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Effect of Plyometric Training on the Time-Course of Adaptations to the Elastic Properties of Tendons

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Chapter 1: Introduction

Background

Sports such as (basketball, baseball, swimming, track & field, hockey, and football) require dynamic, powerful, fast, and agile movements. To prepare athletes many training programs consist of various forms of jumps, hops, bounds, and shock movements to develop speed, power, and balance. This type of training has been termed plyometrics, which is now commonly used by athletes in an effort to increase performance.

The first to describe and organize the concept of plyometrics, in the literature, was a Soviet Jump coach (Verkhoshanski, 1966). The term plyometrics was first introduced in the United States by track and field coach by the name of Fred Wilt in 1975 (Wilt, 1975). The word plyometric is derived from the Greek word “pleythin,” which means to increase, while “metric” means to measure (Voight, & Dravovitch, 1991). While initially plyometrics training was used primarily for jumpers and throwers in track and field, this type of training is commonly used in any sport that requires quick powerful movements (Chu 1992; Boraczyński & Urniaż 2008; Lehnert, Lamrová, Elfmark 2009; Takahashi 1992).

Plyometrics takes advantage of the elastic properties of muscle and connective tissue, which allows the development of stored elastic energy during an eccentric phase and release of that energy during a concentric phase (Asmussen & Bonde-Peterson 1974; Cavagna 1977). The goal of plyometric training is to reduce the amount of time in the amortization phase, which is defined by the time interval between the eccentric phase and the concentric phase (Voight & Draovitch 1991). Plyometric training studies have demonstrated improvements in lower body power production (Bebi, Cresswell, Engel, & Nicoli 1987; Bobbert 1990; Potteiger., *et al.,* 1999;

Wilson, Newton, Murphy & Humphries 1993), upper body power production (Crowder, Jolly, Collins, & Johnson 1993; Schulte-edelmann, Davies, Kernozek, & Gernerbing 2005; Heiderscheit, Palmer-Mclean, & Davies 1996), vertical jump (Adams, O'Shea, O'Shea & Climstein 1992; Gehri, D., Ricard, M., Kleiner, D., & Kirkendall, D. 1998; Makaruk & Sacewicz 2010; Stemm & Jacobson 2007; Miller., *et al.*, 2007; Fatouros., et al., 2000), speed (Boraczyński & Urniaż 2008, Lehnert, Lamrová, Elfmark 2009; Miller 1980; Calloway 1978; Chu 1983) and agility (Matsudaira, Toyoda, & Saito 1974; Roper 1998). Plyometrics has reported to invoke specific neural adaptations, such as an increased activation of motor units, and less muscle hypertrophy than typically observed after heavy-resistance strength training (Hãkkinen, 1985; Hãkkinen, 1994; Sale, 1991).

Stretch Shorting Cycle

Success of plyometric training programs is attributed to the transfer force from an eccentric to a concentric phase, which facilitates greater overall force development and faster speeds of movement. Plyometric exercises begin with an eccentric phase, during which the target muscle lengthens as it contracts. The eccentric contraction elicits the start of what is known as the stretch shorting cycle (SSC). During the "stretch" portion of the SSC, the target muscle stores elastic energy as it is lengthen. If the performer can quickly transition from the stretch to the "shorting" portion of the SSC, then stored elastic energy can be added to the target muscle's force, and overall force production is greater. Furthermore, the onset of elastic energy applied at the start of the shortening results in faster speeds of contraction. (For a complete review, see Komi, 1984). There are two types of SSC's, a long and a short. The long SSC (e.g. to jump for a spike in volley ball) is characterized by large angular displacements in the hip, knee and ankle joints and by a time period of more than 250 ms. The short SSC (e.g. ground contact phases in a baseball player rounding the bases, a sprinter or high jumper) shows only small angular displacements and lasts between 100-250 ms (Schmidtbleicher 1986).

Mechanisms of the Stretch Shorting Cycle

The production of power in the short SSC is based on the interaction of several mechanisms. Power production in the SCC is fundamentally dependent on the innervations pattern structure and the state of the musclotendonus unit, in terms of their contractile and elastic capabilities (Komi, 1986). Before ground contact the extensor muscles are activated as part of the central motor program (Dietz *et al.,* 1981). The cross-bridges related are responsible for the short range elastic stiffness (SRES). This SRES reduces the lengthing of the muscle during the initial ground contact (Flintney & Hirst 1978a, b; Ford *et al.,* 1981). Segmental stretch activity, at the same time, serves to enhance muscle force (Nichols & Houk, 1976). This allows the majority of the elastic energy to be stored in the tendons of the main extensor muscles of the leg (Gollhofer et al., 1984). This allows for a powerful push off of the body, whereas neuronal activation of leg muscles during the concentric phase of the movement is low (Komi, 1985; Noth, 1985).

The stretch reflex also increases muscle force through propreoception (Nichols & Houk, 1976). Muscle spindles are proprioceptive organs that lay parallel to muscle fibers within muscles. Muscle spindles are stimulated by excessive stretch, and the amount of stretch that activates a muscle spindle in generally defined by the flexibility of an individual. A stimulated muscle spindle signals the body that the muscle in which it lies is being stretched to the limits of its range of motion where injury is more likely to occur. When stimulated, a two-fold protective response is initiated. One response occurs as the muscle spindle sends a reflexive signal to the muscle in which it lies (and to synergistic muscle) to initiate contraction in an effort to resist furth stretching. This known as autonomic facilitation (Gollhofer *et al.*, 1994).

It has been theorized that during maximal voluntary contractions, a small percentage of muscle fibers (~10%) are not activated (as a protective mechanism), and some of these inactivated fibers can be activated through reflexive action (autonomic facilitation)(REF). The result is a greater number of muscle fibers contributing to force production that can be reached through voluntary contraction alone. With an effective plyometric countermovement inducing stretch in targeted muscle, additional force from proprioceptively recruited muscle fibers can be applied during concentric phase of the SSC.

The second response to muscle spindle activation occurs as a reflexive signal to antagonistic muscles to inhibit contraction, thereby inhibiting further stretching. This is known as reciprocal inhibition. The combination of autonomic facilitation and reciprocal inhibition attempts to protect the muscle from lengthing to the point of injury. It can be suggested that reciprocal inhibition may end activation of antagonist muscles earler than when under exclusive voluntary control. As a result, the transition during the SSC (i.e., the amortization phase) can be more efficient, and more energy is conserved for the concentric phase (Komi, 1991). (For a complete review of muscle spindle activation and response, see Komi, 1992)

The third mechanism in the production of power in the SSC is the development of stored elastic energy. If the performer can take advantage of the amortization phase and quickly transition from the “stretch” to the “shorting” portion of the SSC, then stored elastic energy will be added to the combined muscle force. In plyometrics a counter movement is used to elicit the SSC. Through a plyometric program, the performer is trained to reduce time in the amortization phase and transfer force from an eccentric to a concentric phase. This counter movement facilitates greater overall force development and faster speeds of movement.

The production of power's quality of power production in the SSC depends essentially on the training state of the tendomuscular system in terms of their contractile and elastic abilities (Komi, 1988; Schmidtbleicher et al., 1988). It can also be concluded that power and maximal strength are not separate entities; that have a direct relationship with each other. For power correlation between maximal strength and power is considered low (Schmidtbleicher, 1991).

Plyometric exercises begin with an eccentric phase during which the target muscle eccentrically contracts. The eccentric contraction, in which the contracting muscle lengthens, elicits the stretch shorting cycle (SSC) (Voight & Draovitch 1991).   During the segmental stretch reflex portion of the SSC, the target muscle lengthens will store elastic energy for a short period of time.

The SSC's purpose is to the make the concentric phase of the final action, more powerful than the concentric phase alone. (Norman & Komi, 1979; Komi, 1984). The stretch reflex components are counted on to play a vital role in situations where stretching loads are high or efficient stretch-shorting behavior is necessary. Under these circumstances muscle stiffness is required to be well coordinated to uphold external loading conditions. Check this out.

Typical Plyometric Programs

A program's general goal should reflect the training for a particular period; respect basic training principles, use a progressive increase in intensity, and use the principle of specificity. It is equally important to take into consideration condition, competitions, experience, and combination with other exercises (Lehnert, Lamrova, & Elfmark, 2009).

Lehnert, Lamrová, & Elfmark investigated the changes in speed and strength of female volleyball players. The group used an 8 week study with volleyball players age of 14.8 and height of 169cm. The types of plyometric exercises that were performed were push-offs, hops, jumps, lateral movements (e.g. zig zags). The tests used were the standing vertical jump (the second was the vertical jump with approach and speed was measured by the shuttle run (Miller *et al.*, 1998). The study indicated that all three areas showed improvements in speed and strength after the eight week training program. (Lehnert, Lamrová, & Elfmark, 2009)

Burgess, Connick, Graham-Smith, & Pearson investigated the difference between plyometric vs. isometric training and muscle output. The subjects were of men with the average of 23 and average height of 179 cm. The exercises were used were a maximal straight-legged concentric jump; an isometric plantar flexion, and a graded isometric planter flexion. The study indicated that both plyometric and isometric training increase the muscles rate of force development. (Burgess, Connick, Graham-Smith, Pearson, 2007)

Grosset, Piscione, Lambertz, and Pérot researched the electromechanical delay and musculo-tendinous stiffness after endurance or plyometric training. The subjects were composed of nine sedentary college students (six males & three females) who underwent plyometric training. The exercises started with a dynamic warm-up (e.g. hoping, jogging, zig zags, etc…), the subjects then did drop jumps, and vertical jumps with tense legs. The investigators used EMG, a stimulating apparatus, and vertical jump for pre and post test measures. The study suggests that plyometric training increased in both jumping activities but changes were found in MAV before and after 10 weeks of training. The study showed an increase in peak twitch performance for the plyometric group as well as the rate of torque development. (Grosset, Piscione, Lambertz & Pérot 2009)

Makaruk & Sacewicz 2010 investigated the effect of plyometric exercise performed with minimum ground contact time on the maximal power output on the legs and jumping ability. The subjects consisted of 44 untrained adults split into a plyometric and control group. The exercises consisted of a series of jumps, hops, and counter movements. Test consisted of two of vertical jumps done on a force platform, and five hop jump test.The data collected was done three days before the start and three days after the program finished. The study indicates that the plyometric training group significantly improved their maximal power output (Makaruk & Sacewicz 2010).

Boraczyński & Urniaż investigated the effect of plyometric training on the strength and speed abilities of basketball players. The subjects did plyometric exercises with benches, vaulting boxes, hurdles, weighted belts and medicine balls. The series consisted of 6-12 repetitions of the exercise. The study indicated that the improvements in the strength and speed abilities in the subjects.

Mechanisms of Neural Adaption

Strength training causes changes within the nervous system that allow a trainee to more fully activate prime movers in specific movements and to better coordinate the activation of all relevant muscles, thereby affecting a greater net force in the intended direction of movement. These changes in the nervous system may also allow force to be developed more rapidly and peak force to be maintained longer the training-induced changes with the nervous system are referred to as neural adaptations. Electromyography (EMG) studies have provided the most direct assessment of neural adaptations to training. An increase in the quality of recorded EMG (Integrated EMG, IEMG) typically indicates that more motor units were recruited, or that some combination, of the two adaptations has occurred (Sale, 1991). IEMG analysis has also indicated neural adaptations to high stretch loads, typically seen in plyometric exercise (Schmidtbleicher & Gollhofer 1982). The mechanisms of neural adaptation may include increased activation of prime mover in specific movement, and appropriate changes in activation of synergist and antagonists. The latter mechanism would be express as improved skill coordination (Rutherford & Jones 1986).

Purpose of This Study

The vast majority of the literature involving plyometric training has focused on muscles and their adaptations. Numerous training studies have demonstrated improvements in muscle power; additional studies have addressed neurological adaptations. A widely accepted time-course model of neuromuscular adaptations has been presented by Sale (1988). The Sale model suggests Explaintion of sale model. However, there is little information regarding the time-course adaptations of the elastic properties of tendons. The purpose of this study is to investigate the effect of plyometric training on the time-course of adaptations to the elastic properties of tendons.

Chapter 2: Literature Review

A programs general goal should reflect the training for a particular period, respect basic training principles use a progressive increase in intensity, and use the principle of specificity. It is equally important to take into consideration condition, competitions, experience, and combination with other exercises (Lehnert, Lamrova, & Elfmark, 2009).

Lehnert, Lamrová, & Elfmark used an 8 week training program to study the changes in speed and strength in female volleyball players. The athletes completed a three-month preparatory training program to focus on general strength. The training sessions occurred twice a week and each started out with a warm-up and a 2 minute resting period was giving between exercises. In the first two weeks the athletes did 4 different exercises alternating push offs, two foot ankle hop, Front barrier hop, and Spike jump at the volley ball net. The next four weeks the athletes did zigzag double leg jumps, tuck jumps, lateral box jumps, single foot side to side ankle hop over medicine ball. The last 2 weeks the athletes lateral medicine ball hops with a 180 degree turn, front barrier hops back and forth, block jumps, alternate bounding with single arm action. To determine whether or not the athletes experienced any gains in speed and strength, three different types of tests were used throughout the training program. The first test was the standing vertical jump (measured in cm) the second was the vertical jump with approach (also measured in cm) and speed was measured by the shuttle run for 6 x 6m (measured in seconds) (Ejem, 1998; Kouba, 1998). The study showed that all three areas showed improvements in speed and strength after the eight week training program as demonstrated by the gains the three tests. (Lehnert, Lamrová, & Elfmark, 2009)

Burgess, Connick, Graham-Smith, & Pearson did a study to try and determine the difference between plyometric vs. isometric training on tendon properties and muscle output. They used a group of men with the average being 23 and were put through either a plyometric program or an isometric program. Each subject did not undergo any additional training while participating in the study and went through a screening to investigate any evidence of lower limb injuries. The plyometric regimen consisted of repetitions of maximal one-legged straight-legged drop jump. The training volume was progressively increased over the 6-week period, from 2 sessions a week to 3 sessions a week consisting of 4 sets of 20 repetitions in the final week. Each participant did several submaximal repetitions to warm-up. The subjects were tested before and after the 6-week training period, and were described the protocol. The follow exercises were used to test each subject (1) a maximal straight-legged concentric jump; (2) an explosive maximal isometric plantar flexion, and (3) a graded isometric planter flexion used in the determination of tendon stiffness. The subjects were adequately warmed up by performing several submaximal trials of the tests. The results showed that there was no significant deference between, the programs isometric training and the plyometric training programs in the stiffness of the gastrocnemius tendon. The results for concentric jump height showed a trend toward significance in isometric training; however a significant difference was found in the plyometric jump from the pre to post testing. Both the plyometric and the isometric group showed improvements in their rate of force development, but they were minor gains. This study provides evidence that through excise tendons may stiffing, however never plyometric or isometric training was proving to be better than the other. (Burgess, Connick, Graham-Smith, Pearson, 2007)

Grosset, Piscione, Lambertz, and Pérot researched the electromechanical delay and musculo-tendinous stiffness after endurance or plyometric training. The subjects were composed of nine sedentary college students (six males & three females) who underwent plyometric training. The second group consisted of 21 sedentary college students (14 males and 7 females) who underwent endurance training. Anthropometric parameters were measured before training that included the calf circumference, height and body mass. The plyometric training program was comprised of 20 sessions performed twice a week for 10 weeks. A session of plyometric training was divided in two parts: a warm up and training. Every participant underwent a 25 minute dynamic warm-up, including jogging, jumping rope, bounding zigzag, bounding run, lateral jumps, single leg bounding and frog jumps, as well as stretching at the start of each session. The plyometric program consisted of drop jumps (height 70 cm; 4-9 sets of 8 repeats) and vertical jumps with tense legs (4-9 sets of 10-20 repeats) with hands on the hips to isolate leg work. Progressive overload principles were incorporated into the program by increasing the number of sets of each exercise. The subjects were instructed to perform all jumps at maximal effort with minimal ground contact in between reps. The endurance training lasted 10 weeks with two training sessions. Maximal aerobic velocity (MAV) was assessed three times during the endurance training using the "Université de Montreal track test" (Leger & Boucher 1980) before training, after 5 weeks of training and after 10 weeks of training. These MAV data were also used to adapt the training, based on the improvement in the subject's MAV after the preceding 5 weeks of training. The subjects ran for 45 min continuously at a speed corresponding to 70% of their MAV for the first for the first 5 weeks of training. During the second 5 weeks, they underwent interval training on synthetic track. This training consisted of alternately running at 100 and 50% of MAV (30-s each) until exhaustion (Billat et al. 200). The tests were performed using an ankle ergometer. The function used in this study was: isometric torque measurements and quick release tests. The erogmeter had two main parts: an electronic device and a mechanical device. The EMG recording was Bipolar surface electrodes and they were placed over the belly of the gastrocnemius muscles on the Achilles tendon for the soleus. The ground electrode was placed over the tibia. The skin was rubbed with an abrasive past and cleaned with alcohol to reduce the inter-electrode impedance to approximately 5 kΩ. A constant current stimulator delivered single electrical pulses to the posterior tibial nerve. The cathode was placed on the distal part of the thigh, proximal to the patella. These two electrodes were covered with electrolyte gel to insure a good electrical contact with the skin. The intensity of the pulses was adjusted to give maximal motor direct response, M-wave, on each part of the TS and mechanical twitch of the muscle group. EMGs and mechanical signals were sent to the analogue/digital board and stored for further signal processing. Each subject sat on an armchair that could be adjusted vertically and horizontally. The left foot was firmly held in a sports shoe (same for all subjects) which was fixed to the footplate of the actuator. The ankle rotation axis corresponded with the rotation axis of the actuator. The knee was extended to 120° and the ankle was placed at 90°. Five maximal stimulations were given at rest and the corresponding M-waves and twitches of the TS were stored and later averaged. Then, a maximal voluntary contractions (MVC), corresponding to maximal isometric plantar flexions torque, was developed as fast as possible ad maintained for 3 s. This was repeated three times, with 2 min rest after each trial. The best of the three attempts gave the MVC for that day's session. For both groups the quick-release movements were achieved from the neutral position by a sudden release of the footplate while the subject maintained a submaximal voluntary isometric torque in planter flexion. Three attempts were performed at 20, 40, 60 and 80% MVC, in a random order. The field for both groups was performed on an athletic track after the respective endurance or plyometric training. Two maximal jumping activities were performed a vertical jump and five bounding jumps and the subjects were given three attempts to perform and the best attempt was taken. The study suggests that plyometric training increased in both jumping activities but changes were found in MAV before and after 10 weeks of training. The study showed an increase in peak twitch performance for the plyometric group as well as the rate of torque development. The plyometric training program showed a significant increase in the electromechanical delay, while the endurance program showed a decline. Musculo-tendinous stiffness was just the opposite and increased in endurance training while showing a decrease in plyometric training (Grosset, (Grosset, Piscione, Lambertz & Pérot 2009)

A study on the effects of plyometric training on maximal power output and jumping ability was done by (Makaruk & Sacewicz 2010). The purpose of the study was determine the effect of plyometric exercise performed with minimum ground contact time on the maximal power output on the legs and jumping ability. The study was comprised of 44 non-training college aged students the subjects were randomly split into two groups; plyometric and control. The experimental group performed plyometric twice a week for six weeks. The plyometric exercises that the participants did as shown in the picture above. Each session commenced with a 5-min run of low intensity, followed by five minutes of stretching exercises. During the session subjects were instructed to perform jumps as quickly as possible with the minimum ground contract time. After each rebound the legs were to be straightened in the hip, knee and ankle joints. The feet during jumps were set slightly outwards and the jumps were performed on the synthetic surface. During the exercises no subject complained of muscle or joint pains. The plyometric training program is as follows. For testing the researchers used a vertical jump test with a force platform with the sampling frequency of 1000Hz. Two types of vertical jumps were measured: counter movement jump (CMJ) and depth jump (DJ) with the drop box height of .31m. The subjects were to achieve maximal height in CMJ and DJ after a rebound. They each performed three trials and the best was taken for data collection. The five-hop test the subjects stood approximately 10-11 meters away from a sand pit. Each subject performed 5 consecutive jumps:

Table 2. Plyometric training program

Week	Plyometric training program number of sets × number of rebounds
1–2	Standing vertical hops 2 × 10 Single foot hops 4 × 8 Multiple two-foot hurdle jumps (hurdle height 0.55 m) 6 × 6 Counter movement jumps 3 × 5 Depth jumps (drop box height 0.20 m) 3 × 6
3–4	Lateral two-foot jumps 2 × 10 Two-foot jumps 4 × 8 Counter movement jumps 3 × 5 Multiple two-foot hurdle jumps (hurdle height 0.65 m) 6 × 6 Depth jumps (drop box height 0.30 m) 3 × 6
5–6	Two-foot jumps forward and backward: 2 × 10 Single foot jumps 2 × 8 on each foot Counter movement jumps 3 × 5 Multiple two-foot hurdle jumps (hurdle height 0.76 m) 6 × 6 Depth jumps (drop box height 0.40 m) 3 × 6

a two-foot push off four consecutive single alternate leg jumps and two-feet landing in the sandpit. The longest distance was taken of three trials for data collection. The data was taken three days before the programs start and three days after its completion. The data collected showed that the plyometric training group significantly improved their maximal power output in the both the DJ and 5-hop test (Makaruk & Sacewicz 2010).

Boraczyński & Urniaż did a study that aimed to assess the effect of plyometric training on the strength and speed abilities of basketball players. The players did an 8 week program over which they had 25 sessions. The subjects did plyometric exercises with benches, vaulting boxes, hurdles, weighted belts and medicine balls. The series consisted of 6-12 repetitions of the exercise. This program of plyometric training was based on the guidelines drawn up by (Radcliffe & Farentinos 1999) the table below shows how the program was run.

Table 2. The general characteristics of the 8-week training period of basketball players (n=14)

Week	Number of trainings	Technique tactics	General endurance	Specific endurance	Global strength	Plyometric training
1	10		4	2	4	
2	12	4	3	2	3	3
3	12	7	3	3	3	4
4	11	8	3	3	3	4
5	12	9	3	3	3	4
6	10	8	2	2	2	4
7	9	7	2	2	2	3
8	8	6	2	2	1	3
Total	84	49	22	19	21	25

The study concluded that the improvements in the strength and speed abilities is a proof of the effectiveness of the implemented training program as well as justifying the application of CMJ jumps in assessment of the effects of training of special strength-speed abilities of basketball players.

These types of training programs have been shown to produce improvements in performance attributes, may also come at a risk of injury. The chance of injury generally occurs due to preexisting injury, poorly trained participants, being exposed to a new exercise routine especially, eccentric activities, and the increased production of force in the musculoskeletal system which can create delayed-onset muscle soreness. (Miller, Berry, Bullard, & Gilders, 2002)

In comparing plyometric drop jumps and eccentric and concentric resistance exercises, it has been reported that drop jumps and eccentric exercises produce significantly greater muscle soreness than concentric exercises. (Stemm, & Jacobson, 2007).

Chapter 3: Methods

A group of approximately 30 college-age males will be asked to participate in this study. The testing procedure will be explained prior to receiving each subject's written informed consent in accordance with The College at Brockport Institutional Review Board standards. A physical activity questionnaire and a Medical Par-Q see Appendix A and B will be given. Applicants will be excluded who are unable to walk unassisted with normal gait, who have or have had severe or acute lower limb injuries with the past 2 years, or who have any lower extremity pathology.

Subjects will be seated in a chair with a hip and knee at 90^o angles and with their feet above the ground. The arms will be in full extension at the shoulder and elbow, and subjects will be told to grasp the lateral edges underneath the seat. An ankle strap will be connected to a chain with an in-line load cell attached to the distal end of the non-dominant lower leg to measure tensile forces to indicate mechanical force generation (muscular force application to the segment). Subjects will perform several trials consisting of a rapid, maximal, isometric contraction of the knee extensors of the non-dominant leg.

In the fractionated reaction time paradigm that will be used in the study, EMD_T is analogous to motor time. Following a variable foreperiod of 1-3 seconds beginning with the auditory command “ready,” subjects will receive a visual stimulus. The visual stimulus will be the illumination of a diode (LED). The LED will be positioned directly in front of each subject at approximately eye level. Subjects will be instructed not to anticipate the stimulus, to relax until it is perceived, and then to maximally contract the knee extensor in an explosive knee extension type of movement. In addition, subjects will be instructed to immediately relax after maximal muscular force is achieved such that there was no sustained contraction. Care will be taken to isolate the knee extension and to eliminate any unwanted motion (i.e., pivoting at the foot, twisting at the trunk).

Prior to commencement of data trials, subjects will be allowed to practice trials until they are competent with the task and their reaction times and force curves (peaks) were consistent. Visual examination of IEMG and force graphs (as a function of time) will be used to determine successful practice trials and provide visual feedback to the subjects. In addition, RT, $P_{IEMG,}$ and P during practice will be examined for consistency. Practice will be continued until reliable results are demonstrated (within two standard deviations from the mean values of successive practice trials), and mean values will be used as criterion to determine if data trials were successful. During data trials, if the movement does not meet experimental criteria established during practice, the trial will be repeated. Values within two standards deviations of the criteria will be accepted. In order to calculate and evaluate performance variables measured in practices and during data collection, a Visual Basic programming code will be developed such that each trial can be processed immediately after completion and prior to the next trial. The interval during practice and data trials should be no less than two minutes. Average values for three successful data trails should be no less than two minutes. Average values for three successful data trials will be included in the data set.

Surface EMG will be recorded from the vastus lateralis of the non-dominant leg using bipolar, 1-cm diameter, and silver/silver-chloride electrodes with an interelectrode distance of 1.5 cm. An additional electrode (ground) will be positioned on the lateral malleolus of the opposite leg. Electrodes will be aligned with the longitudinal axis of the muscle fibers at a point located one handbreadth (using the subject's hand) proximal to the superior, lateral corner of the patella with the knee fully extended (Delagi, Perotto, Iazzetti, & Morrison, 1981). Before applying the electrodes, all hair will be removed, and the skin lightly abraded and washed with alcohol to minimize resistance. Surface EMG waveforms will be amplified and integrated by a LaFayette amplifier with a 60 Hz notch filter. Stimulus onset IEMG, and force onset data will be recorded by an IMB compatible computer after analog-to digital conversion at a sampling rate of 2000 Hz.

Muscle activation (IEMG) and segmental acceleration (force) will be identified when the respective signals exceeded mean baseline values plus 4 standard deviations (established during the foreperiod with no less than 200 samples), thereby reducing the effect of system noise (Grabiner, 1986). Using this convention, the following temporal parameters (expressed in milliseconds) were determined: reaction time (RT), $EMD_{T,}$ time to peak IEMG (TP_{IEMG}), and time to peak force (TP_F). IEMG analysis allowed for determination of peak IEMG (P_{IEMG}) of initial muscle burst and $EMD_{IEMG,}$ which represented the total energy of the muscle burst that was observed during the EMD. EMD_{IEMG} was expressed as a percentage of $P_{IEMG.}$ A load cell positioned in-line with the cable attached to an ankle strap will determine peak force (P_F) of the initial burst.

To examine neuromuscular activation, IEMG values (V*s) will be expressed in volts (V) by dividing the IEMG value by its associated time interval ([IEMG during EMD]/[EMD_T] and [P_{IEMG}] / [TP_{IEMG}]). This normalization technique will be used to control for within and between subject variance (Grabiner, 1986). The final value of EMD_{IEMG} will be calculated by dividing the normalized IEMG during the EMD by the normalized peak IEMG of the initial neuromuscular burst and expressed as a percentage.

To predict force generation during the EMD, linear regression analysis will be used to determine the relationship between IEMG and mechanical force. Using the model, the y-intercept (F_{pred}) was calculated for each subject. Regression equations for the subjects will be in the form of: $y = ax + b$; where y = force (predicted), a =slope of the function, x = IEMG (observed), and b = the y-intercept. Data for the regression equation will enter beginning from the onset of force production and ending at P_{IEMG}, which represented mechanical (observable force output associated with neuromuscular activation. Since the onset of mechanical force production identifies the end of the EMD, force generated during the EMD must be inferred. Therefore, linear extrapolation of the regression equation will be necessary to predict force generated during the EMD (F_{pred}) that is required to stretch the tendon to its load-dependent length.

Since the end of the EMD is defined by the onset of mechanical force output that is reflected in segmental acceleration, the regression equation is such that the IEMG value at the end of the EMD predicts a force value of zero. This reflects the nature of the relationship between IEMG and observable (mechanical) force. However, muscular force (tension) production begins with the onset of neuromuscular activity that denies the beginning of the

EMD. Using techniques of extrapolation, the IEMG-mechanical force relationship was used to determine muscular force production during the EMD.

Training

The plyometric exercise training program will consist of 12 sessions performed twice a week for 10 weeks. A session of plyometric training will be divided in two parts: warm up and training. All subjects will undergo a 20 minutes dynamic warm-up consisting of jogging, skipping rope, bounding run, zigzag bounding run, lateral jumps, single leg bounding and fog jumps, as well as stretching at the start of each session. The training session will consist of drop jumps (height 70 cm; 4-9 sets of 8 repetitions) and vertical jumps with tense legs (4-9 sets of 10-20 repetitions) with hands on the hips to isolate leg work. Progressive overload principles will be incorporated into the program by increasing the number of sets of each exercise. The subjects will be instructed to perform all jumps at maximal effort (maximal height or amplitude and minimal ground contact time. (Grosset, Piscione, Lambertz, and Pérot 2008)

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