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Plyometric training and its effects on the neuromuscular system

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PLYOMETRIC TRAINING AND ITS EFFECTS ON THE NEUROMUSCULAR SYSTEM

by

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Abstract

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Plyometric training is commonly employed by athletic trainers, personal trainers, and strength and conditioning coaches, especially for those athletes who require quickness, agility, and high vertical jump performance. It is well documented in its ability to increase these aspects of performance.[12, 14, 16, 20] There are many proposed mechanisms in place which attempt to explain why it is so effective, however, many of the proposed mechanisms are still theoretical. The purpose of this study is to examine some of those proposed mechanisms that drive the success of plyometric training. This project investigates the neurological effects of plyometric training by examining the stretch reflex response and the rates of force development and relaxation in recreationally active college aged subjects. The mechanisms of interest in this study include the stretch reflex response and the rate of force development and relaxation. With an enhanced understanding of the neurological adaptations caused by plyometric training, more efficient and effective protocols may be adopted into common practice.

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Chapter 1

Introduction

Plyometric training has been well documented in its ability to increase the power output of individuals evident by enhancing vertical jump height, horizontal jump distance, as well as sprint speed.[12, 14, 16, 20] It is often employed for sports such as basketball and volleyball where these skills are essential for elevated performance.[20] Plyometric exercises are also commonly used in the later stages of rehabilitation because they more closely resemble the sport specific demands and stresses paced on the body.[9] Most sport specific actions occur at higher velocities and over multiple joints at the same time.

A plyometric exercise utilizes the stretch shortening cycle of a muscle to increase the maximal force output of that muscle.[2, 8, 12, 14, 16, 20, 44] This consists of a rapid eccentric contraction immediately followed by a strong and fast concentric contraction.[2, 8, 12, 14, 16, 20, 44] Though there are many mechanisms to which plyometric training is theorized to increase performance, many of them are still theoretical.[8] Some of the proposed mechanisms responsible for an increase in power following a plyometric training program include a decreased pennation angle in the muscle,[44] converting elastic potential energy to kinetic energy during the concentric contraction, and enhancing the stretch reflex, thereby adding to the intensity of the concentric contraction.[2, 8, 9, 12]

The stretch reflex has also been referred to as the tendon tap reflex because it can be elicited by a reflex hammer striking the mid-substance of a tendon.[3, 41, 43] When the hammer strikes the tendon it elicits a rapid stretch of the tendon, lengthening its corresponding muscle.[3, 41, 43] The change in length of the muscle activates the muscle spindles, causing a reflexive contraction within the muscle.[26, 33] This reflex has been used to assess the integrity of the central and peripheral nervous system[20] as well as the neuromuscular system.[3] The large variability among subjects has led previous researchers to develop methods of quantifying the stretch reflex, including motion capture analysis, force transducers, accelerometers, and surface electromyography.[3, 41]

Electromyography (EMG) is a technique used to record and analyze myoelectric signals caused by the variations in the degree of activation of muscle fiber membranes.[22, 45] An EMG is capable of quantifying the magnitude of the stretch reflex caused by a tendon tap by measuring the myoelectric response caused by the activation of the muscle spindles.[3, 25, 26, 41, 43] The EMG is based on the action potentials in the muscle fibers resulting from the depolarization and repolarization processes during a muscular contraction.[45] The EMG activity detected represents the sum of the motor unit action potentials which are primarily determined by the level of motor unit recruitment.[22]

Rate of force development consists of attempting to achieve the maximal amount of force as quickly as possible and is commonly used as an indicator of explosive strength or power.[35] The rate of force relaxation is how quickly a muscle can relax after applying that force.[35] Explosive strength, or rate of force development, have been suggested to be a superior predictor of athletic performance when compared to a one repetition maximum test.[35] The rate of force development and relaxation are believed to reflect different properties of the neuromuscular system because of the lack of a correlation between them.[14] A high rate of force relaxation does not always follow a high rate of force development because they are believed to represent different aspect of the neuromuscular system.[14] Although the rate of muscle relaxation is considered to be as functionally important as its counterpart, it has received much less attention in the literature.[14]

The purpose of the current study is to examine the effects of a six-week lower extremity plyometric training program on the neuromuscular system. This study will compare the following variables pre- and post-plyometric training: the stretch reflex response as measured by EMG, rate of force development and relaxation scaling factors, maximal voluntary isometric contraction, and vertical jump height performance. With a better understanding of the effects plyometric training programs have on the neuromuscular system, better and more efficient programs may be developed to further increase explosive performance.

Plyometric Training

Plyometric training exercises are used to aid in the development of power[8, 12, 14] and rate of force development[35, 44] leading to improvements in jumping and sprinting ability as well as agility.[20] Common examples of lower extremity plyometric exercises include box jumps, squat jumps, wall touches, jumping lunges, tuck jumps, depth jumps, drop jumps, single and double leg bounding, and lateral cone hops.[12, 20] Quality is much more important than quantity in terms of plyometric training, because repeated stretch shortening cycle exercises have been shown to cause decreased muscular performance and fatigue.[2] In order for plyometric training to be effective, each exercise must be performed with maximal intensity during each repetition.[12] It is partially for that reason training volume is kept low so that high levels of intensity and motivation can be maintained.[12] Repetitions are also limited to prevent injuries such as medial tibial stress syndrome or stress fractures from the excessive skeletal loading that takes place during landing.[12]

A plyometric exercise involves a rapid eccentric contraction (counter-movement) immediately followed by a quick and strong concentric contraction.[2, 8, 12, 14, 16, 20, 44] This is known as the stretch shortening cycle and it is the most common type of muscle action required by sport related activities.[9] The amortization phase is the time between the eccentric and concentric contractions.[12] A shorter amortization phase leads to a more powerful concentric movement because the potential energy that is stored in the muscle is converted to kinetic energy more efficiently.[9, 12] If the amortization phase is extended the potential energy dissipates and is lost as heat.[16] One of the primary goals in any plyometric training program is reduction of the amortization phase, leading to greater power output.[12] Effective plyometric exercises can cause eccentric loads over five times the individuals body weight in the active muscles.[14] This amount of force is far beyond what could be voluntarily produced concentrically by the muscle.[9, 14, 16, 44] The stretch shortening cycle increases the force output of a muscle by causing an elastic recoil of the tendon, increasing the time available to develop the force, and eliciting the stretch reflex.[9, 44]

The magnitude, duration, and rate of the counter-movement will affect the resultant stretch reflex.[9, 12] A faster stretch induced by the counter-movement will evoke a stronger signal from the muscle spindles leading to a stronger contraction in the muscle being stretched.[12] The rate at which the stretch is applied is more important than the magnitude of the stretch.[12] The rapid eccentric contraction stimulates the muscle spindles causing a reflexive contraction enhancing the ensuing concentric contraction.[8, 12]

During the concentric contraction the rate of shortening of the musculotendinous unit as a whole depends on the shortening of the tendon due to its elastic recoil.[9] There is minimal displacement of the muscle fibers during the stretch shortening cycle, meaning that the muscle is operating closer to its optimal length.[9] Based on the length-tension relationship, a muscle operating its optimal length can produce more force.[9]

The increase in performance from a plyometric training program often occurs without hypertrophic changes in the muscle.[12, 44] This leads some researchers to believe most of the adaptations imposed on a plyometrically trained athlete originate from the neurological system especially within the first eight weeks.[8, 12, 44] Sugisaki and Kurokawa[44] did however discovered hypertrophic changes after eight to twelve weeks of lower extremity plyometric training.

Plyometric training protocols have shown some variability among different researchers in their effectiveness when examining vertical jumping ability when compared to traditional weight lifting strategies.[16] The extent to which the vertical jump can be improved appears to be dependent on the individual’s strength levels prior to the initiation of the plyometric training program.[16] Fatouros et. al.[16] (2000) reported that individuals with lower strength levels prior to the initiation of a plyometric training program demonstrated more substantial increases in their jumping ability, while previously strength trained individuals showed less of an increase in jumping ability. This is probably due to the fact that previously strength trained individuals have already undergone many of the neurological adaptations to a training program as opposed to untrained individuals.[16]

Neuromuscular Adaptations to Plyometric Training

Many of the neurological adaptations to plyometric training are similar to those observed with resistance training.[4, 8, 38] Increasing the sensitivity of the muscle spindles, decreasing the sensitivity of the golgi tendon organs, altering muscle recruitment and synergy, and increasing rate of force production have all been suggested neurological adaptations to both resistance training and plyometric training.[4, 8, 38] Resistance training has been shown to alter the coactivation of antagonistic and synergistic muscles leading to more efficiency of movement and more force.[4] Plyometric training has been suggested to alter the pennation angle of the muscle fibers involved in the exercises,[44] activate earlier in the stretch shortening cycle,[2, 9] alter lower limb biomechanics,[1, 13, 27, 30] and increase neuromuscular coordination.[8, 12]

Proper plyometric training will increase the excitability of the muscle spindles and decrease the excitability of the Golgi tendon organs.[8, 12] This is similar to what has been observed through resistance training.[4] Plyometrically trained subjects saw significant improvements in the concentric portion of the stretch shortening cycle but not movements consisting of purely concentric movement.[9] Cormie et. al.[9] (2010) believes that stretch shortening cycle exercises lead to enhancements in the stretch reflex but not purely concentric contraction strength. Plyometric training, like traditional weight training, is thought to desensitize the Golgi tendon organs allowing for greater contractile strength.[8, 4] The function of Golgi tendon organs is to protect the muscle and tendon from excessive force by causing reflexive inhibition of the muscle.[8]

A decreased pennation angle of the muscles involved has been demonstrated following a five-week plyometric training protocol which will lead to greater force output at the terminal stages of knee extension.[44] This is because the muscle fibers will work to extend the knee by pulling superiorly on the patella rather than be aligned to stretch the patellar tendon medially and laterally.[44]

Muscles involved in a plyometric action have been shown to activate earlier in the stretch shortening cycle following a plyometric training program.[2, 9] The eccentric portion of the stretch shortening cycle allows the agonist muscles to develop more force and stiffen prior to the concentric portion of the cycle.[2, 9] Preemptive muscular activation could increase the number of active cross bridges present for the stretch leading to increased power output.[9] The consequent higher tension at the beginning of the concentric portion of the exercise result in greater tendinous lengthening and less fascial lengthening.[9]

Many studies show changes in lower limb biomechanics following a plyometric training program which they attributed to the learning effect.[1, 13, 27, 30] The neuromuscular coordination between the upper and lower extremity is extremely important when attempting to perform a maximal vertical jump.[1, 35] Because plyometric training for the lower extremity consists of jumping, it is expected that just through practice, better coordination between the upper and lower extremity will develop leading to increased vertical jump height performance.[1]

Plyometric exercise may also enhance neuromuscular coordination.[8, 12] The stretch reflex enacted by the stretch shortening cycle increases muscle stimulation that, when combined to the voluntary concentric contraction, increases the maximal power output.[2, 9] With training, the neuromuscular system is better able to coordinate the reflex with the voluntary contraction leading to a force output that is greater than what could have been achieved purely voluntarily.[9]

Rate of Force Development and Relaxation

Rapid muscle contractions followed by their subsequent relaxations are essential in most athletic movements.[14] Rate of force development is defined as attempting to achieve the maximal amount of force as quickly as possible and is commonly used as an indicator of explosive strength or power.[35] Explosive strength and rate of force development have been suggested to be a more important predictor of athletic performance compared to a one repetition maximum.[35]

The rate of force development has typically been evaluated during isometric contractions that require the muscle to reach a given force range as quickly as possible.[34] The rate of force development is sensitive enough to depict the differences between subjects and demonstrate neuromuscular adaptations to plyometric training.[34] A high rate of force development is mainly due to the increase in the rate of neuromuscular activation as well as the inherent ratio between fast and slow twitch fibers in the muscle being tested.[34] Mathern et. al.[34] (2019) recorded the time to peak force during rate of force development assessments at submaximal isometric levels and has shown it to be invariant regardless of the magnitude of the force being produced. Rate of force development and relaxation are scaled with the magnitude of the peak force across submaximal ranges.[34]

The rate of force development and relaxation may reflect different properties of the neuromuscular system because of the lack of correlation between them.[34] The magnitudes of the rate of force relaxation were consistently lower than the rate of force production in a study conducted by Mathern et. al.[34] (2019) This study also showed that there was no relationship between the rate of force development and relaxation.[34]

The rate of force relaxation is vastly dependent on the intrinsic properties of the muscle including the ratio of fast and slow twitch muscle fibers.[34] Although the rate of force relaxation is considered to be as functionally important as its counterpart, it has received much less attention in the literature.[34] The rate of force relaxation can be assessed similarly to the rate force development, and therefore can be assessed at the same time.[34] From an isometric submaximal or maximal contraction the task given to the subject is to relax as quickly as possible.[34]

There is significant correlation between vertical jump height and the rate of force development during the counter movement jump.[35] It is suggested that rate of force development is a better predictor of vertical jump height performance compared to a one repetition maximum test.[35] McLellan et al.[35] (2011) suggested that the rate of force development is the largest contributor to vertical jump performance. Because plyometric training is designed to improve rate of force development, it should lead to enhancements in vertical jump height.[14, 35, 44]

Vertical Jump Testing

The vertical jump test is often used to assess the effectiveness of a plyometric training program as well as to assess the explosive strength and power of the lower extremity.[7, 35, 36] Jumping is a complex action affected by several factors including the maximal force developed by the active muscles, the rate at which that force can be developed, and the neuromuscular coordination of the upper and lower extremity.[35] Jump height is defined as the vertical displacement achieved by the center of mass from takeoff to the apex.[36] Jump height depends on the take-off velocity and the position of the center of mass at take-off.[36]

Due to the variability among jump height measurements, many different protocols and devices have been implemented with the goal of achieving the most accurate and reproducible results.[35] Some protocols do not allow the subject to perform a countermovement or swing their arms while others do. Placing the hands on the hips during a jump minimizes the effect the upper extremity has on vertical jump performance.[31] By eliminating arm movement, the results of the vertical jump assessment will more closely resemble the effects of plyometrics on the muscle itself rather than the coordination between upper and lower extremities.[31] Markovic[31] (2004) demonstrated the lowest variability in the countermovement jump and the second lowest in the squat jump. Position transducers, accelerometers, yardsticks, motion analysis systems, belt mat systems, contact mats, and force plates have all been used in an attempt to measure vertical jump height.[7, 35, 36]

Force plate devices are considered to be the gold standard when assessing vertical jump displacement.[7, 35] Force plates not only enable the practitioner to calculate jump height, but they will also show the power production throughout the eccentric and concentric phases of jumping.[3] By measuring the amount of time the subject is in the air, their vertical displacement can be calculated.[36] If the landing mechanics are altered so that the subject remains in the air longer, the validity of this measure will be contaminated.[36] Because the force plate calculations revolve around the amount of time spent in the air, if the subjects land differently from one another they may spend more or less time in the air due to their landing mechanics. This alters the relationship between power produced and flight time achieved. To obtain the most reproducible results the landing mechanics must be carefully monitored between subjects. The formula[36] used to calculate vertical jump height from flight time is as follows:

$$\text{Vertical jump height} = \tfrac{1}{2}\text{ gravitational acceleration x (time of flight / 2)}^2$$

Reflexes

The tendon tap reflex has also been referred to as the myotatic reflex, phasic stretch reflex, and stretch refex.[41] The tendon tap reflex has been used clinically to assess the integrity of the neuromuscular system[2] as well as the central and peripheral nervous system.[33] Tapping the tendon elicits a stretch stimulating the muscle spindle 1a afferents which send a signal to the spinal cord.[26, 33] There, the 1a afferent signals synapse with the alpha motor neurons sending a signal back to the muscle to cause a reflexive contraction.[26, 33]

Previous attempts to quantify the reflex response have included the use of ultrasonography, dynamometry, electrogoniometry, motion capture analysis, and surface electromyography (EMG).[3, 41] Tendon tap responses show a large degree of variability between subjects which could be in part due to the method of stimulation.[43] When attempting to elicit a consistent tendon tap reflex it is common for the clinician to ask the patient to perform the Jendrassik maneuver.[3, 41] This is performed by instructing the subject to close their eyes, interlock their hands in front of their chest, and attempt to pull them apart.[3, 41] Previous attempts to administer reproducible tendon taps have used a reflex hammer mounted on an axle and dropped from a consistent height.[43] By allowing gravity to deliver a consistent force at a consistently aimed location in the mid-substance of the tendon more reproducible results have been shown to occur.[3, 17, 26]

The major parameters of the stretch reflex are amplitude and latency.[26, 33, 41] Latency is defined as the time between when the tendon tap was delivered and the first recorded signal.[2, 26, 33] The delay between the tapping force and the resultant contraction is due to both the afferent and efferent conduction delay and the neuromechanical delay within the muscle.[33] Avela et. al.[2] (1998) showed that on average the first EMG signal is recorded 30-32 milliseconds after the tap was delivered when assessing the quadriceps femoris muscle. There is a large gap in the literature regarding amplitude of the EMG response following plyometric training. to find an increase in the EMG amplitude of a tendon tap following plyometric training would suggest an increase in the sensitivity of the muscle spindles.

Electromyography

The signal recorded by an EMG is a combination of motor unit recruitment, synchronization, and firing frequency.[4] An EMG can quantify the magnitude of the stretch reflex caused by a tendon tap by recording the electrical activity present in the muscle during the response.[3, 25, 26, 41, 43]

According to Beck et. al.[3] the frequency spectrum of the EMG is determined by the shapes of the action potentials and the conduction velocities of the muscle fibers. The shape of the action potentials are dependent on the type of motor units being recruited, the thickness of the tissue between the muscle and the electrodes, and the dispersion of the endplates.[3] Muscles with a higher percentage of fast-twitch fibers showed faster conduction velocity rates.[3] It is likely that the greater depolarization and repolarization rates were responsible for the shortened duration of action potentials seen in the fast twitch fibers.[3] Shortened action potentials lead to greater conduction velocities.[3]

The optimal average baseline EMG reading during relaxation should be between one and two microvolts, but it shouldn't exceed three to five microvolts.[45] If the signal exceeds five microvolts EMG preparation, placement, and ground wire connection should be checked to improve the signal. Muscles in close proximity to the recording electrode may produce an EMG signal significant enough to be recorded by the electrode.[45] This is referred to as cross talk between muscles and typically doesn't exceed ten to fifteen percent of the total EMG activity recorded by the electrode and may be mistaken for background noise.[45]

An increase in EMG activity will typically lead to greater levels of torque being produced by the muscle, however this is not always the case.[45] This EMG reading to force ratio can be used to help determine the neuromuscular training status of the muscle.[45] During static contractions, well trained muscles tend to demonstrate more force with the same level of EMG activation as a subject who is untrained and producing less force.[45]

Conclusion

Plyometric training is well documented in its ability to increase power production[3, 8, 9] and rate of force development.[44] It is commonly used by athletes and coaches to increase vertical and horizontal jumping ability as well as sprint speed, agility, and performance.[8, 12, 14, 20] A plyometric exercise invokes the stretch shortening cycle by beginning with a rapid eccentric countermovement to stretch the muscle before immediately transitioning to a quick and powerful concentric contraction.[8, 12, 14, 16, 20, 44] The rapid counter movement stimulates the muscle spindles causing a reflexive contraction which enhances the concentric contraction.[8, 12]

Many of the hypothesized mechanisms affected by plyometric training are assumed to stem from the neurological system and are still theoretical.[8] Of the proposed mechanisms, stretch reflex response, rate of force development/relaxation, maximal voluntary isometric contraction, and vertical jump height are of the highest concern to the research team in the present study.

If plyometric training increases the sensitivity of muscle spindles it should be evident by a tendon tap reflex test compared pre- and post-intervention. Tapping the tendon with a reflex hammer stimulates the muscle spindles causing a reflexive contraction similar to the eccentric countermovement phase of a plyometric exercise,[26, 33] but on a much smaller scale. An EMG alone can quantify the magnitude of the stretch reflex caused by a tendon tap,[3, 25, 26, 41, 43] but the current study will also use a force transducer strapped to the ankle. The data from both the EMG and the force transducer will be used in conjunction to reveal what effects plyometric training has on the neuromuscular system. If the rate of force development and relaxation are altered by plyometric training that should also become evident through asking the subjects both pre- and post-intervention to produce the maximal amount of force as fast as possible with a subsequent relaxation as quickly as possible.

The current study has multiple objectives. Firstly, the current study will attempt to test if plyometric training will increase the patellar tendon tap reflex response with both an EMG and a force transducer. Secondly, the study will measure the rates of force production and relaxation before and after plyometric training. Third, the study will examine the maximal voluntary isometric contraction of the hamstrings and quadriceps muscle groups with an EMG and a force transducer. Finally, the study will examine the plyometric training protocol's effects on vertical jump height performance as a means of assessing the legitimacy of the program.

If the current study shows no results in stretch reflex, maximal voluntary contraction, or rate of force Development/relaxation, but an increase in jumping ability the research team will suggest that the causes of the increase in vertical jump height is due to other factors. If the current study shows no increase in jumping ability and no increase in any of the other dependent variables being assessed the efficacy of the plyometric training protocol used in the study will be brought into question.

Aims and Hypotheses

This study aims to examine the neuromuscular effects of six weeks of plyometric training on the lower extremity by assessing the stretch reflex response, rate of force development, rate of force relaxation, maximal voluntary isometric contraction, and vertical jump height.

Specific Aim 1: To examine the effects of a 6-week lower extremity plyometric training intervention on the stretch reflex assessed through a patellar tendon tap response with an EMG and a force transducer.

Hypothesis 1: We hypothesis that plyometric training will increase the patellar tendon tap response which will be measured as the EMG response as well as the level of force recorded through the force transducer.

Specific Aim 2: To examine the effects of a six-week lower extremity plyometric training program on the rate of force development of the quadriceps muscle group

Hypothesis 2: We hypothesis that the rate of force development will be higher in the quadriceps muscle group post plyometric training.

Specific Aim 2.1: To examine the effects of a six-week lower extremity plyometric training program on the rate of force relaxation in the quadriceps muscle group.

Hypothesis 2.1: We hypothesis that the plyometric intervention will increase the rate of force relaxation in the quadriceps muscle group.

Specific Aim 3: To determine the effects of a six-week lower extremity plyometric training program on maximal voluntary isometric contraction strength of the hamstrings and quadriceps muscle group.

Hypothesis 3: We hypothesize plyometric training will increase the maximal voluntary isometric contraction values in the hamstrings and quadriceps muscle groups following plyometric training.

Specific Aim 4: To examine the effects of a six-week plyometric training protocol on vertical jump height performance.

Hypothesis 4: We hypothesize that plyometric training will increase vertical jump height.

Chapter 2

Manuscript

Abstract

Plyometric training has been well documented in its ability to increase vertical jump performance,[12, 14, 16, 20] however, many of the proposed mechanisms driving its success are still theoretical. Of the many proposed neurological adaptations to plyometric training, increasing the sensitivity of the muscle spindles leading to enhancements of the stretch reflex and increasing the rates of force development and relaxation are of greatest interest to the current study. Eleven (seven male and four female) participants completed six weeks (12 sessions) of supervised plyometric training. Before and after the completion of training, vertical jump height, the stretch reflex via tendon tap, rates of force development and relaxation scaling factors, and maximal voluntary isometric contraction were assessed with electromyography (EMG) and a force transducer strapped to the ankle. The current study found a significant increase in countermovement jump height, indicating that the plyometric training regimen was successful. Squat jump height was not significantly different following plyometric training. No evidence of an increase in the patellar tendon tap response following plyometric training was found. No statistical significance was found for the peak force or the peak EMG activation, however our results showed an increase in the amount of time required for subjects to reach their peak force during a tendon tap following plyometric training. The maximal voluntary isometric contraction was not significantly different from pretest. The rate of force development scaling factor displayed no increase while the rate of force relaxation scaling factor

improved significantly indicating that subjects were able to relax muscle forces more quickly. Our findings suggest that while plyometric training improves vertical jump performance, it does not increase the stretch reflex response (as measured by muscle activity and force production during a patellar tendon tap). Therefore, we speculate that plyometric training might improve coordination among the segments involved in the complex action of jumping Further studies are required to determine if plyometric training has any effect on the stretch reflex. Future studies should also examine the potential improvements in a subject's form, especially during a countermovement, that could potentially lead to the increases witnessed in vertical jump height.

Introduction

Plyometric training is a common technique used to enhance agility, quickness, and horizontal/vertical jump performance.[12, 14, 16, 20] It is especially important in sports such as volleyball and basketball where vertical jump height and explosive power are paramount to performance. Compared to a one repetition maximum, vertical jump performance has been shown to be the superior method of assessing athletic performance.[35] This is likely because most sports require power as opposed to strength.

Any exercise that utilizes the stretch shortening cycle of a muscle through a rapid eccentric contraction immediately followed by a strong and rapid concentric contraction is a plyometric exercise.[2, 8, 12, 14, 16, 20, 44] For the lower extremity, that criteria is most commonly met by jumping. The countermovement of flexing at the knees and hips creates a stretch and an eccentric contraction in the quadriceps. The rapid eccentric contraction stimulates muscle spindles eliciting a reflexive contraction that when added to the voluntary contraction increases power output beyond what could be achieved purely concentrically.[2, 8, 12, 14, 16, 20, 44]

Despite the wide success of plyometric training, many of the proposed mechanisms that drive that success are still theoretical.[20] Many of the benefits to plyometric training are believed to revolve around neural adaptations rather than hypertrophic changes in the muscles.[9, 12, 20] Sugisaki and Kurokawa;[44] (2014) however, discovered hypertrophic changes after eight to twelve weeks of lower extremity plyometric training. Similarly to resistance training, it appears that plyometric training requires an individual to undergo neurological adaptations prior to hypertrophic alterations in the muscle. Despite the absence of hypertrophy, vertical jump height improvements have been recorded in as few as three weeks from the initiation of the plyometric training program.

The proposed adaptations to plyometric training of interest to this study include increasing the sensitivity of the muscle spindles to produce a greater stretch reflex response, increasing the rate of force development, and increasing the rate of muscle relaxation. Secondarily, the present study will examine the effects of plyometric training on maximal voluntary isometric contraction values and vertical jump height performance. The current study will attempt to evaluate these neurological adaptations believed to be caused by plyometric training. This will be achieved by recording the stretch reflex elicited by a patellar tendon tap with electromyograph (EMG) and the corresponding isometric force produced by the quadriceps via a force transducer attached to the ankle. The rate of force development/relaxation scaling factors will be assessed through brief isometric force pulses performed to various sub-maximal ranges. Maximal voluntary contraction will also be assessed using the EMG and the force transducer. Finally, vertical jump height during a squat jump and two countermovement jumps under different conditions will be assessed using a force plate.

We hypothesize that plyometric training will increase the patellar tendon tap response measured by relative EMG activation and force. We also hypothesize that plyometric training will increase the rates of force development and relaxation as well as the maximal voluntary isometric contraction. Finally, we hypothesize that plyometric training will improve vertical jump height performance.

Methods

Subjects. Eleven healthy, non-injured, recreationally active subjects between the age of 18 and 22 were recruited for the present study. Recreationally active was defined as physically active for a minimum of three 30-minute periods per week. The subjects consisted of seven males and four females with an average height of 1.77 (±0.09m) and an average weight of 71 (±12.2kg). Subjects with any current injury, pain, swelling, or a history of surgical intervention in the lower extremity were excluded from the study. Further inclusion criteria included: adequate range of motion in the lower extremity examined by observation of hamstring and quadricep assisted stretching, adequate balance as tested using the modified balance error scoring system,[12] and the ability to perform five squats within five seconds with 60% of their body weight maintaining proper form.[12] The subjects were informed to only perform the prescribed exercises under the supervision of the research team and not to perform any other lower extremity exercises for the duration of the study. Subjects were permitted to continue upper body weight training and cardio exercises as normal during the training period. No dietary alterations were made by the research team. Subjects were told to continue eating and drinking as they have been prior to the initiation of the study. Training session times were picked by the subjects; however pretest and post tests were performed in the morning around the same time of the day for each subject. All subjects read and signed the informed consent form approved by the IRB of Rowan University prior to the initiation of any testing or exercise protocols.

Procedure. Prior to the beginning of data acquisition, the subjects were instructed not to perform lower extremity exercises for at least two days prior to any testing procedures and not to perform any exercise the day of their testing prior to the testing procedures. The subject’s dominant leg was placed in a position similar to the testing position before the electrodes were placed. In accordance with the SENIAM[42] guidelines for EMG placement, a mark on the skin was placed 2/3 the distance from the anterior superior iliac spine (ASIS) and the superior lateral border of the patella for the vastus lateralis. A second mark was placed 2/3 the distance from the ischial tuberosity to the lateral boarder of the popliteal fossa for the biceps femoris. In accordance with standard EMG procedure, each marked area was first shaved with a razor to remove any hair then scraped with fine grain sandpaper to remove any dead skin cells. The marked areas were then cleaned with alcohol preparatory pads and allowed to dry before placing the electrodes on the skin perpendicular to the orientation of the muscle fibers. A strip of tape was then applied over each electrode to prevent slippage. The reference electrode was placed on the patella because the lateral malleolus was unavailable due to the placement of the force transducer.

The subject was then instructed to sit down on the custom-made wooden box with their dominant ankle resting on the force transducer. The force transducer was adjusted for height to rest just above the lateral malleolus of each subject. The height of the transducer was recorded to ensure that it was placed in the same position for the post test. Their ankle was secured to the force transducer allowing for quasi isometric contractions. Two straps were tightly wrapped around the dominant thigh securing it to the box, and one more strap around the hips to prevent any compensatory motions. When sitting on the box, subjects' hips were flexed to approximately 90 degrees and knees to approximately 70 degrees of flexion (figure 1a).

A B

Figure 1. Subject positioning for the tendon tap and the reproducible tendon tap delivery device. The picture on the left (figure a) shows the swinging arm in the ready position and the picture on the right (figure b) shows after the release has been pulled and the hammer drops. Picture shoes placement of EMG channel 1 on the vastus lateralis, reference electrode on the patella, the force transducer at the ankle, and the three straps used to restrain the subject. EMG channel 2 on the hamstrings is out of sight due to the subject being seated.

Patellar tendon tap. A custom-made and height adjustable swinging arm was used to deliver tendon taps at a consistent force and location to elicit a stretch reflex. The moving arm was brought up to a consistent height and dropped to ensure it was striking with the same amount of force in the mid-substance of the tendon. To further remove human error a pin was inserted through a hole to hold the swinging arm in place. When the tap was ready to be delivered the pin was removed allowing the arm to fall and the reflex hammer to strike the tendon (figure 1b). All tendon tapes were performed while the subject was holding the Jendrassik maneuver.[3, 41] One trial consisted of four tendon taps with 20 seconds of rest between each. Four trials were performed resulting in a total of 16 patellar tendon taps per subject.

Maximal voluntary isometric contraction (MVC). Subjects were asked to cross their arms across their chest and rest while the new baseline recording of the force was collected, whose value was subtracted from the recorded force values in the experimental protocol. Quadriceps strength was assessed first and hamstring strength was assessed second with the instruction being “kick out/pull back as hard as you can and hold that effort until instructed to stop.” Subjects received verbal feedback and motivation during the MVC testing using the words “kick!” and “pull!” for the quadriceps and hamstrings, respectively. The subjects alternated quadricep and hamstring trails until they had completed three for each with 60 seconds of rest between each trial of the same muscle. Within each tested muscle group the highest of the three was taken as the MVC value.

Rate of force development/relaxation. Four horizontal lines corresponding to 20, 40, 60, and 80% of the highest recorded MVC were displayed on the feedback screen. These horizontal lines were used to define three force ranges termed small (20-40%), medium (40-60%), and large (60-80%). The subjects were instructed to cross their arms across their chest and kick out as fast as they could and then relax as fast as they could within the requested force range shown on the monitor. Each subject was told to pay little attention to accuracy and focus more on the speed at which they produce the force pulse and then relax after producing that force. Each subject was also allotted up to two minutes to practice producing the force pulses in each range using the monitor for continuous and instantaneous visual feedback. When ready, an audio recording was played for the subjects ensuring the same pace and order of force ranges for each subject. The force ranges always come in groups of five. Trial one started with small, then medium, then large, and back around again for ten total repetitions within each range per trial. The order of the force ranges changed after each trial. Over the course of four trials there was a collection of 40 force pulses in each range for a total of 120 force pulses per subject.

Following the resolution of this portion of the test the subjects were unstrapped from the box and the force transducer. The electrodes were removed and sanitized with an alcohol prep pad, and the subjects were allowed to walk around briefly before the final portion of the testing.

Vertical jump height. Each subject was then allowed up to five minutes on a stationary exercise bike followed by self-prescribed dynamic and ballistic stretching activities to prepare for the vertical jump assessment. While the subjects were preparing for the vertical jump assessment the three different types of jumps were explained to them.

During the squat jump subjects were instructed to maintain their hands on their hips for the duration of the jump. A box was positioned underneath them, and they were instructed to hold a squat so that they had slight contact with the box. The box height was selected so that the subject thighs were parallel to the ground. The height was recorded to ensure the same height was used pre- and posttest. Upon contact with the box the subjects were given a verbal count down from three. Subjects were instructed to explode straight up as high as they could from the squat without dropping down first. The ground reaction force graph was carefully monitored for a countermovement prior to the initiation of the jump. If a countermovement was detected the test was repeated.

Two types of countermovement jumps were recorded: with and without arm swing. The subjects were given very little instruction on the countermovement with arm swing. They were instructed to jump as high as possible. They were allowed to drop as low to the ground as they wanted and swing their arms to achieve a maximal vertical jump. The countermovement without arm swing required the subjects to keep their hands on their hips, but still allowed them to drop as low as they wanted.

For all the jumping conditions, the subjects were instructed to land on their toes with their knees mostly straight. They were also instructed to take off and land on both legs. Subjects were also informed that they must land with both feet on the force plate for the jump to be counted, however they were told not to sacrifice jump height for landing accuracy. If the subjects failed to follow takeoff or landing instructions the data was deleted, and the test was repeated. The subjects were allowed a practice jump for each of the three jumping conditions. The order of the jumps was randomized for each subject. After a successful completion of one condition the subjects were asked to perform one of the other two types of jumps. Including the practice jumps, each subject had to perform a minimum of 12 jumps. Most did not have to perform more than 15 jumps. Sixty seconds of rest was allotted between each trial. Both the highest of the three maximal vertical height jumps for each condition, and their average, was calculated.

Plyometric training. All subjects completed two training sessions per week, for a total of six weeks. Every training session was observed by one of two practitioners trained in the diagnosing and correcting improper biomechanics. New exercises were introduced every two weeks. Prior to the initiation of each new exercise, subjects were sent written instructions as well as a video demonstrating the exercise. No subjects were removed from participation in the study due to a failure to correct improper movement mechanics or injury.

Every exercise session began with a self-prescribed warm up, and questions about injury status as well as recovery from the past session. Each subject was given the opportunity to include any warmup procedures they felt necessary. Each plyometric exercise was demonstrated and described on videos that were sent to them prior to the initiation of that week. The subjects were instructed to bend the knees to about 90 degrees and immediately explode up into the air as high as they could for every repetition. They were instructed to minimize the amount of time they spent on the ground. Subjects were given verbal feedback about their performance and their mechanics. Any improper movement mechanics that were noticed by the observer were explained and corrected. The subjects were also given verbal encouragement throughout the workout in an effort to keep motivation levels high.

During the first two weeks of plyometric training the exercise protocol was as follows; squat jumps, jumping lunges, and wall touches. Three sets of ten repetitions were performed for each of the exercises for a total of 90 foot contacts (beginner intensity). A 30 second rest was allotted between each set and a two-minute rest was allowed between each exercise. During weeks three and four the double jump replaced the jumping lunges for a total of 120 foot contacts (intermediate intensity). Weeks five and six included all of the same exercises with the addition of the "out and up" exercise. The total sets for squat jumps and wall touches was brought down to two for a total of 160 foot contacts (advanced intensity).

Table 1

Layout of the plyometric training program given to the subjects including the sets, reps and rest periods.

week 1-2		
exercise	sets	reps
squat jumps	3	10
jumping lunges	3	10
wall touches	3	10
week 3-4		
squat jumps	3	10
double jumps	3	10
wall touches	3	10
week 5-6		
squat jumps	2	10
double jumps	3	10
out and ups	3	10
wall touches	2	10

30 second rest between each set
2 minutes rest between each exercise
2 training sessions per week

The double jump exercise is meant to simulate a drop jump. It is performed by having the subject perform an initial smaller jump, then upon landing, very quickly bend the knees to about 90 degrees and get back up into the air as high and as quickly as possible. The landing from the smaller initial jump is similar to the landing from a small stack of boxes that would be seen in a drop jump. The “out and up” exercise is also meant to simulate a drop jump but at a much higher intensity. It requires the subject to broad jump as far as possible and then immediately upon landing jump as high and as quickly as possible without moving forward again. Forcing the subject to cancel out all their forward momentum and instead force themselves to jump as high as possible places a large eccentric load on the quadriceps for a more intense exercise.

At the conclusion of every plyometric workout static stretching of the quadriceps, hamstrings, and triceps surae muscle group were prescribed. The subject could use any cool down procedure they felt necessary following the static stretches given to them. At least four days were allowed between the final training session and the post test. Each subject was also asked if they still felt sore from their last exercise session prior to any testing.

Data acquisition and analysis. EMG is recorded at 1000 Hz through a Delsys Bagnoli 2-channel system (delsys, Boston, MA) and the force data is recorded using a force transducer (SM-500, Interface Inc., Scottsdale, AZ). All EMG data were demeaned, rectified, and low-pass filtered at 20 Hz to create a linear envelope, which was used to calculate the dependent variables.

In tendon tap analysis, both the recordings of EMG and force data were displayed on the computer screen. The software found each tendon tap instances by searching local peaks in the force data and displayed one second of both EMG and force data on the screen such that the force peak was in the middle of the recording. Cursors were automatically placed to the initiation, peak, half relaxation, and full relaxation instances of both EMG and force signals (figure 2). As recommended by Maffiuletti et. al.[29] the plotted points were visually confirmed by the researcher and adjusted if necessary. Both the force and EMG initiation was defined as when their values reach greater than three standard deviations above the baseline preceding the tendon tap. The following dependent variables were calculated from the tendon tap trials: peak force, the time to peak force, the peak EMG activation, the time to peak EMG activation, and the electromechanical delay. The electromechanical delay is defined as the time between the initiation of the EMG and the initiation of the force.

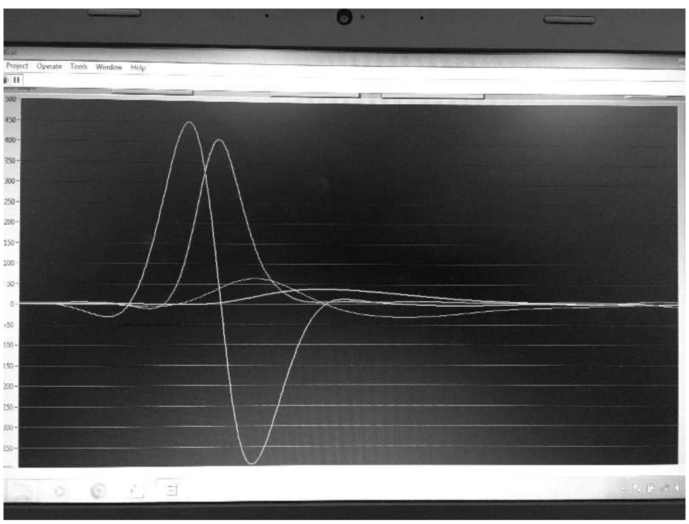

Figure 2. A representative recording obtained from a tendon tap, color coded for force, EMG channel 1 (vastus lateralis), and EMG channel 2 (biceps femoris) prior to the placement of the cursors.

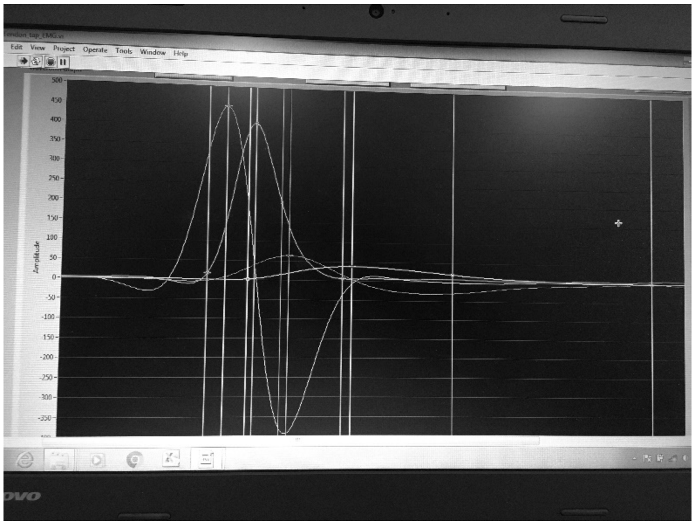

Figure 3. Picture of the same pulse recorded from a tendon tap color coded for force, EMG channel 1 (vastus laterlis), and EMG channel 2 (biceps femoris) following the placement of the cursors.

Another LabView software was used to analyze rates of force development and relaxation scaling factors. Both the recorded force and its time derivative were plotted together on the computer screen. Similar to the tendon tap, each force pulse was displayed on the screen individually and cursors were placed automatically on the curves corresponding to the force initiation, peak force, force termination, and their values were recorded for further analysis. Both the rate of force development and rate of force relaxation were calculated by dividing the peak force values by its time to peak and its time to relax, respectively. The regression parameters obtained from the relationships between peak force-rates of force development and peak force-rate of force relaxation were used as dependent variables. Namely, the slope of the linear relationship between peak forces and corresponding peak rates of force development is called the rate of force development scaling factor (RFD-SF). A similar slope obtained from the linear relationship between peak forces and peak rate of force relaxation is termed the rate of force relaxation scaling factor (RFR-SF). The R-squared obtained from the aforementioned relationships revealed the consistency of scaling of the rates of force development and relaxation within the magnitudes of the force pulses produced.[34]

Vertical jump height used custom LabView software designed to pick the first frame where there is no force reading on the force plate and pick the frame where the first force reading is picked up again to determine the amount of time each subject spent in the air. By determining their flight time, the program was then able to calculate vertical jump height from the following calculation:

$$\text{Vertical jump height} = \tfrac{1}{2}\ \text{gravitational acceleration} \times (\text{flight time} / 2)^2$$

Maximal vertical jump height and flight time as well as average vertical jump height and flight time were assessed for each subject pre- and posttest.

Statistical analysis. Dependent variables for rate of force development and relaxation testing include maximal voluntary isometric contraction (newtons), rate of force development scaling factor, R^2 of RFD-SF, rate of force relaxation scaling factor, and R^2 of RFR-SF. Since R^2 values are inherently not normally distributed their values were fisher transformed prior to the statistical analysis. The dependent variables for the tendon tap are as follows: the peak force, the time to peak force, the peak EMG activation, the time to peak EMG activation, and the electromechanical delay. Dependent variables for the vertical jump assessment include the maximal vertical jump height over three trials, the average vertical jump height of the three trials, maximal flight time, and average flight time. These variables are assessed over three different types of jumps.

In the current study, each subject acted as their own control and all the dependent variables were assessed prior to plyometric training and reassessed following the completion of plyometric training. Two tailed paired sample t-tests were used to compare the selected dependent variable before and after the completion of training. Significance values were set at $p<0.05$

Results

Stretch reflex. The electromechanical delay, defined as the time between the initiation of the EMG and the initiation of the force, was not significantly different following plyometric training ($t=1.54$; $p=0.16$.) The peak force, although not significant, decreased on average by 0.25N ($t=0.53$; $p=0.6$.) The time to peak force significantly increased by an average of 0.002s ($t=4.14$; $p=0.002$) following plyometric training. The EMG value reported as a percentage of the maximal voluntary isometric contraction value was decreased by an average of 21.6% ($t=1.96$; $p=0.08$) (table 2).

Table 2

Results from the tendon tap portion of the testing

	pre		**post**		**statistics**		
	mean	**SD**	**mean**	**SD**	**% difference**	**t-value**	**p-value**
peak force (%MVC)	4.189	3.417	3.939	3.002	-5.97%	0.531	0.607
time to peak force (s)	0.077	0.010	0.091	0.011	18.70%	4.056	**0.002**
EMG peak value (%MVC)	44.261	42.255	34.689	33.694	-21.60%	1.950	0.080
EMD (s)	0.037	0.010	0.035	0.007	-7.38%	1.536	0.156

Rate of force development/relaxation. Maximal voluntary isometric contraction was insignificantly increased by 56.89N (t=2.12; p=0.06) which is equivalent to a 7.8% increase. The rate of force development scaling factor calculated by the time required to reach peak force was not statistically different (t=1.24; p=0.24.) The rate of force relaxation scaling factor measured the same way significantly increased by 16.8% (t=2.63 p=0.03) (table 3).

Table 3

Results from the RFD/RFR testing.

	pre		post		statistics		
	mean	**SD**	**mean**	**SD**	**% difference**	**t-value**	**p-value**
MVC (N)	725.09	157.69	781.91	135.97	7.84%	2.10	0.06
RFD_r^2_ttp	0.63	0.24	0.61	0.28	-2.54%		
fisher R2-RFD-SF	0.86	0.49	0.87	0.57	0.81%	0.07	0.94
RFD_SF_ttp	5.15	2.05	4.53	1.82	-12.06%	1.24	0.24
RFR_r^2_ttp	0.70	0.16	0.79	0.16	12.47%		
fisher R2-RFR-SF	0.93	0.31	1.15	0.34	23.97%	2.15	0.06
RFR_SF_ttp	-4.18	1.64	-4.89	1.80	16.80%	2.63	**0.03**

Note that RFD_R^2_ttp and RFR_R^2_ttp do not have a t value or a p value because they are not normally distributed.

Vertical jump height. The countermovement jump condition, in which subjects were allowed to swing their arms, improved significantly compared pretest to posttest. Maximal vertical jump height increased on average by 0.02m (t=2.33; p=0.04) corresponding to an increase of 6%. Following completion of the plyometric training program the average vertical jump height of the three trials increased by 0.02m (t=3.1; p=0.01) which relates to a 4.4% increase. The increased maximal vertical jump height is associated with an increase in maximal flight time by an average of 0.01s, or 2.9% (t=2.6; p=0.03). The mean flight time of the three trials increased by an average of 0.02s (t=2.7; p=0.02) indicating an increase of 4.8%.

The countermovement jump, in which the subjects were not allowed to swing their arms, saw similar results to the countermovement jump allowing an arm swing in all variables assessed. Maximal jump height increased by an average of 0.03m, or 10.3% (t=2.5; p=0.03) and maximal flight time increased by an average of 0.02s, or 4.5% (t=2.3; p=0.05). The mean jump height increased by an average of 0.02m (t=2.9; p=0.02) as well as average flight time increase of 0.02s (t=2.8; P=0.02). These results are associated with an increase of 8.9% and 4.9% respectively.

The squat jump did not see the same results as the countermovement jumps. The only condition assessed in the squat jump that saw any improvement was in the average flight time category (t=2.8; p=0.02) which increased by 0.02s or 5.4%. Maximal flight time on the other hand did not see the same statistically significant results with an increase of only 0.02s or 4.1% (t=2.0; p=0.08) Maximal vertical jump height, although not statistically significant, increased on average by 0.02m, or 9.1% (t=2.0; p=0.08). The mean vertical jump height actually decreased on average by 0.002m corresponding to a loss of 1.5% (t=0.14; p=0.89).

Table 4

Results from the vertical jump assessment.

	pre		post		statistics		
	mean	**SD**	**mean**	**SD**	**% difference**	**t-value**	**p-value**
max height CMJA (m)	0.3079	0.0760	0.3228	0.0723	6.0%	2.32	**0.04**
mean height CMJA (m)	0.2963	0.0706	0.3164	0.0702	4.4%	3.10	**0.01**
max flight time CMJA (s)	0.4978	0.0605	0.5110	0.0566	2.9%	2.54	**0.03**
mean flight time CMJA (s)	0.4825	0.0583	0.5046	0.0556	4.8%	2.66	**0.02**
max height CMJN (m)	0.2647	0.0627	0.2898	0.0699	10.3%	2.52	**0.03**
mean height CMJN (m)	0.2522	0.0600	0.2723	0.0619	4.5%	2.87	**0.02**
max flight time CMJN (s)	0.4604	0.0554	0.4784	0.0603	4.4%	2.25	**0.05**
mean flight time CMJN (s)	0.4500	0.0541	0.4676	0.0527	4.9%	2.79	**0.02**
max height SJ (m)	0.2536	0.0704	0.2703	0.0601	9.1%	1.98	0.08
mean height SJ (m)	0.2425	0.0688	0.2447	0.0963	-1.5%	0.14	0.89
max flight time SJ (s)	0.4505	0.0641	0.4669	0.0518	4.1%	1.98	0.08
mean flight time SJ (s)	0.4400	0.0651	0.4605	0.0511	5.4%	2.56	**0.03**

Discussion

The current study aimed to identify any relationship between plyometric training and vertical jump height, stretch reflex assessed by a tendon tap, maximal voluntary isometric contraction, and rates of force production and relaxation across submaximal ranges (i.e. rates of force development and relaxation scaling factors). After completion of the plyometric training program, countermovement vertical jump height significantly increased, while there was no change in the squat jump. In the tendon tap, contrary to the hypothesis, we found no significant differences in the electromechanical delay, peak force, or the peak EMG activation levels. The only change was an increase in the time required to reach the peak force. Finally, while the maximal voluntary isometric contraction and rate of force development scaling factor did not improve, the rate of force relaxation scaling factor was significantly increased after the completion of plyometric training.

Vertical jump. We investigated the effects of plyometric training on three different vertical jump conditions (i.e. countermovement jump with and without arm swing, and a squat jump without arm swing). Two out of the three studied vertical jumping conditions improved following six weeks of plyometric training. The squat jump, in which the subjects were not allowed an arm swing or a countermovement, was the only condition that was not significantly different after completion of the training. This is consistent with previous literature on the subject.[2, 5, 9, 31, 32] One potential reason for the lack of improvement in the squat jump could be due to the nature of the jump, which didn't include a countermovement. During the countermovement of the jump, the rapid eccentric descent prior to the concentric phase of the jump elicits a stretch reflex causing an involuntary muscle contraction.[2, 9] This involuntary muscle contraction can then be added to the concentric contraction for a greater power output.[9] Removal of the countermovement in a squat jump forced subjects to jump without the assistance of the stretch reflex. While plyometric training has been shown to increase stretch shortening cycle movements, it is not effective in increasing the performance of purely concentric exercises.[5, 31, 32] Another potential reason for this is due to the learning effect. Subjects were practicing maximal vertical jumps where they were allowed the use of a countermovement and an arm swing for six weeks in between their testing sessions. None of the exercise selections included in our plyometric training regimen restricted the use of an arm swing or a countermovement. This may help to explain why an increase in countermovement jump height was witnessed when similar increases in vertical jump weight without the use of a countermovement or an arm swing were not.

The two countermovement jumps, with and without an arm swing, both improved significantly following the plyometric intervention. This is consistent with the results of previous literature as plyometric training is well documented in its use to increase vertical jump height.[12, 14, 16, 20, 28] During plyometric training subjects were practicing jumping as high as possible for six weeks and, therefore, increases in performance are to be expected simply from the learning effect. However, subjects had limited space to land (i.e. force plate) for their pretest and posttest measurements, but when training were not instructed to land in a specific area. Attempting to land in a specific area alters biomechanics of not only landing but of takeoff as well[13] suggesting that not all the results observed are due to the learning effect. Forcing subjects to land on a one square foot force plate could add a layer of complexity that was not present during their training sessions. Other potential reasons for the increase in vertical jump height according to Luhtanen and Komi[28] (1978) are attributed to better synchronization in producing power among all of the segments (e.g. ankle knee and hip) involved in the complex movement, which is primarily determined by the training status of the individual.[28] Synchronization between the upper and lower extremity is also important for achieving maximal vertical jump performance.[28] Because vertical jump height was improved, the research team concludes that the plyometric training program was a success and that the results of the study stem from the training program.

Tendon tap. Contrary to our hypothesis, the current study found no statistically significant change in the electromechanical delay (i.e. the time between the initiation of the EMG and the force pulses) following plyometric training. Grosset et. al[18] (2008) did however find a significant increase in the electromechanical delay following 10 weeks of plyometric training which they attributed mainly to the musculotendinous stiffness. The most important determining factor for the electromechanical delay is the time taken to stretch the musculo-tendinous unit.[18] Because we used a reproducible tendon tap delivery device in our study, each tendon tap stretched the tendon at exactly the same rate, leaving the tendinous stiffness the most important variable in determining electromechanical delay.[18] Conu et al.[11] (1997) found a decrease in tendinous stiffness following seven weeks of plyometric and Grosset et. al[18] (2008) found a decrease in musculo-tendinous stiffness after ten weeks of plyometric training, suggesting that our study may not have had a long enough intervention to observe these physiological changes. Future studies should examine not only the electromechanical delay of the stretch reflex, but also of voluntary contractions.

The peak force as recorded from the patellar tendon tap was decreased insignificantly and the peak EMG value (as a percentage of the maximal voluntary isometric contraction value) recorded during tendon tap decreased, although not significantly, following training. This is contradictory to the hypothesis that plyometric training would increase the stretch reflex response. Our results showed no increase in the amount of EMG activation or force produced by the stretch reflex elicited by a tendon tap. To our knowledge, no previous studies exist that compared the muscle activation and the force produced during a tendon tap reflex pre- and post-plyometric training. Based on our findings, plyometric training does not increase the stretch reflex response; however, we speculate that it may allow an individual to take better advantage of the stretch reflex. A faster countermovement will lead to a greater stretch reflex response, which would also lead to a greater power output and, therefore, increased vertical jump height. If the only alterations in the stretch reflex are observed during a countermovement, assessing the stretch reflex with an isometric tendon tap would yield no results. Future studies that examine the electrical activity within the muscle during a countermovement may yield different results. Future studies should also measure the rate of the countermovement to determine if there are any differences following plyometric training.

The amount of time required to reach the peak force following a tendon tap increased significantly following plyometric training, which is also contradictory to the original hypothesis. These findings suggest that plyometric training actually increases the duration of the stretch reflex. By increasing the duration of the stretch reflex, the active muscles could produce force involuntarily over a longer period, therefore potentially adding to the force output over a longer period. Future studies should examine the effects a longer stretch reflex response may have on overall power and force production during a vertical jump to determine if this adaptation could lead to enhancements in vertical jump height.

Despite the best efforts of the research team, EMG data is inherently highly variable.[45] To account for the high degree of variability, a much larger sample size is necessary. Furthermore, the EMG device used in the current study had limited gain options which limited our ability to obtain EMG activity with a high resolution. Future studies with larger sample size and more technologically advanced EMG systems are required to determine if plyometric training has any effects on the patellar tendon tap reflex. Future studies should also examine the electrical activity present within the muscle during a countermovement and alterations in a subject's biomechanics.

Rates of force development and relaxation. The maximal voluntary isometric contraction and the rate of force development scaling factor did not improve significantly following plyometric training. This is contradictory to the original hypothesis. One potential reason for this is due to the specificity of training.[4, 16, 27] Plyometric exercise is very dynamic, and our isometric testing involved no movement. In a traditional weightlifting program, increases in maximal voluntary isometric contraction would be expected because it more closely relates to the task or the goal attempting to be achieved. Most commonly, the goal of a weight lifting program is to increase strength, as measured by a one repetition maximum or a maximal voluntary isometric contraction,[4, 16] however the goal of a plyometric training program is most commonly to increase power, as measured by vertical jump performance.[12, 32, 16] The effectiveness of a plyometric training program is not assessed by maximal voluntary isometric contraction strength, it is measured by an increase in vertical jump height performance. Another potential reason we did not find any statistically significant change in the rate of force development scaling factor is because a maximal vertical jump requires a maximal voluntary contraction as quickly as possible through a dynamic range of motion. In the current study, rate of force development and relaxation scaling factors were assessed across submaximal ranges isometrically. Future studies should examine maximal rate of force development dynamically using an isokinetic dynamometer following a plyometric training program to determine if there are any effects of plyometric training on the rate of force development.

The rate of force relaxation scaling factor improved following plyometric training, which is in line with the original hypothesis. To the knowledge of the research team there are no previous studies relating the rate of force relaxation with plyometric training. A high rate of force relaxation allows for greater torque production in movements that require quick and consecutive contractions between agonist and antagonist muscle groups (e.g. sprinting).[34] A higher rate of force relaxation may also indicate improved coordination between agonistic and antagonistic muscle groups as seen with resistance training.[4] By being able to limit antagonistic muscle activity, the agonists encounter less resistance and achieve greater efficiency which could lead to enhancements in vertical jump performance.[28]

Conclusion

Following plyometric training, subjects significantly increased vertical jump performance in the countermovement jump. This indicated that the program was a success and that the results stem from their training. The present study failed to show improvements in the electromechanical delay, the peak force, or the peak EMG values as represented by a percentage of the maximal voluntary isometric contraction obtained from the tendon tap trials. The only dependent variable assessed for the tendon tap with statistical significance was the time required to reach the peak force. Contrary to the original hypothesis the time to peak force during a tendon tap increased after completion of the plyometric training program. Despite being contradictory to the original hypothesis, a longer involuntary contraction could still increase force output potentially leading to enhancements in vertical jump performance, however, future studies are required to confirm this.

The maximal voluntary isometric contraction and the rate of force development scaling factor did not increase significantly following plyometric training. These results are in line with previous literature regarding the specificity of training.[4, 27, 16] Maximal vertical jump requires maximal rates of force development dynamically. The rate of force relaxation scaling factor was significantly increased suggesting better coordination between agonistic and antagonistic muscles leading to greater efficiency.[28]

Future studies are required to determine the effects plyometric training has, if any, on spinal reflexes. To the knowledge of the research team, no prior studies exist relating patellar tendon tap responses to plyometric training. The results from the current study brings the theory that plyometric training increases the stretch reflex response into question. A large sample size and more precise equipment is necessary to combat the large degree of variability in EMG recordings. Future studies should also examine the electrical activity within the muscle during a countermovement to determine if the only increases in the stretch reflex response are caused by biomechanical alterations. Alterations in biomechanics should be assessed in future studies as well to determine the extent, if any, that the learning effect accounts for the increases in vertical jump height witnessed following a plyometric training program. Finally, rates of force development and relaxation should be assessed dynamically and maximally in future studies to more closely resemble the goals of a plyometric training program.

Chapter 3

Conclusions and Future Works

The current study found no improvements in peak force, peak EMG activation, or the electromechanical delay between the initiation of the EMG and the initiation of the force curve in response to a patellar tendon tap following the completion of a six week plyometric training program. The only change regarding the patellar tendon tap was an increase in the amount of time required to reach the peak force after the stimulus was applied. The maximal voluntary isometric contraction and rate of force development scaling factor were not statistically significant; however, the rate of force relaxation was found to be significantly increased. Finally, countermovement jump height increased significantly while squat jump height did not. These results indicate that any differences in the stretch reflex are due to biomechanical alterations leading to an enhancement in the stretch reflex. Other potential explanations for the increases in vertical jump performance stem from the coordination between all the segments involved in the complex motion of jumping.[28]

Future studies should examine the rate of force development dynamically and maximally with an isokinetic dynamometer to determine if plyometric training has any effects on them. Future studies with more technologically advanced EMG systems that can obtain a larger sample size are necessary to account for the large degree of variability among EMG data to determine if plyometric exercise has any effect on reflexes. Future studies should examine the electrical activity within the muscle during the countermovement phase of jumping and measure the rate of descent to determine if alterations in coordination and biomechanics could result in an increase in the stretch reflex response following a plyometric intervention.

Finally, we believe that the main contributing factor to the success of plyometric training programs stems from practice and alterations in a participant's form. By practicing the act of jumping, individuals can achieve higher efficiency by better coordinating the agonist and antagonist muscles.[28] Future studies should examine the effects of a plyometric training program on subjects' biomechanics and form specifically in the rate of the countermovement phase.

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