledge and were instructed to rebound as high as possible (the height was set to 70% of their maximal rebound height). The session was stopped once the subject could no longer reach the sub-maximal rebound height. On average the subjects performed 92 repetitions which corresponded to 2.7 minutes of work. To examine the fatigue effect on isolated concentric and SSC muscles function, two maximal jumps were performed on the sledge apparatus before and after the SSC fatigue exercise and repeated 2 days and 4 days later. The jumping measurements consisted of two jumps with maximal effort: one DJ from a pre-determined height of 70 cm and a SJ on the sledge with no active stretch. These measurements were performed along the gliding track of the sledge. The SJ measurements were performed before and immediately after 0 minutes and then 10 minutes, 20 minutes, 2 days, and 4 days after SSC fatigue exercise. DJ measurements were performed before and then 20 minutes, 2 days and 4 days after the SSC fatigue exercise. Surface electromyography activity was recorded from the vastus lateralis (VA), vastus medialis (VM), medial gastrocnemius (GA) and soleus (SO) muscles of the right leg. The results revealed that the force curve during the contact period
showed a decrease in the peak force and increase in duration as the SSC exercise progressed. The average contact time during the last ten consecutive jumps was much higher than that during the initial ten jumps. SJ performance decreased immediately after the SSC exercise bout, but recovered within 10 minutes after exercise, and remained at the same level during the subsequent follow-up sessions (2 days and 4 days after exercise). DJ performance showed a delayed decrease 2 days after the exercise bout. Thus, these two jumps demonstrate different patterns of performance change during the follow up period of 4 days. In the SJ, the EMG activity showed no significant changes after the SSC activity bout. GA EMG showed an average 20% decrease immediately after exercise. However, due to the large inter-individual variation, this change was statistically non-significant. In the DJ, the pre-activity of the knee extensors (VL and VM) significantly decreased on day 2 and day 4 after the exercise bout. GA also showed a delayed decrease in EMG on day 4. DJ also showed a marked and delayed decline both in the braking phase and the push-off phase. One of the main findings was that exhaustive SSC exercise induced different fatigue responses in DJ and SJ performance in terms of EMG activity and that isolated concentric muscle function is primarily affected by an acute metabolic fatigue after SSC exercise.

Ishikawa and colleagues (2006) examined the events inside the muscle-tendon unit in humans after exhaustive SSC exercises. Eight healthy males volunteered to take part in the present study. Fatigue was induced by an exhaustive SSC exercise, and the primary mechanical fatigue effects were followed with force measurements of the plantar flexor muscles. Measurements were taken before (BEF), and immediately after (AFT) as well as 2h (2H), 2 days (2D) and 8 days (8D) after the SSC exercise. Subjects were dropped with the sledge from different starting heights to determine optimal dropping height that led to their
highest rebound performance. The fatigue protocol used in the present study was derived from Kuitunen and colleagues (2002) which included first 100 repeated maximal single sledge-drop jumps from the optimal dropping height, repeated every 5 seconds. This series of jumps was immediately followed by a continuous rebounding exercise to a sub maximal height representing 70% of their maximal initial rebound performance. Torque measurements and EMG were also measured during the present study. Plantar flexor torque was measured from the right leg during MVC. The knee and ankle joint angles were set at 130 and 103 degrees, respectively. EMG was recorded from the soleus muscle using bipolar surface electrodes. Blood samples were taken from the finger to determine blood lactate concentrations BEF and AFT the SSC exercise and 5 min, 2H, 2D, and 8D post-exercise. Muscle thickness was measured by ultrasonography to estimate possible swelling during the follow up period. The authors reported that MVC torque decreased significantly by 25.1% ± 3.8% at AFT (P<0.05) corresponding to the average EMG reduction of 5.1% ± 5.0% (P<0.05). Both parameters recovered at 2H and MVC showed a secondary reduction at 2D (P<0.05), followed by the recovery of both parameters at 8D. Blood LA concentrations increased to 9.0 ± 1.3 mmol l⁻¹ at AFT, and then recovered progressively toward the 2H point. Architectural changes of the soleus muscle were clearly observed during this study. The measured muscle thickness increased at 2D as compared with BEF and AFT. There was no significant relationship in the relative changes in MVC torque and those in the muscle thickness between BEF and 2H (BEF→2H). The relative changes in MVC torque were positively related to the corresponding average of EMG changes between BEF and →2H, but then the significance disappeared in the comparison between 2H and →2D. The main findings of the present study were that MVC torque decreased significantly at AFT followed
by a delayed reduction (2D) after the exhausting SSC exercise and that the muscle thickness gradually increased until 2D post-exercise which was strongly related to a secondary reduction in MVC.

Fatigue to the system can cause fatigue in different locations such as the peripheral region which lies distal to the stimulated motor nerve and the central region which is located proximal to this location. Asmussen (1979) discussed the causes of central and peripheral mechanisms associated with fatigue. Maximum intensity of exercise is determined by such physiological functions as the maximum rate of oxygen uptake, maximum heart rate and stroke volume, and maximum muscle strength. When a maximum amount of physical work has been reached, it is usual to say that fatigue has put limits on the continuation of the activity. With regards to muscular fatigue, Asmussen separated fatigue into two regions: a peripheral region distal to the stimulated motor nerve and a central region proximal to this location. In peripheral fatigue there are at least two different sites where repeated contractions may cause impairments: the transmission mechanism (neuro-muscular junction, muscle membrane, and endo-plasmic reticulum) and contractile mechanism (muscle filaments). The appearance of peripheral muscle fatigue is undoubtedly associated with local changes in the muscle fibers. These may be biochemical, consisting of depletion of glycogen, high energy phosphate compounds in the muscle fibers, and acetylcholine in the terminal motor nerve branches, or they may be due to accumulation of metabolites or other substances liberated from the muscle during exercise. Peripheral muscle fatigue can be defined as a transient decrease in a muscle group’s capacity for exercise. Central muscle fatigue refers to the impairment of nerve cells in the central nervous system (this may not always be the case). Central muscle fatigue might as well be explained as the result of an
increasing inhibition of the voluntary effort. According to Asmussen, central fatigue is caused by an inhibition elicited by nervous impulses from receptors (probably some kind of chemoreceptor) in the fatigued muscles. The inhibition may act on the motor pathways anywhere from the voluntary center in the brain to the spinal motor neurons. According to the author, this type of fatigues manifests itself by a decrease in the outflow of motor impulses to the muscle. The author states that peripheral and central fatigue may appear separately or combined, depending on the specific situation. If the variables (duration, rest intervals, volume, and intensity) are not monitored at an adequate level, fatigue may be induced. Although the overload principle plays a fundamental role in the progression during a plyometric program it important to understand the mechanism associated with fatigue in a plyometric exercise. According to Asmussen, there is no evidence that suggest that either central or peripheral fatigue is more involved in limiting plyometric performance.

**Manipulation of training variables.** As with all training programs, specific training variables can be manipulated in a plyometric training program in order to induce desirable physiological adaptations. Resistance training, aerobic endurance training, and speed and agility training have a broad base of research surrounding the manipulation of these variables in order to induce the precise stimuli. This is not the case with plyometric training. The manipulation of training variables within a plyometric training program is mainly based off anecdotal evidence or personal experience and rarely founded on the recommendation from scientific research. The lack of research that surrounds plyometric training duration, frequency, volume, intensity, and rest periods has hindered the ability of practitioners to build adequately designed research based programs.
Training programs use different variables that can be manipulated to prevent overtraining, optimize adaptations, and prevent plateaus in physiological development. These variables are important to the success of the training program when the training level of the athlete increases. The variables that can be manipulated throughout plyometric training programs are also the variables that are manipulated for resistance training, endurance training, agility training, and speed training and include training duration, frequency, volume, intensity, and rest periods.

The duration of a plyometric training program is based on the time of year and phase of the macrocycle which the athlete is training. Duration can also be associated with session duration or length of the plyometric training program (week, month, etc). In other types of training, such as aerobic endurance training, ‘duration’ is referring to a single training session. The duration involved with a plyometric training program can exhibit various time frames in order to see benefits within the plyometric training program. Although many of the available research studies are short-term, (4-12 weeks) (Brown, Mayhew, & Boleach, 1986; Gehri, Ricard, Kleiner, & Kirkendall, 1998; Luebbers et al., 2003; Ronnestad, Kvanme, Sunde, & Raastad, 2008; Turner, Owings, & Schwane, 2003; Villarreal, Gonzalez-Badillo, & Izquierdo, 2008), the evidence still shows that sport performance benefits can be observed through these short duration plyometric training programs. Traditional training duration can be broken down into specific time periods termed macrocycle, mesocycle, and microcycle. Breaking the duration of a training program down into these three time periods is typically referred to as periodization. A macrocycle is the largest of the three and typically constitutes the entire training program (can consists of many months of training and even up to 4 years) (Baechle & Earle, 2000). A mesocycle tends to last up to several weeks or even several
months (Baechle & Earle, 2000). Microcycles last around one week but can last for up to four weeks depending on the programming (Baechle & Earle, 2000). Due to the needs of the athlete and training program goals, the practitioner can take into account these time periods in order to accurately map out the duration of the training program. The available research indicates that effective plyometric programs can span one to several mesocycles (4-12 weeks) (Brown, Mayhew, & Boleach, 1986; Gehri, Ricard, Kleiner, & Kirkendall, 1998; Luebbers et al., 2003; Ronnestad, Kvamme, Sunde, & Raastad, 2008; Turner, Owings, & Schwane, 2003; Villarreal, Gonzalez-Badillo, & Izquierdo, 2008).

Another training variable that has a significant effect on athletic performance is training frequency. Training frequency is defined by the NSCA as the number of times per week an individual takes part in a training program (Baechle & Earle, 2000). The frequency at which an athlete takes part in a plyometric training program is based on the time of year (off-season, pre-season, and in-season), intensity, and training status. The manipulation of training frequency will allow for the athlete to be ready and adequately rested for the next training session.

Along with training frequency, volume is vital component to any periodized plyometric training program. Training volume associated with plyometric training programs is defined as the number of ‘touches’, ‘distance’ or ‘throws’ completed by an individual through a plyometric training session (Baechle & Earle, 2000). Volume can also be defined as the amount of work per exercise repetition multiplied by the total number of repetitions for the training session (Vissing, et al., 2008). According to the NSCA plyometric training volume should be 80-100 contacts per session for a beginner with no experience, 100-120 contacts per session for an intermediate level athlete with some experience and 120-140
contacts per session for an advanced level athlete with considerable experience (Potach & Chu, 2000).

Villarreal, Gonzalez-Baldillo, and Izquierdo (2008) examined the effects of 3 different training frequencies (1 day a week, 2 days a week, and 4 days per week) associated with three different plyometric training volumes on maximal strength, vertical jump performance, and sprinting ability. The study took place over a seven-week span and involved 42 physical education students between the ages of 21 and 26 with no previous plyometric training experience. Subjects were broken up into 4 different groups based on training frequency and volume. The first group trained once a week and completed seven sessions that totaled 420 drop jumps during the seven week intervention. The second group trained twice a week and completed fourteen sessions that totaled 840 drop jumps during the seven week intervention. The third group trained four times a week and completed 28 sessions that totaled 1680 drop jumps during the seven week intervention. The fourth group served as the control group and did not participate in the intervention. The drop jumps accomplished during this study were done at three separate heights (20 cm, 40 cm, and 60 cm). Before the intervention there was no significant difference between groups when comparing 20-m sprint time, maximal dynamic and isometric strength (in the leg press), and height in CMJs and in 20-cm DJs, 40-cm DJs, and 60-cm DJs. The subjects were tested in CMJ and DJ (from 20, 40, and 60 cm) along with isometric maximal strength test and 1RM test. The authors reported a significant decrease in 20m sprint time, increased maximum 1RM leg press and an increase in isometric strength after the intervention period. The groups that completed 28 sessions and 14 sessions saw a significant increase in countermovement jump height and drop jump height but there was no significant improvement for the group
that completed 7 sessions. No significant difference in magnitude of height observed or contact time decreases were documented across all the groups. After a seven-week detraining period, 20m sprint time decreased for the group that participated in 28 sessions and the group that participated in 14 sessions. The group that participated in 7 sessions also saw a decrease in contact time after the detraining period. Short-term plyometric training using moderate training frequency and volume produced similar enhancements in jump performance but greater training efficiency (less session and jumps which produced similar enhancements) when compared with the high training frequency in previously recreationally trained subjects. This allows for performance enhancements to be seen in a more efficient manner with a lower training frequency and volume.

Intensity is another training variable that is important in determining improvements in overall performance and adequate program design for plyometric training. Plyometric intensity has been defined as the amount of stress placed on involved muscles and connective tissue and joints, and this is dictated mainly by the type of exercise that is being preformed (Baechle & Earle, 2000). Factors involved in determining plyometric intensity are typically speed of the exercise, height of the jump, type of exercise being performed, and athlete’s body mass (Baechle & Earle, 2000). These factors can be manipulated in order to increase or decrease the intensity of the plyometric program, depending on what the situation calls for. Progressing the intensity of a plyometric program can be done by increasing the height of the box or hurdles involved in the program (Vising, et al., 2008). This training variable can have an effect on peak ground reaction forces and peak joint forces involved in each exercise. Intensity of plyometric training is designated as low intensity, moderate intensity, and high intensity. Two-foot ankle hop, squat jumps, jump and reach, double leg vertical jump, single
leg push-off, alternate leg push-off, lateral push-off, and jump to box plyometric exercise are all considered ‘low intensity’ by the NSCA (Potach & Chu, 2000). Double leg tuck jump, split squat jump, hurdle jumps, double leg hops, lateral hurdle hops, side to side, box jump, box to floor, and lateral box jump plyometric exercise can all be considered ‘moderate intensity’ when following the NSCA guidelines. Cycle split squat jump, pike jump, single leg tuck jump, single leg vertical jump, double leg zig-zag hop, single leg hop, depth jumps, and single leg depth jumps can be considered ‘high intensity’ by the NSCA (Potach & Chu, 2000).

Ebben, Simenz, and Jensen (2008) evaluated electromyography (EMG) activity of the gastrocnemius (G), hamstrings (H), and the quadriceps (Q) muscle groups during a variety of plyometric exercises to quantify the differences among the exercises. The subject sample consisted of twenty-four adults (13 women and 11 men), all of whom have participated in resistance training and either recreational or intercollegiate sports and were familiar with the plyometric exercises evaluated in the study. The plyometric exercises used in the study were primarily accomplished in the vertical plane and were thought to represent a continuum of intensities. The exercises that were used during the study were: depth jumps (from 30.48 cm and 61 cm), pike jump, tuck jump, single leg vertical jump and reach, double leg vertical jump and reach, squat jump holding dumbbells (with 30% of 1 RM squat), two foot ankle hop, 15.34 cm cone hop, and a 61-cm box jump. A one-minute rest interval was maintained between each exercise to allow recovery of the energy system and to ensure maximum effort for each exercise. The author reported that depth jumps exhibited the lowest Q EMG of all the exercises. Cone hops, box jumps, and tuck jumps resulted in a greater Q EMG than exercises such as the single leg jump, and depth jump from 30 cm and 60 cm.
Furthermore, the vertical jump generated greater Q EMG activity than the depth jumps, and ankle hops. Ankle hops also offer more Q EMG than depth jumps from 61cm boxes. G EMG also indicated that exercises such as vertical jump and cone hop resulted in greater motor unit recruitment than single leg jumps or depth jumps. Exercises such as tuck jump, ankle hop, and box jump all resulted in greater motor unit recruitment than 61cm depth jumps. For both the Q and G muscle groups, the bilateral vertical jump resulted in greater average levels of motor unit recruitment than the single leg jump, the unloaded vertical jump resulted in more motor unit recruitment than squat jumps with 30% of 1 RM squat, and the 30cm depth jump resulted in higher levels of motor unit recruitment than the 61cm depth jumps. A possible explanation for these results is that increased loading selectively activates passive force-producing structures of the SSC more than the stretch reflex, which would increase motor unit recruitment. The present study contradicts previous recommendation from the NSCA surrounding plyometric intensity and what classifies plyometric exercises intensity (Potach & Chu, 2000). The NSCA classifies depth jumps as high intensity but through the present study it is revealed that greater motor unit recruitment was observed in cone hops, box jumps, and tuck jumps when compared to depth jumps.

Jensen and Ebben (2007) examined the rate of eccentric force development (E-RFD), peak GRF, ground reaction forces relative to body weight (GRF/BW), knee joint reaction forces (K-JRF), and knee joint reaction forces relative to body weight (K-JRF/BW) for a variety of plyometric exercise in order to further quantify their relative intensities. The authors recruited six national collegiate athletic association (NCAA) division 1 track and field, volleyball, and wrestling athletes. All subjects used the plyometric exercises that were used in the study as a part of their regular strength training regime. The plyometric exercises
used included: depth jumps from 46 cm (DJ46) and 61 cm (DJ61), pike jumps (PJ), tuck jump (TJ), single left-leg jumps (SLJ), countermovement jumps with arm swing (CMJ), squat jumps with hand on top of head (SJ), and a squat jump holding dumbbells equal to 30% of their 1RM in the squat (SJ30). A one minute rest interval was allotted between each exercise. All data was collected on one day and a force platform was used to analyze GRF within the study. The results of the present study revealed that peak GRF and GRF/BW were not significantly different across the eight conditions. The amount of variability demonstrated by the different exercises explained 17.9 and 17.0 of the total variance for peak GRF and GRF/BW, respectively. The results of the present study also suggest that E-RFD was lower for the SJ and SJ30 than the DJ, CMJ, SLJ, and TJ. Differences were found in the E-RFD as well as in the K-JFR and K-JRF/BW. These results suggest that when compared to previous studies, the differences in results may be due to lack of statistical power as a result of the number of subjects and the relatively large variability in plyometric performances. The differences in E-RFD across jumping conditions appear to indicate variability among plyometric exercises and thus differences in their relative intensity. With regards to the intensity of these various plyometric exercises, the authors recommended that TJ, PJ, and SLJ should be introduced later in the program due to their high K-JRF and K-JRF/BW.

A plyometric training program needs to progress in order to induce improvements within the systems and the manipulations of exercise intensity helps facilitate this progression. The ability to quantify the intensity of various plyometric exercises such as one legged and two legged countermovement jumps can benefit plyometric programming a great deal. Van Soest and associates (1985) looked at unilateral and bilateral performances during
single leg and two-legged countermovement jumps (CMJ). These two motor skills were compared with respect to biomechanical variables and with respect to EMG levels. The study sample consisted of ten well-trained volleyball players that performed one legged and two-legged countermovement jumps during the course of the study. Ground reaction forces, cinematographic data, and electromyographic (EMG) data were recorded while subjects performed CMJ with both one leg and two legs. During the one leg trials individuals were required to keep the opposite leg inactive under the body. The authors examined vertical ground reaction forces, point of application, jump height, and peak torque. The jump height was measured by taking the highest value for each CMJ. The results indicated that single leg CMJ height was 58.3% of the two-legged CMJ and that the push off phase was longer in the single leg CMJ than the two-legged CMJ. It was also observed that more work was performed in the single leg CMJ than the two-legged jumps. Torque was smaller in the knee joint with the single leg CMJ as opposed to two-legged CMJ, but greater in the ankle for the single leg as compared to the two leg CMJ’s. Vastus medialis and gastrocnemius had increased EMG levels in the single leg CMJ when compared to the two-legged CMJ. The results of the present study suggest that single leg CMJ’s are more ‘intense’ as compared to two-legged CMJ. This is evident from the increase EMG activity and increased ankle joint torque during the single leg CMJ. The present study was able to quantify intensity of single leg vs. two-legged CMJ. Practitioners can use the evidence provided in the present study to accurately involve single leg CMJ and due to the increase intensity they should be added to the program once the athlete is able to complete two legged CMJ efficiently and needs a greater stimuli.
Along with previous mentioned training variables, rest intervals or rest periods between sets and exercises are a vital component to a successful plyometric training program. Adequate rest intervals allow for the athlete to have an optimal time to recover in order to give maximum effort during the proceeding repetitions and sets. Due to the nature of plyometric training, longer rest periods are needed in order to get maximal effort out of each set and repetition. Work-to-rest ratios of 1:5 to 1:10 appear adequate for plyometric training rest periods (Potach & Chu, 2000). These work-to-rest ratios have been recommended because plyometric training should not be seen as cardio-respiratory conditioning exercises but as a form of power training (Potach & Chu, 2000). Time for complete recovery should be allowed between plyometric exercise sets (NSCA Position Statement Explosive/Plyometric Exercise, 2009).

Recovery allows the body to regenerate after a training session and gives the athlete a proper amount of time to be physiologically/neuromuscularly ready for the next training session. According to Chu (1998), recovery should range from 48 hours between plyometric workouts when the frequency is 3 times per week and 72 hours between plyometric workouts if the frequency is 2 times per week. Along with recovery, rest periods between exercise sets in a training session play an important role in the program design of a plyometric training program.

Read and Cisar (2001) measured the effects of varied rest interval lengths on the vertical jump heights and ground reaction forces during the execution of a depth jump (DJ) from a predetermined optimal height. Optimal DJ height was determined by executing a series of DJ from 10-80cm, increasing by 10cm for each jump. The height at which they accomplished their highest rise of the iliac crest was considered their optimal DJ height.
Vertical jump height was measured using the peak performance motion measuring system. The subjects reported to the laboratory on four separate occasions, separated by 24 hours of rest. The first session consisted of determining the optimal DJ height for each subject, the second session consisted of 10 DJ from the optimal height with a 15-second rest period, the third session consisted of performing 10 DJ from optimal height with a 30-second rest period, and the fourth and final session consisted of performing 10 DJ with a 60-second rest period. Ground reaction forces were measure using a force platform and were recorded for each 10 jump trial for the 15-, 30-, and 60-second rest period. The author reported no difference in jump height among the 15-, 30-, and 60-second rest trials for any of the jumps. Jump height did not differ among jumps 1-10 with the 15 or 60 second rest groups. No differences were observed in ground reaction forces among 15, 30, and 60 second rest trials for any of the jumps. Ground reaction forces did not differ among jump 1-10 within groups. The primary finding of the present study revealed that rest interval length during single attempt DJ did not influence vertical jump height. The reason for this finding may be due to the fact that the duration of an exercise directly influences muscle fatigue and the DJ lasted less than 1 second and did not deplete the phosphagen stores. It appears that high intensity plyometric training using exercises such as single attempt DJ can be performed with rest intervals as short as 15 seconds without affecting neuromuscular performance.

Summary

This review of literature reveals the associated mechanisms with plyometric movements and also reviews the overall concept behind the movements and the performance enhancement seen after a training program has been implemented. The present review of research revealed that an improvement of force production, improved running economy,
decreased sprint times, increased jump height, and an increase in peak power (Brown, Mayhew, & Boleach, 1986; Gehri, Ricard, Kleiner, & Kirkendall, 1998; Luebbers et al., 2003; Ronnestad, Kvamme, Sunde, & Raastad, 2008; Turner, Owings, & Schwane, 2003; Villarreal, Gonzalez-Badillo, & Izquierdo, 2008) are all associated benefits of plyometric training programs. Along with the improvement of these physiological characteristics the present review also discussed the mechanisms that are involved with plyometric movements. The mechanisms involved are SSC, storage and release of elastic energy, stiffness within the musculoskeletal system, stretch reflex and muscle spindles, time in which it takes the muscle to develop force, the length tension relationship within skeletal muscle, motor unit recruitment, fatigue, and delayed onset muscle soreness. All these mechanisms play a part in plyometric movements and plyometric programming, and among various authors there remains some debate as to which mechanism predominates. With regards to the manipulation of acute training variables it has been revealed that rest periods greater than 15 seconds are adequate enough for single effort DJ’s, the intensity of various plyometric exercises are not adequately defined and are up for debate, and moderate frequency plyometric training can induce adaptation similar to high frequency programs. The information provided give practitioners a better understanding of the manipulation of these acute variables but also reveals that there is a significant lack of information regarding the manipulation of these variables. The manipulation of training variables within a plyometric training program is mainly based off of personal experience and rarely is the recommendation from scientific research. The lack of research that surrounds plyometric training duration (macrocycle which can be broken up into mesocycles and microcycles), frequency, volume, intensity, and rest periods has hindered the ability for practitioners to
build scientifically based programs. Since there is a lack of evidence regarding the manipulation of the program variables researchers will need to directly target certain variables such as volume. The ability to quantify volume of plyometric training is a vital component of adequately designed programs. The reason for this is that if there is not adequate information regarding the manipulation of this variable then the program may progress too quickly (too many ‘touches’ or distance too soon) and may have a detrimental effect on adaptation. Amongst all the present research there is yet to be information provided for practitioners that directly studies volume of repetitions. Since this training variable has not been directly studied in detail the present study will take a direct look at the effects exercise intensity on volume of repetitions completed in trained and un-trained subjects.
Chapter III
Methods and Procedures

Introduction

The present study set out to examine the effect of training status and exercise intensity on the volume of repetitions completed before propulsive force output decreases below 90 percent maximum force output. We examined the effect of training status and exercise intensity on the change in eccentric rate of force development (E-RFD) and contact time (CT) across exercise repetitions (depicted as the slope of the regression line connecting the E-RFD and CT for each repetition completed). The present study was undertaken to provide practitioners with more information on plyometric training volume and how they might manipulate repetition volume to create an environment that maximizes physiological and neuromuscular adaptation. Data collection took place over two days, separated by at least 96 hours but no more than a week. On day one subjects completed a full body dynamic warm-up, a jump assessment to evaluate the subjects ability to perform countermovement jumps, a one-repetition maximum (1RM) leg press and six maximal effort jump (three CMJs and three box jumps) in order to evaluate leg strength and the values associated with subjects maximal effort jumps. Once this data was collected, the individual completed continuous plyometric exercises at a low (CMJs) and moderate (box jump) intensity while landing on a force platform on day two. The CMJ and the box jump exercises were chosen because they represent relatively low and moderately intense exercises, respectively (Potach & Chu, 2000). Individuals were provided two minutes of rest after each maximal effort jump at each intensity and a five minute rest between each exercise on day one and on day two subjects were allotted five minutes of rest between each exercise. This was done in order to obtain maximal effort during the course of the data collection and provide adequate recovery.
Description of the Subject Population

Fifteen male Division II athletes and 15 weight matched (± 5 lbs) male recreational individuals were recruited to participate in this study; all subjects fell within a range of ages that were considered college age. The male Division II athletes all had at least 1 year of plyometric training experience, which was implemented into their year-long macrocycle, prior to the start of the present study. The plyometrically trained group consisted of four basketball players, nine soccer players and two track and field athletes. The recreationally trained group consisted of individuals who had not trained regularly with plyometric exercise prior to the start of the present study, but who were apparently healthy (as defined by the American College of Sport Medicine), were currently participating in a resistance training program, and were able to leg press one and a half times their body weight (Read & Cisar, 2001). Subjects were excluded from participating if they had a history of ankle, knee or back pathologies within in the last three months preceding the study, any medical or orthopedic problems that compromised their participation or performance in this study, any lower extremity reconstructive surgery within the past two years or unresolved musculoskeletal disorders. In addition, any subjects reporting current or previous use of anabolic steroids, growth hormones, or related performance enhancing drugs of any kind were excluded from the study. All subjects were informed of experimental procedures and about the possible risks involved with the present study, in compliance with the Institutional Review Board at Western Washington University.

Design of the study

This study followed a 2x2x4, mixed factor design, with the within subjects factors being exercise intensity (low vs. moderate) and quartile (1 through 4), and the between
subjects factor being training status (plyometrically trained vs. recreationally trained). The dependent variables were E-RFD and CT and the regression slope and quartile analysis depicted the changes in E-RFD and CT across repetitions. The current study is not a true experimental design because it is not randomized; the study consists of two groups that are assigned to a group based on experience. The design is a quasi-experimental design because it examines plyometrically trained vs. recreationally trained individuals and looks at the variables that distinguish the two groups.

**Data Collection Procedures**

**Instrumentation.** An Advanced Mechanical Technology, Inc. (AMTI) OR6-6 high frequency force platform (Watertown, MA) was used to collect ground reaction forces (GRFs), sampled at 1200 Hz, during ground contact in both the squat jump and box jump exercises. The force platform was interfaced to display real-time GRF data in order to identify when vertical GRFs in the propulsive phase of the jump decreased below 90% of maximum propulsive force output during exercise execution. The E-RFD was also calculated using force platform data. This was done by taking the first peak of the vertical GRF divided by the time from onset of landing to the first peak of the vertical GRF (Jensen & Ebben, 2007).

A plate-loaded standing leg press machine was used to evaluate lower body muscular strength. The standing leg press machine utilized an upright position with a large nonskid footplate along with a multiple position weight release. Plyometric boxes with heavy duty steel construction and a solid non-skid ribbed rubber top (NewYorkBarbell, Elmira, NY) of 12in, 18in, and 24in were used within the present investigation in order to provide a moderate intensity plyometric exercise for each subject. The plyometric boxes were able to
move up in heights of ¾” increments to allow for a more accurate height associated with 25% of the subject’s standing height.

**Measurement Techniques and Procedures.** Testing for each subject was carried out over two sessions, separated by at least 96 hours. On each day, testing began with a five-minute warm-up on a stationary cycle ergometer (Monark, Sweden) and dynamic stretching for the major muscle groups of the upper and lower body (lower body: CMJs, high knees, heel to buttock, knee to chest, mountain climbers, inchworm, lateral lunges, and forward lunges; upper body: pushups, shoulder circles, back scratchers, arm across chest, and arm hugs). Following the warm-up on day one, the height and weight of each subject was recorded. Along with these anthropometric measurements there was a jump assessment performed to evaluate excessive valgus or varus and balance and knee positioning during landing from a CMJ. This was done in order to make sure that subjects were capable of performing plyometric exercises safely. The maximum weight lifted in the leg press exercise was then determined using the process outlined by Baechle, Earle, and Wathen (2002). Briefly, the subject began by performing a warm-up set of leg press for 5-10 repetitions at a comfortable resistance. Following the warm-up set and a 1-minute rest, a set of 3-5 repetitions was performed with 20% added to the previous load. After a 2-minute rest, a near-maximum load was estimated by adding 10-20% of the previous load, depending on individual performance. Following a 4-minute rest, subjects attempted to perform a one-repetition maximum lift with 10-20% added to the previous load. This process continued, with each attempt followed by a rest interval of 4 minutes. If the subject failed to complete a repetition, the load was decreased by 10% and another attempt was made after a 4-minute
rest. Only those individuals capable of performing a leg press with a load equal to or greater than 1.5 times their body weight (Read & Cisar, 2001) were involved in further testing.

Following a rest interval of 10 minutes, qualified subjects were next tested to determine the maximum vertical GRF recorded in the propulsive phase of a CMJ. To do this, each subject stood on the force platform and then performed a CMJ involving arm swing from a standing position. Subjects were instructed to perform a CMJ and to jump with maximum effort. Three maximal efforts were recorded, and the peak vertical GRF during the propulsive phase was averaged over the three trials (mVJ-GRF), and was used as the reference criterion for subsequent testing. Subjects were allotted 1-2 minutes between maximal efforts during CMJ maximal efforts.

After a five-minute rest interval, subjects were asked to perform jumps from a position with both feet on the force platform to a box approximately 25% of body height, attempting to maximize the force exerted against the force platform and minimize the contact time with both the box and the force plate. The box was placed close enough to the force platform so that the majority of the forces exerted on the force platform during ground contact were directed vertically. As in the CMJ, three practice trials, followed by three maximal efforts separated by 1-2 minutes of rest, were recorded, and the peak vertical GRF in the propulsive phase of the box jump, averaged over the three trials (mBxJ-GRF) was used as the reference criterion for subsequent testing.

After a rest period of at least 96 hours, individuals commenced the second day of testing. Following the dynamic warm-up on day two (same as day one), subjects performed one set each of the squat and box jump exercises, in a randomized order, to eliminate order effects. For the CMJ exercise, subjects were asked to perform continuous CMJs involving
arm swing with no pause between repetitions on the force platform. Vertical GRF was displayed via AMTI NetForce software during each jump and compared to the average peak force recorded during the three trials of maximal vertical jump testing (mVJ-GRF). Subjects continued performing CMJs until the peak vertical propulsive GRF dropped below 90% of the mVJ-GRF for two consecutive jumps, or until the end of the 30-second data acquisition period. The number of repetitions performed above 90% was recorded and used for analysis. In addition, the eccentric rate of force development (vjE-RFD) and contact time (vjCT) was calculated from the vertical GRF during the landing phase of each repetition. E-RFD provides an indication of the change in reactive strength across multiple repetitions (Baechle & Earle, 2000; Walsh et al. 2004). The vjE-RFD for each repetition was plotted during the execution of the exercise and used for subsequent statistical analysis. Along with E-RFD, vjCT was also analyzed across repetitions by taking the time at which the vertical GRF exceeded 3 newtons and subtracting it from the time at which the vertical GRF again dropped below 3 newtons. This data was then plotted during the execution of the exercise and used for subsequent data analysis.

The same process was undertaken for the box jump exercise. Subjects began on the force platform. They performed a CMJ onto the top of the box in front of them, and immediately jumped back down onto the force platform. As soon as the feet contacted the force platform again, subjects were instructed to attempt to jump explosively back onto the box and repeat the process continuously, and to spend the least amount of time on the ground as possible. As in the CMJ, vertical GRF was displayed via AMTI NetForce software during each jump and compared to the mBxJ-GRF during maximal box jump testing. Subjects continued performing box jumps until the peak vertical GRF dropped below 90% of
the mBxJ-GRF for two consecutive jumps, or until the end of the 30-second data acquisition period. The number of repetitions performed above 90% and the vertical propulsive GRF across repetitions were recorded and used for analysis. Also, the bxjE-RFD and bxjCT during foot contact with the floor during box jumps was calculated using the force platform data, and analyzed across repetitions.

**Data Analysis**

Once data acquisition was complete the raw force platform data was exported in to Excel (Microsoft, WA). In excel the E-RFD and CT were calculated for each jump completed by all thirty subjects across both intensities (CMJs and Box Jump). The E-RFD was calculated by taking the first peak of the vertical GRF divided by the time from onset of landing to the first peak of the vertical GRF (Jensen & Ebben, 2007). CT was calculated by taking the time at which the vertical GRF exceeded 3 newtons and subtracting it from the time at which the vertical GRF again dropped below 3 newtons. This data was then graphed to examine the trends of E-RFD and CT across repetitions for each group at both intensities. In order to get a more organized look at the regression lines portrayed through each subjects data the regression equation from each subject’s graph was used to formulate four graphs for E-RFD (Box Jump for the plyometrically and recreationally trained groups and CMJ for the plyometrically and recreationally trained groups) and CT (Box Jump for the plyometrically and recreationally trained groups and CMJ for the plyometrically and recreationally trained groups) for all thirty subjects.

Due to the variability within the number of repetitions completed at each intensity it was imperative for statistical analysis that we break down the number of repetitions completed at each intensity for each subject into four quartiles. Each number of repetitions
completed by each subject was broken down into four quartiles for Box Jump E-RFD, CMJ E-RFD, Box Jump Contact Time, and CMJ Contact Time. The average across the four quartiles for all subjects was then graphed in order to subjectively analyze the differences within each group at each intensity with E-RFD and CT over the four quartiles. The average within each of these quartiles for E-RFD and CT for plyometric trained and recreationally trained subjects were graphed in order to get a better depiction of the trends between the two groups based on the averages of each quartile for each intensity.

**Statistical Analysis**

Using PAWS, version 17.0 (SPSS, Inc., Chicago, IL) statistical software, two three-way mixed factors analyses of variance (ANOVA) were used to evaluate the effect of exercise intensity, repetition quartile, and training status on E-RFD and CT. A simple effect was also used on significant interactions to further investigate the relationship between variables. In both analyses, if a significant effect was detected, a Bonferroni correction was applied to correct the alpha value (α) in order to account for multiple comparisons.
Chapter IV
Results and Discussion

Introduction

The purpose of the present study was to examine the effect of training status and exercise intensity on the volume of repetitions completed before power output decreases below 90 percent maximum power output. We also set out to examine the effect of training status and exercise intensity on the change in eccentric rate of force development (E-RFD) and contact time (CT) across exercise repetitions (depicted as the slope of the regression line connecting the E-RFD and CT for each repetition completed). The results of the present study revealed that there is a great deal of variability within E-RFD and CT across repetitions among plyometrically trained and recreationally trained subjects at low (CMJ) and moderate intensity (box jumps) plyometric exercises.

Subject Characteristics

The subject sample within the present study fell within the age range that can be considered college age and were all apparently healthy. The plyometrically trained group average weight was 82.8kg ± 16.9kg with an average height of 1.84m ± 0.08m. The recreationally trained group averaged weight was 83.6kg ± 14.7kg with an average height of 1.81m ± 0.07m. All subjects within the present investigation were able to leg press one and half times their body weight thus showing adequate strength ratios to participate in plyometric exercise within the present investigation.

Volume of Repetitions

The trained group completed 22.3 ± 7 jumps during the low intensity exercise and the recreationally trained subjects completed 18 ± 6.41 jumps. The recreationally trained group
completed 20 ± 4.3 jumps at the moderate intensity on average and the trained group completed 21 ± 3 jumps. It should be noted that these average numbers may not be an adequate depiction of the maximum possible volume of repetitions completed by the two groups at the two intensities. This is the case because, for many subjects, the numbers obtained were determined via subjective methods (if an individual was visibly fatigued they were asked to stop repetitions or if the subject completed jumps through the allotted thirty second acquisition time before maximum force output dropped below 90 percent etc.)

The average number of cumulative jumps (± SD) completed across quartile for the box jumps in the plyometrically trained and recreationally trained groups are provided in Table 1. The average number of cumulative jumps completed across quartile for the CMJs for the plyometrically trained and recreationally trained group are provided in Table 2.

<table>
<thead>
<tr>
<th>Table 1. Average Cumulative Box Jumps Repetitions Per Quartile</th>
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<tbody>
<tr>
<td>Qrt 1</td>
</tr>
<tr>
<td>-------</td>
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<tr>
<td>Plyo Trained</td>
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<tr>
<td>Rec Trained</td>
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<table>
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<tr>
<th>Table 2. Average Cumulative CMJ Repetitions Per Quartile</th>
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<tbody>
<tr>
<td>Qrt 1</td>
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<tr>
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<tr>
<td>Plyo Trained</td>
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<td>Rec Trained</td>
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**Eccentric Rate of Force Development**

In looking at the regression analysis for eccentric rate of force development for box jump (bxjE-RFD), it is evident that the plyometrically trained subjects display more negative regression slopes (indicating a decrease in E-RFD across repetitions) than the recreationally trained group (Figure 1 and Figure 2, respectively). There were eight negative regression
slopes observed within the trained subjects and seven negative regression slopes observed for the recreationally trained subjects during the box jumps. Although there is little difference between the two groups when looking at the number of negative and positive slopes seen in the groups, there appear to be sharper changes occurring in the recreationally trained group due to the visible differences observed through the subjective analysis.

Figure 1 – E-RFD Box Jump Regression Slopes for Plyometrically Trained Subjects
Figure 2 – E-RFD Box Jump Regression Slopes for Recreationally Trained Subjects

The regression analysis for the eccentric rate of force development in CMJs (vjE-RFD) for the recreationally trained subjects showed that there was a greater number of subjects that exhibited a decrease in E-RFD across subjects when compared to the trained subjects. The trained group displayed nine negative regression slopes (Figure 3) among the fifteen subjects where as the recreationally trained group displayed twelve (Figure 4). This reveals that, within our subject sample, the recreationally trained group saw a greater decrease in vjE-RFD when compared to the trained group during the low intensity plyometric exercise when visually analyzing the negative or positive slope of the regression line. This indicates that with our sample, more recreationally trained subjects tended to have a decrease in E-RFD across repetitions in the CMJ, as compared with the plyometrically trained subjects.
Figure 3 – E-RFD CMJ Regression Slopes for Plyometrically Trained Subjects

Figure 4 – E-RFD CMJ Regression Slopes for Recreationally Trained Subjects
The mean quartile analysis of the eccentric E-RFD between box jumps and CMJ revealed differences within the mean of each quartile between the two groups. The graphical depiction of bxjE-RFD across the four quartiles (Figure 9) revealed a slight increase in the mean E-RFD among the recreationally trained subjects and a fluctuating pattern in the plyometrically trained subjects between quartiles. The box jumps E-RFD mean values for quartiles one, two, three, and four for the recreationally trained and plyometrically trained groups are provided in N/s in Table 3.

![Figure 5 – Mean Box Jumps E-RFD (±SD) Across Quartiles](image)

| Table 3. Mean Box Jump E-RFD Plyometrically Trained and Recreationally Trained |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
|                            | Qrt 1          | Qrt 2          | Qrt 3          | Qrt 4          |
| Plyo Trained               | 43940.46±17921.19 | 47302.22±22349.98 | 39493.71±17312.68 | 47497.88±18830.68 |
| Rec Trained                | 43313.04±42213.04 | 43560.52±43560.52 | 43036.76±43036.76 | 45557.23±45557.23 |
The mean quartile analysis for the low intensity countermovement jumps (Figure 10) revealed that there was a decrease in the mean E-RFD across the four quartiles for the recreationally trained and a fluctuating decrease in mean E-RFD for the plyometrically trained which is depicted as N/s in Table 4.

![Figure 6 – Mean Countermovement Jumps E-RFD (±SD) Across Quartiles](image)

<table>
<thead>
<tr>
<th>Qrt 1</th>
<th>Qrt 2</th>
<th>Qrt 3</th>
<th>Qrt 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plyo Trained</td>
<td>45408.40±21249.21</td>
<td>44593.57±17949.77</td>
<td>38194.91±20214.43</td>
</tr>
<tr>
<td>Rec Trained</td>
<td>37002.70±15118.03</td>
<td>32682.60±14283.72</td>
<td>28666.91±9626.30</td>
</tr>
</tbody>
</table>

The statistical analysis of E-RFD across quartiles for both groups revealed that Mauchly’s test of sphericity was significant, so the Greenhouse-Giesser correction for degrees of freedom was used to evaluate all F-ratios. There was no significant interaction effect of exercise, quartile, and group \((F[2.29, 63.98] = 0.346, p = .737)\) on E-RFD. In
addition, there was no significant interaction between exercise and group \( (F[1, 28] = 4.097, p = .053) \). The interaction between quartile and group also displayed a non-significant effect \( (F[2.04, 57.20] = 1.195, p = .311) \) and there was also no significant effect of group on E-RFD \( (F[1, 28] = 1.35, p = .255) \). There was a significant interaction effect of exercise and quartile on E-RFD \( (F[2.29, 63.99] = 3.51, p = .03) \) (Figure 13). The simple effects analysis revealed no significant difference in E-RFD between exercises in quartile 1 \( (p = .517) \) and quartile 2 \( (p = .066) \), but there was a significant difference in E-RFD between exercise in quartiles 3 \( (p = .01) \) and quartiles 4 \( (p < .001) \) with E-RFD being significantly higher in quartile 3 than in quartile 4 in the CMJs and quartile 3 being significantly lower than in quartile 4 for the box jumps (Figure 13). In comparing the two groups, it is evident that when comparing the mean E-RFD for the countermovement jumps, that the recreationally trained subjects saw a greater decrease in E-RFD across the four quartiles as compared to the trained subjects Figure 13.

![Figure 7 – E-RFD Exercise by Quartile Interaction](image-url)
Contact Time

The analysis of regression slopes for CT among the two groups for box jumps revealed that the recreationally trained subjects (Figure 6) had seven positive slopes, which indicates an increase in contact time, as opposed to the six positive slopes displayed by the trained group (Figure 5). Although the difference is not large between the two groups there was still a difference seen when comparing the slopes across repetitions. The analysis of CT for the CMJs revealed that the trained subjects (Figure 7) had six individuals with an increased contact time, as opposed to the ten such individuals in the recreationally trained group (Figure 8). This finding indicates that, within our subject sample, recreationally trained subjects exhibited more positive regression slopes (increased CT) compared to the trained group across repetitions for each intensity.
Figure 9 – Contact Time Regression Slopes in Box Jumps for Recreationally Trained Subjects

Figure 10 – Contact Time Regression Slopes CMJs for Plyometrically Trained Subjects
When comparing the mean CT for box jumps and CMJs across the four quartiles it was evident that there were differences observed between the two groups. Mean box jump CT for the recreationally trained group saw an increase in mean CT over the four quartiles and is depicted graphically in Figure 11. Mean box jump CT for the trained subjects saw a decrease in mean CT over the four quartiles and is also depicted in Figure 11. The averages and standard deviation are provided in Table 5 in seconds for the box jump CT for the plyometrically and recreationally trained groups. When comparing the two groups it is evident that during the box jump exercise the recreationally trained group saw an increase in mean CT across the four quartiles and the trained group saw a decrease in mean contact time over the four quartiles.

Figure 11 – Contact Time Regression Slopes in CMJs for Recreationally Trained Subjects
When analyzing the mean CT time for the countermovement jumps between the trained and recreationally trained group it was evident that there was an increase in mean CT time across the four quartiles for both groups (Figure 12). The recreationally trained subject displayed an increase in mean CT across the four quartiles, the means and standard deviations are depicted in Table 6 in seconds. The trained subjects displayed similar mean CT across the first three quartiles but an overall increase in mean CT for the countermovement jumps over the four quartiles, the averages and standard are depicted in Table 6 in seconds. When comparing the two groups the recreationally trained group had a higher mean CT across quartiles when compared to the trained group, although the trained
group had an increase in CT the recreationally trained subject revealed a greater increase in mean CT across the quartiles.

![Graph showing mean countermovement jump contact time across quartiles]

**Figure 13 – Mean Countermovement Jump CT (±SD) Across Quartiles**

<table>
<thead>
<tr>
<th>Table 6. Mean CMJ CT Quartiles</th>
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<tbody>
<tr>
<td>Qrt1</td>
</tr>
<tr>
<td>-----------------------------</td>
</tr>
<tr>
<td>Plyometrically Trained</td>
</tr>
<tr>
<td>Recreationally Trained</td>
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</tbody>
</table>

With regards to the statistical analysis of CT, Mauchly’s test of sphericity was significant, so the Greenhouse-Geisser correction for degrees of freedom was used to evaluate all F-ratios. There was no significant interaction effect of exercise, quartile, and group ($F[1.89, 53.18] = .691, p = .498$) along with no significant interaction between exercise and quartile ($F[1.89, 53.18] = 2.52, p = .0930$) on CT. There was a significant quartile by group interaction observed for CT ($F[1.80, 50.53] = 5.48, p = .009$)(Figure 14). The simple effects analysis revealed no significant differences in contact times between
quartiles in group 1 (plyometrically trained) \( (p = .117) \) and a significant effect of quartiles on contact times in group 2 (recreationally trained) \( (p = .002) \). There was also a significant exercise by group interaction observed for CT \( (F[1, 28] = 4.32, p = .047) \)(Figure 15). Simple effects analysis revealed a significant difference in contact times between exercises in both group 1 (plyometrically trained) \( (p = 0.021) \) and group 2 (recreationally trained) \( (p < .001) \).

The CMJs had the highest CT for both the plyometrically trained group and the recreationally trained group as compared to CT for the box jumps.

Figure 14 – CT Quartile by Group Interaction
Figure 15 – CT Exercise by Quartile Interaction

Discussion

We set out to determine if exercise intensity and training status had a significant effect on the volume of repetitions completed during low (CMJ) and moderate (box jump) intensity plyometric exercises. We hypothesized that there would be a significant difference in the rate of decline in performance of E-RFD for the low and moderate intensity plyometric exercises with the rate of decline being higher in the moderate intensity plyometric exercise as oppose to the low intensity exercise. We also hypothesized that there would be an increase in CT seen for the low and moderate intensity plyometric exercise when trained and recreationally trained subjects performed low (CMJ) and moderate (box jumps) intensity plyometric exercises, with a greater increase in CT seen in the recreationally trained sample and during the moderate intensity exercise. The primary finding of the present study is that
there is a great deal of variability in both E-RFD and CT across continuous repetitions in both exercises among the plyometrically trained and recreationally trained subjects.

The E-RFD values obtained within this investigation were similar to the E-RFD values observed in Ebben and colleagues’ (2010) work. With regard to E-RFD, it was evident that our first hypothesis was not fully supported. The E-RFD in the moderate intensity box jumps did not see a sharp rate of decline over the four quartiles for trained and recreationally trained subjects as originally hypothesized (Figure 10 and 13). There was actually an increase in E-RFD from quartile one to quartile four in the two groups based on a subjective visual analysis of means in each of the four quartiles. The E-RFD for the low intensity CMJs over the four quartiles for both trained and recreationally trained subjects supported our hypothesis in that there was an evident rate of decline in E-RFD over the four quartiles, especially between quartiles three and four (Figure 9 and 13). When looking at E-RFD there was a significant interaction between quartile and exercise with the simple effects revealing a significant difference in E-RFD between exercises in quartiles three and four. This shows that across repetitions for low and moderate intensity plyometric exercises, the subject sample displayed a decrease in E-RFD across quartiles for the CMJs but did not display a sharp decrease in E-RFD for the moderate intensity box jump (Figure 13). With this being the case our original hypothesis was not fully supported through the present study. It can be noted that the E-RFD observed in the moderate intensity box jumps increased from quartile one to quartile four (Figure 9) regardless of training status. The reason for these differences in E-RFD between the two exercises may have been due to the fact that the trained subjects involved with the present study might not use moderate intensity continuous box jumps as a regular plyometric modality during their yearlong macrocycles. The increase
in E-RFD observed during the moderate intensity box jump for both sample groups may be attributed to the ability of the individuals to adequately generate force across the repetitions and consequently decrease the time it takes a muscle to develop force (Enoka, 2002). This could be due to the possible increase in activity of the muscular proteins desmin and titin (Powers & Howley, 2006). These proteins are associated with improved stiffness and ability to store elastic energy within the sacromere (Powers & Howley, 2006). This increase in E-RFD can also be associated with an increased stiffness within the musculoskeletal system which can allow for better recoil ability and can help the individuals decrease CT during the amortization phase of the movement (Radcliffe & Farentinos, 1990). In both subject samples seeing an increase in E-RFD across quartiles it is possible that the trained and recreationally trained subjects land with an increased stiffness over the course of the repetitions which can be associated with an increase in E-RFD. It is also possible that the subjects utilized the pre-activation of lower extremity musculature prior to landing in order to combat the fatigue that is possibly being experienced across quartiles in an attempt to maintain power output.

The present study did not use motion capture to analyze joint kinematics, so this possible increase in stiffness (musculotendinous or otherwise) is simply speculation as to why the E-RFD did not decrease over the course of the repetitions in the moderate intensity exercise. It should be noted that the mechanisms underlying the maintenance or increase in stiffness may be different in the two groups. In trained subjects, a maintenance or increase in joint stiffness may be associated with their improved ability to utilize 1a afferent pathways to increase firing rate during the eccentric landing phase (Aura & Komi, 1986). The recreationally trained group’s observed increase in E-RFD can possibly be due to the pre-activation of the musculoskeletal system as a protective mechanism against injury over the
course of the repetitions (Chappell, Creighton, Giuliani, Yu, & Garret, 2007). During data acquisition it was evident that the recreationally trained group was visibly more ‘fatigued’ at the end of the moderate intensity exercise as compared to the trained subjects. The present study did not incorporate electromyography (EMG) during data acquisition thus leading to speculation of the pre-activation in the musculature before landing as a possible reason why there was not a decrease in E-RFD see across quartiles for both groups. The increase in E-RFD during the moderate intensity box jump within the present study is interesting, due to the fact that as an individual becomes fatigued over numerous repetitions, it may become more difficult for the individual to develop force in a rapid manner (Gollhofer, Komi, Fujitsuka, & Miyashita, 1987) which was not seen in the present study. Although both groups saw an increase in E-RFD during the moderate intensity box jumps across the four quartiles (which was an unexpected result) it was also observed that there was a decrease in E-RFD during the low intensity exercise which was something we expected to observe thus slightly supporting our hypothesis.

We hypothesized that there would be an increase in CT across repetitions for both the low and moderate intensity plyometric exercise for both plyometrically and recreationally trained subjects and we also suspected that a greater increase in CT would be observed for the recreationally trained group at both intensities. According to the results of the present study this was not observed and in turn our hypothesis was not completely supported. There was a significant interaction between quartile and group, with the simple effects revealing a significant effect of quartile on contact time in recreationally trained subjects. This result indicates that the CT increased across quartiles, but only for recreationally trained subjects (Figure 14). This result partially supports our hypothesis that CT would increase over the
course of the repetitions completed during data acquisition. There was also a significant interaction of exercise by group, with simple effects revealing that CT was significantly higher in CMJs in both groups (Figure 15). For the box jump exercise, the plyometrically trained subjects maintained and eventually decreased CT over the four quartiles (Figure 11) and the recreationally trained group saw a gradual increase in CT over the four quartiles (Figure 11) based on a subjective analysis. For the low intensity CMJs it was observed that the recreationally trained subjects exhibited an increase in CT over the four quartiles while the trained subjects maintained contact time for the low intensity exercise, which leads to the possible notion that among the trained subjects there was a continued maintenance of CT during the CMJs and a slight increase in CT for the moderate intensity exercise (Figure 11 and 12). Although our results support our hypothesis that CT would be greater in CMJs than in box jumps, our results do not support our hypothesis that there would be an increase in CT observed for both the moderate and low intensity exercise in both groups across quartiles.

Although the recreationally trained group saw an increase in CT for the CMJs and box jumps, this pattern was not entirely evident in the plyometrically trained group. This finding may be related to the training status of the plyometrically trained subjects. Due to the fact that they participate in plyometric activities during their year-long macrocycle, they may be equipped with the ability to maintain CT during continuous repetitions at these two intensities. Arampatzis (2001) has reported that as ground CT decreases or is maintained (as seen in the plyometrically trained subjects), leg and ankle stiffness increased along with decreased hip, knee, and ankle flexion. Although we did not use motion capture to analyze changes in joint kinematics across repetitions, it may be that the trained subjects exhibited these lower extremity kinematics as the repetitions progressed. Stiffness within the
musculoskeletal system allows for better recoil ability and can help the individual’s decrease CT during the amortization phase of the movement. With the increase in CT observed for the recreationally trained subjects at both intensities, it was evident that this increased stiffness may not have been present to the extent seen in the trained subjects. Our original hypothesis was not fully supported due to the fact that both groups did not observe a substantial increase in CT over the course of their repetitions at the two intensities, although an increase in CT was observed in the recreationally trained group at both intensities.

In the present study we hypothesized that trained subjects would complete a greater number of repetitions than the recreationally trained subjects before propulsive force output decreased below 90 percent of max power output during low and moderate intensity plyometric exercises. We also hypothesized that both groups would complete more repetitions at the low intensity exercise as opposed to the moderate intensity exercise. Although the average jumps between the two groups reveal some differences in the volume of repetitions completed at each intensity (plyometrically trained: box jumps, 21 ± 3 and CMJs, 22.3 ± 7; recreationally trained: box jump, 20 ± 2.3 and CMJs, 18.46 ± 6.41[Figure. 16]) these figures do not directly address our hypothesis. During data analysis it was revealed that there was a large amount of variance between each subject with regards to number of repetitions completed at each intensity. In some cases individuals were able to complete jumps above 90 percent of their maximum force output for the entire data acquisition period. The data collection in this study can, therefore, provide us with only a partial answer to our research question. Within the quartile analysis for the low intensity and moderate intensity exercises, it was evident that after the third quartile there were some changes observed for E-RFD and CT, but especially CT. During the CMJs after quartile
three the plyometrically trained subjects and recreationally trained subjects saw an increase in CT along with a decrease in E-RFD. Based on the average number of jumps within the third quartile between the two groups it can be suggested that 16.35 ± 5 and 13.85 ± 4.81 (plyometrically trained and recreationally trained, respectively) were an adequate number of repetitions to halt plyometric activity during the low intensity exercise due to the decrease in E-RFD and increase in CT observed. With regards to the moderate intensity exercise, the plyometrically trained subjects completed 15.6 ± 2.4 jumps and the recreationally trained subject’s completed 15.7 ± 2.8 jumps within the third quartile before seeing an increase in CT and a variable change in E-RFD. This data is also depicted in Table’s 1 and 2.

Figure 16 – Average Number of Jumps completed for each group at both intensities.

To our knowledge, E-RFD and CT have not previously been measured across continuous repetitions during low and moderate intensity plyometric exercises. The results of the present study suggest that there is a great deal of variability in E-RFD and CT across
repetitions of both low and moderate intensity plyometric exercises in plyometrically and recreationally trained subjects. This variability should be taken into account when analyzing volume of repetitions at different intensities. The lack of research surrounding the evaluation of E-RFD and CT across repetitions gives little data to which the results of the present study can be compared. Although a study by Gollhofer, Komi, Fujitsuka, and Miyashita (1987) evaluated the effect of continuous SSC movement on mechanical performance after fatiguing SSC activity, it is difficult to use the results presented by these authors due to the lack of specificity between studies. Gollhofer and colleagues found that training programs heavily based on SSC movements can have a detrimental effect on mechanical performance. Gollhofer and colleagues used a fatigue protocol to reveal a decrease in rate of force development, decrease in force production and increased CT when individuals took part in plyometric exercise following a fatigue protocol. Due to the thirty second data acquisition time during data collection in the present investigation, it was thought that subjects would exhibit results similar to those of Gollhofer and colleagues, but that was not the case. The results from Gollhofer and colleagues’ work do not support the results found through the present investigation with regards to rate of force development and CT. This may be due to the lack of intensity involved with the plyometric exercises used within the present investigation and the time the subjects spent actually participating in the plyometric exercises (time under tension). Although some of the subjects displayed some visible characteristics associated with fatigue the time at which the subjects participated in the low and moderate intensity exercise may not have been long enough to induce radical changes in E-RFD and CT, more specifically E-RFD, due to the single set protocol used. For instance, if the protocol called for two to three sets of thirty second data acquisition (instead of one) it can
be suggested that the results obtained within the present investigation may be different from the results observed within the present study due to the change in protocol (from single bouts to multiple bouts).

The two plyometric exercises used in the present study, CMJs and Box Jumps, were chosen in order to represent low and moderate intensity exercises, respectively, according to the guidelines set forth by the National Strength and Conditioning Association (NSCA) (Potach & Chu, 2000). Although the NSCA designates these exercises as low and moderate intensity, there is some discrepancy in the literature as to the classification of different plyometric exercises and their associated intensities. This difference has led to a body of research dedicated to looking at the intensities of different plyometric exercises based on EMG, E-RFD, peak GRF, ground reaction forces relative to body weight (GRF/BW), knee joint reaction forces (K-JRF), and knee joint reaction forces relative to body weight (K-JRF/BW) and also time to stabilization (Ebben, Simenz, & Jensen 2008; Jensen & Ebben; 2007). Although this intensity research exists, there is still a shortage of research that pertains to the volume of repetitions for plyometric exercise that are needed throughout a mesocycle or microcycle in order to induce the most beneficial training adaptations. It was one of the goals of the present study to determine a volume of repetitions at low and moderate intensity plyometric exercises for a trained and recreationally trained subject sample. This was done in an attempt to provide practitioners with more adequate information pertaining to volume of repetitions completed before E-RFD decrease and CT increased at each intensity.

The present investigation has several limitations. One of the limitations of the present study was the specificity of exercise used when testing maximal vertical jump (CMJs) and
maximal box jumps on day one. The way the subjects were tested to gain information with regards to maximal propulsive force output at the two intensities on day one was different from the way the subjects were tested during data acquisition on day two. Day one of testing consisted of six maximal effort jumps (three CMJs and three box jumps) which were all single effort that incorporated a rest period of two minutes after each jump and a five minute rest between the sets of three jumps. Day two consisted of continuous maximal effort CMJs and box jumps for a maximum of 30 seconds each. The task of jumping one time for maximal height (CMJ) or minimal ground contact time (box jump) may be fundamentally different from the task of jumping continuously. This task difference possibly led to an inaccurate crossover of data between testing on day one (max vertical jump and max box jump) and day two (continuous CMJs and continuous box jumps). Another limitation of the present study is the variability between jumps at each intensity. It is naive to think that trained or recreationally trained subject can perform ‘perfect’ maximal effort jumps during every repetition at each intensity over a thirty second data acquisition. This variability across jumps could have a large influence on the variability within our results and thus lead to a more accurate depiction of what actually transpires over the course of continuous effort plyometric exercises with regards to E-RFD and CT.

The training status of our trained subject sample could have been another limitation within the present study due to the similarities seen when compared to the recreationally trained group with regards to number of jumps, E-RFD, and CT. We targeted Division II student athletes from the Western Washington University Athletic Department (Soccer, Track and Field, and Basketball). Each individual was required to participate in plyometric activity regularly during their yearlong macrocycle in order to be included in the trained
subject sample. Although each subject within the trained group exhibited these characteristics it is hard to say if each of these subjects participated in an adequately structured plyometric training program.

Another limitation that could have played a factor in the results of the present study was the psychological aspect of the testing. Subjects were informed that data acquisition was set for thirty seconds and once their propulsive force output decreased below 90 percent of their average maximum output from day one (for each intensity) they were asked to stop. Knowing the total acquisition time could have affected the subjects effort level across the repetitions completed. Along the same lines, the use of 90 percent of maximum output from day one to predict a stopping point on the second day of testing limited the study further. The fact that some of subjects stayed above this 90 percent threshold for the entire thirty second acquisition, puts the use of this decrease below 90 percent of maximal power output as a stopping point into question. Although through the literature a decrease below 90 percent of maximum effort is said to be an adequate stopping point, the use of this 90 percent seemed to have missed the mark within the present study but this could also have to do with the lack of specificity of testing on day one as compared to day two.

Further investigation using E-RFD and CT to evaluate the changes over the course of continuous effort plyometric exercise is extremely important to the body of research surrounding plyometric exercise. Due to the large amount of variability seen within E-RFD and CT among the two groups it is imperative that further research target the same performance measures in order to verify this variability within E-RFD and CT between subject samples.
Although the present study was limited in several instances there still can be some beneficial applications of the present findings. With regards to training recommendations from the present study it can be suggested that practitioners can use the numbers provided for the low and moderate intensity plyometric exercises as a possible halting point for single bout plyometric activity due to the change in E-RFD and CT observed for the two groups. Practitioners can use these numbers as a starting point. Practitioners should subjectively analyze the athletes during the course of the repetitions and if the subjects display fatigue characteristics that are visible during the plyometric activity practitioners should adjust the volume accordingly (allowing for quality repetitions). Due to the fact that most practitioners will not have a force platform available to analyze the decrease in propulsive force output it seems that a subjective analysis of individuals during the course of the plyometric activity is the most efficient way to analyze possible decreases in performance.
Chapter V  
Summary, Conclusions, and Recommendations

Summary

We set out to examine the effect of training status and exercise intensity on the volume of repetitions completed before propulsive force output decreases below 90 percent maximum force output. We also set out to examine the effect of training status and exercise intensity on the change in eccentric rate of force development (E-RFD) and CT across exercise repetitions (depicted as the slope of the regression line connecting the E-RFD and CT for each repetition completed and a quartile analysis for E-RFD and CT).

We hypothesized that plyometrically trained subjects would complete a greater number of repetitions than the recreationally trained subjects before force decreased during low and moderate intensity plyometric exercises. We also hypothesized that both groups would complete a greater number of repetitions at the low intensity exercise than at the moderate intensity exercise.

Finally, we hypothesized that there would be a significant difference in the rate of decline in performance of eccentric rate of force development (E-RFD) and increase in contact time (CT) for the low and moderate intensity plyometric exercise when plyometrically trained and recreationally trained subjects performed low (CMJ) and moderate (box jumps) intensity plyometric exercises with the moderate intensity exercise inducing a greater decrease in E-RFD and a greater increase in CT in both groups as compared to the low intensity exercise. It was also hypothesized that the recreationally trained group would experience a greater decrease in E-RFD and a greater increase in CT at both intensities as compared to the plyometrically trained subjects.
Studies have examined the benefits of plyometric training and the resulting enhancement of performance, but there has been little research done on the manipulation of corresponding program design variables. The present study was undertaken to provide practitioners with more information on plyometric training volume and how they might manipulate repetition volume to create an environment that maximizes physiological and neuromuscular adaptation to stretch-shortening cycle exercises. By examining different training intensities and repetitions for both trained and untrained participants, more specific training protocols might result. The eventual goal of the present study was to give strength and conditioning practitioners a better understanding of training volume and in turn allow for a better utilization of this training variable in plyometric training programs.

Within the present subject sample it was revealed through this investigation that there is a great deal of variability within E-RFD and CT across repetitions during low and moderate intensity plyometric exercises. Our hypothesis that there would be a significant decline in E-RFD between both groups at the low and moderate intensity (recreationally trained having a greater decrease at both intensities) was not fully supported due to the lack of decline in E-RFD during the moderate intensity exercise in both groups. Although there was a decrease in E-RFD observed in the CMJs for both plyometrically trained and recreationally trained subjects, this does not fully support our original hypothesis. With regards to CT, we hypothesized that there would be a significant increase in CT for both groups at the low and moderate intensity exercise with the recreationally trained subjects seeing a greater increase in CT over the course of the repetitions. This hypothesis was again partially supported due to the decrease in CT observed for the plyometrically trained subjects at the low and moderate intensity exercise. It was also observed that the trained subjects saw
a decrease in CT for both the low and moderate intensity exercise leading to the partial support of our hypothesis. We also hypothesized that there would be a significant difference in the volume of repetitions completed between the plyometrically trained subjects and the recreationally trained subject with the plyometrically trained subjects completing a greater volume of repetitions at the low and moderate intensity exercise when compared to the recreationally trained subjects. It was also hypothesized that both groups would complete a greater volume of repetitions at the low intensity exercise as oppose to the moderate intensity exercise. Due to the large variability in the number of jumps done between each subject and associated limitations we were unable to provide an accurate depiction of the number of jumps completed at each intensity for both the plyometrically trained group and the recreationally trained group, thus, preventing us from adequately answer our research question that pertains to the difference in volume of repetitions completed between the two groups at each intensity.

Conclusions

It can be concluded that the literature surrounding the changes in E-RFD and CT during low and moderate intensity plyometric exercises needs to be further supported. Within our subject sample, the major finding in this investigation was that there is a large amount of variability in E-RFD and CT across repetitions between the two intensities with plyometrically trained and recreationally trained subjects. With regards to the practical application of these findings it can be noted that during a single set of low and moderate intensity plyometric exercises, subjects experienced decreased E-RFD and increased CT across repetitions, especially with the low intensity exercise. There was a decrease in E-RFD and a marked increase in CT observed with both groups during the CMJs between
quartile three and four. The average number of jumps for the CMJs through quartile three for the plyometrically trained and recreationally trained group was 16.35 ± 5 and 13.84 ± 4.81, respectively. With regards to the moderate intensity box jumps the plyometrically trained group completed 15.6 ± 2.4 jumps, while the recreationally trained group completed 15.7 ± 2.8 jumps through the third quartile. These averages may represent an adequate number of jumps to complete during low intensity and moderate intensity plyometric exercises before E-RFD decreases and CT increases; however, further investigation is warranted to provide more definitive numbers. One of the main reasons for this recommendation is that the increase in contact time observed after the third quartile is associated with an increased amortization phase during the plyometric movement, which is counterproductive to repetitive plyometric exercise. Along with the decrease in CT observed after the third quartile it can noted that there was a decrease in E-RFD after the third quartile in the CMJs which can also be associated with decrease force production which is counterproductive to repetitive plyometric exercise. Although specific to our subject sample, practitioners can utilize these numbers as a possible point at which to cap single bout plyometric activity at low (CMJs) and moderate intensity (box jumps) in order to allow for the optimal usage of these plyometric exercises.

Specific training recommendations that can be taken from the present investigation are that for single effort plyometric exercise at low and moderate intensity practitioners can use the volume of repetitions completed during the third quartile as a starting point for volume of repetitions at both intensities. Although the present investigation allows for some insight into the volume of repetitions completed before a decline in performance for E-RFD and CT are seen, it should be reiterated that there is still a lack of literature that looks directly
at the manipulation of training volume during plyometric training programs. With that being said, it can be suggested that practitioners can use the volume of repetitions provided through the available research (the present investigation included) that uses plyometric training protocols to improve athletic performance in order more adequately apply volume of repetitions to training protocols being implemented on various subject samples. In using the present investigation and the research protocols provided, practitioners can have a more research based application of the volume utilized across these investigations for plyometric exercises. It is imperative that practitioners match the subject samples used within these interventions with the subject sample they are applying the plyometric training protocol to in order to possibly provide the greatest transfer between the subject samples. The present investigation gives practitioners a starting point for which a volume of repetitions can be applied to low and moderate intensity plyometric exercises among recreationally and plyometrically trained subjects before declines in E-RFD and increase in CT are seen.

**Recommendations**

The recommendations that follow are suggestion for future investigations pertaining to the evaluation of volume of repetitions for plyometric exercise. First and foremost, there should be an increased level of research that concentrates on the manipulation of training variables for plyometric exercise. This will allow practitioners an improved literature supported base of information that pertains to the manipulation of plyometric training variables. Another recommendation would be to implement more strict inclusion criteria, with regards to plyometric training, in order to prevent any questions that may pertain to the limitations surround a subject training status. Another recommendation would be to conduct the present study again with the trained subject sample all being from the same team or sport.
This would allow for some uniformity of exercise prescription across the year long macrocycle among the trained subject sample. It is also recommend that studies incorporate low, moderate, and high intensity plyometric exercises in order to give a range of information across the different intensities. It is also recommended that the present study be repeated with the same subject sample but with a 5 repetitions average taken on day one for maximum force output in both intensities over three trials instead of the three maximal effort trials taken at each intensity on day one of testing. This way the testing will be more specific to the actual task the subject will be completing during data acquisition, thus leading to the possibility of more accurate results. Along with the changes to day one measures, three dimensional motion capture and EMG should be incorporated in order to evaluate the changes in lower extremity kinematics and changes in activation patterns over the duration of the data acquisition. The addition of three dimensional motion capture and EMG will allow for the evaluation of possible changes in joint angles and lower extremity muscle activation during the low and moderate intensity exercise, and allow for an analysis of stiffness and pre-activation across repetitions for each group and intensity. With the incorporation of the three dimensional motion capture it would add the ability to complete and inverse dynamics analysis in order to estimate the reaction forces at the joints during the completion of these plyometric exercises.
References


Appendix A.
Appendix A. Informed Consent

Western Washington University
Consent to Take Part In a Research Study

Project: Effect of Training Status and Exercise Intensity on Plyometric Training Volume

You are invited to participate in a research study conducted by Kevin Cronin, CSCS, from the department of Physical Education, Health, and Recreation at Western Washington University. The purpose of this investigation is to assess how training experience with plyometric exercise and the intensity of the exercise determines the appropriate number of repetitions to perform within a set. You were selected as a possible participant in this study because you have no history of low back or lower extremity pathology.

If you decide to participate, you understand that the following things will be done to you. You will report to the Western Washington University Biomechanics Laboratory on two separate occasions, separated by 96 hrs but no more than 1 week. On day 1, you will first perform a 10 minute dynamic warm-up for the muscles and joints of your upper and lower body. You will then be asked to perform a jump assessment to allow the practitioner to determine if you are capable of participating in the present study. You will then be asked to perform multiple sets of the leg press exercise in order to determine the maximum weight you can lift in this exercise. After a sufficient rest, you will then be asked to perform three repetitions of a maximum vertical jump and three repetitions of a jump to a box with maximum effort. The total estimated time for participation on day 1 will be 75 minutes.

On day 2, you will again perform a 10-minute dynamic warm-up. You will then be asked to perform one set of multiple repetitions of the vertical jump and one set of the jump to a box, exerting maximum effort on each repetition. The total estimated time for participation on day 2 will be 75 minutes.

There is no direct benefit to you by participating in this study. However, you understand that information gained in this study may help to provide more definitive guidelines for performing plyometric (jumping) exercises.

Participation in any research study carries with it possible risks. Because multiple repetitions of explosive exercises will be performed, there is a risk of muscle fatigue. In addition, due to the large forces and possibility of falls associated with plyometric activity, participation in this study also carries with it the risk of injury. To minimize the risk of muscular fatigue, sufficient time for full recovery will be allotted following each set of exercise on both days of participation. Injury risks will be minimized by providing an appropriate exercise environment, including an area clear of debris, as well as a rubberized surface on which to perform plyometric exercises. You may discontinue participation at any time during testing.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential. Subject identities will be kept confidential by coding the data with subject numbers, rather than names.
Your participation is voluntary. Your decision whether or not to participate will not affect your relationship with Western Washington University. If you decide to participate, you are free to withdraw your consent and discontinue participation at any time without penalty.

If you have any questions regarding the research study, please feel free to contact Kevin Cronin, CSCS (cronink4@students.wwu.edu), Department of Physical Education, Health, and Recreation, Western Washington University, Bellingham, WA, 98225. If you have questions regarding your rights as a research subject, please contact the WWU Human Protections Administrator (HPA) at Western Washington University, (360) 650-3220. You have been offered a copy of this form to keep.

Your signature indicates that you are at least 18 years of age, have read and understand the information provided above, that you willingly agree to participate, that you may withdraw your consent at any time and discontinue participation without penalty, that you have received a copy of this form, and that you are not waiving any legal claims, rights or remedies.

Print Name________________________________________________________

Signature__________________________________________________________

Date_________________________
Appendix B.
Appendix B. Day 1 - Medical History Jump Assessment

Western Washington University

Effect of intensity and training status on volume of repetitions

DAY1

Name: ___________________________ Training Status: ___________________________
Date: ______________ Sport: ___________________________
Subject #: ______________

Medical History

Any History of ankle, knee, or back pathologies? YES NO

If YES, when? Within the last three months? YES NO

Any medical or orthopedic problems that compromise your participation in the present study?

YES NO

Any Lower Extremity reconstructive surgery? YES NO

If YES, when? Within the last two years? YES NO

Any Unresolved musculoskeletal disorders? YES NO

Do you use or have you used Anabolic Steroids Growth Hormone, or related performance enhancing drugs?

YES NO

CMJ Jump Assessment:

Excessive Valgus _______ Poor Balance During Jumps _______
Excessive Varus _______ Knees Excessively over Toes _______

Inclusion? YES NO
Appendix C.
Appendix C. Day 1 - 1RM Record Sheet and CMJ and Box Jump Record Sheet

Western Washington University

Effect of intensity and training status on volume of repetitions

DAY1

Name: ____________________________  Training Status: ____________________________

Date: ____________________________  Sport: ____________________________

Subject #: ____________________________

--- 1 Repetition Max Leg Press: ---

Body Weight (in Lbs) ______________  Projected 1RM @ 1.5 times BW ______________

Set #1: __________  (5-10 rep warm up)  Inclusion?  YES  NO

Set #2: __________  (add 20% - 3-5 Reps)

Set #3: __________  (add 10-20% - Near max 1-3 Reps)

Set #4: __________  (add 10-20% - MAX LOAD)

Additional Sets: __________  1 RM Maximum Achieved: __________

--- Counter Movement Vertical Jump Testing: ---

3 Attempts (GRFs): __________  __________  __________

--- Moderate Intensity Box Jump Testing: ---

3 Attempts (GRFs): __________  __________  __________

Vertical Jump Average: __________  Box Jump Average: __________
Appendix D.
Appendix D. Day 2 - Record Sheet CMJs and Box Jumps

Western Washington University

Effect of intensity and training status on volume of repetitions
DAY2

Name: ___________________________ Training Status: ___________________________
Date: ___________________________ Sport: ___________________________
Subject #: _______________________

Repetitions Completed at Low and Moderate Intensity (Stopped once 90% was not met two consecutive rep

**Counter Movement Jumps**

Average GRFs for 3 Trials _____________ 90% of average GRFs _____________

Number of Repetitions Completed _______ Number of Repetitions Completed _______
Above 90%

**Moderate Intensity Box Jumps**

Average GRFs for 3 Trials _____________ 90% of average GRFs _____________

Number of Repetitions Completed _______ Number of Repetitions Completed _______
Above 90%
Appendix E.
Appendix E. Raw data. E-RFD and CT across Quartiles for Plyometrically Trained and Recreationally Trained.

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