NEUROMUSCULAR CHARACTERISTICS OF DROP AND HURDLE JUMPS WITH DIFFERENT TYPES OF LANDINGS

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Neuromuscular characteristics of drop and hurdle jumps with different types of landings

by

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Chapter 1 - Introduction

1.1 Background of the study

Plyometric exercises combine speed and strength to produce an explosive-reactive movement (Debnam, 2007) involving eccentric and concentric muscle contractions (stretch-shortening cycle) generally using the body as an overload stress (Schmidtbleicher, 1992; Cormie et al, 2011a). These exercises use the accumulated elastic energy during the eccentric phase of the contraction (Komi and Bosco, 1978a). Furthermore the rapid stretch shortening cycle plyometric activity is purported to cause an excitation of the muscle reflexes (Komi and Gollhofer, 1997). These exercises are utilized to increase the velocity of other specific sport movements such as change of direction, jumps, running and sprinting to increase the possibility of athletic success. There are a great number of plyometric exercises, however less is known about quantifying drill intensity and the optimal technique for an effective training program (Ebben et al, 2008).

Frequently plyometric actions are characterized as ballistic or explosive movements. Plyometric activities can include drop jumps, hops, bounding, countermovement jumps (CMJ) and other activities. These various activities may involve different movement speeds, EMG activity, rate of force development, ground contact times, leg stiffness and reaction forces. All these variables can generate different short or long-term training adaptations.

Generally a power training programs can use a great variety of plyometric exercises which can exceed 20 a year (Miller et al, 2006). It is important to know which exercises have the greatest power output or what landing technique must be used to induce changes in specific sport actions.

To classify explosive-ballistic actions, Schmidtbleicher defined two types of stretch shortening cycle (SSC) actions (Schmidtbleicher, 1992). A movement performed with a contact time below 250 ms was classified as a short SSC and above 250 ms was considered a long SSC. Generally coaches utilize jump drill training with a short contact time and maximal height or maximal movement velocity to induce changes in muscular power performance (Young et al, 2000; Young et al, 2001; Flanagan and Comyns, 2009; Bobbert et al, 1987a; Chelly et al, 2010; Ronnestad et al, 2008; Mcbride et al, 2002). Some examples of short SSC are jumps over low to moderately high obstacles, sprinting, lateral hopping or drop jumps from low drop heights.

Furthermore training drills have been classified into categories such as jump in place (e.g. CMJ, squat jump and knee tuck jumps), standing jumps (e.g. standing broad jumps, jumps over hurdles, single leg jump), multiple hops (e.g. hurdle jumps, ankle jumps, triple jumps), bounds, box drills and drop jumps (DJ) (Cissik, 2009; Potach and Chu, 2008). All these jumps can be developed in different directions, with one or two legs at maximal or submaximal efforts. None of these classifications include information on landing technique during plyometric drills even though when there is information about foot landing and power production (Mero and Komi, 1994b; Bobbert et al, 1987a; Kovacs et al, 1999).

Bobbert et al (1987a) showed that when a drop jump was performed with a rebound technique (using just the fore foot) the force generated was higher (4099 N) than a drop jump with a slow countermovement technique (2649 N) or a traditional countermovement jump using the whole sole to land (2094 N).

Accordingly, an optimal explosive-ballistic training exercise is a movement that uses similar contact time and force production as the specific sport actions. In sports like soccer, tennis, rugby and others these actions are: maximal sprinting, running, change of directions, rapid decelerations, run-up and jump and jumping from a stationary position. With plyometric techniques coaches' attempt to increase plyometric performance (i.e. increase explosive power, higher jump height, shorter contact periods) for sport specificity. In training science this principle is called training specificity and the concept states that athletes must train similarly to the competitive environment (Behm and Sale, 1993).

An important aspect during plyometric training is technique. It has been shown that a change of technique when performing drop jumps and hopping alters many kinematic and kinetics variables (Bobbert et al, 1987b; Kovacs et al, 1999; Young et al, 1995; Young et al, 1995; Arampatzis et al, 2001a; Farley and Gonzalez, 1996).

Jumps over obstacles are one of the most common types of plyometric drills used to increase power (Viitasalo et al, 1993; Ruben et al, 2010; Ronnestad et al, 2008; Aura and Viitasalo, 1989). However, it is not known if a change of technique can generate changes in other variables. Maybe it is possible with a simple technique instruction to positively modify training quality or specificity.

During jumps, athletes can use different parts of the foot. For example in a CMJ the athlete is well balanced on his/her entire foot and this position is maintained during the entire eccentric and the initial concentric phase of the contraction. Nonetheless in successive jumps over hurdles, the athlete can land with the entire foot, sometimes called flat foot or can just land with the fore foot similar to hopping. These two specific landing techniques were used in previously published papers (Young et al, 1995; Bobbert et al, 1987a; Kovacs et al, 1999). When the authors refer to a bouncing technique, the athlete lands on the fore foot, attempting to change the direction of the force while minimizing contact time. The other technique called slow countermovement refers to a heel-toe landing sometimes called a flat foot landing, increasing the knee angle in order to provide a greater emphasis on quadriceps force production. This technique allows the athlete to reach more height during the drop jump (52 vs 48 cm in Bobbert paper). The EMG activity of the vastus medialis, gastrocnemius and soleus was higher in both drop jump techniques when compared with traditional CMJ. However it is important to mention that the drop height used by Bobbert was relatively low (20 cm). This height is lower than most other studies: 50 cm (Leukel et al, 2011), 30-45-60-75 cm (Young et al, 2000), 12-24-36-48-60-72-84 cm (Barr and Nolte, 2011) or the recommended training height (Verkhoshansky and Siff, 2006; Schmidtbleicher, 1992). Controversies regarding results derived from drop jumps may be attributed to the great variety of drop jump heights.

Based on the aforementioned, many questions regarding jump landing remain unknown. These include:

Aare particular landing styles more appropriate to develop muscular power?

Is a flat foot landing an appropriate training technique for sports that involve short contact periods and repetitive high speed rhythmical motions like sprinting?

Are continuous hurdle jumps with short contact times a proper technique to optimize strength or power?

Thus, the main objective of this thesis was to compare the neuromuscular characteristics of two types of jumps: hurdle and drop jumps. In addition 3 types of landing techniques were investigated: preferred, flat foot and fore foot technique.

1.2 Significance of study

There is a great number of plyometric exercises, however actually, little is known about plyometric drills, especially with respect to quantifying the drill intensity and how is the best form to introduce it into an optimal training program that increase performance (Ebben et al, 2008).

If a coach develops training programs to improve specific sport movement velocity, it should to analyze the biomechanics of these movements. For example, during a forward sprint, the horizontal force is very important in achieving a high speed (Brughelli et al, 2011; Lockie et al, 2011). Horizontal force increases 24 % when maximal speed increase from 80 to 100% meanwhile vertical force just increases 2 % (Brughelli et al, 2011). However not all plyometric exercises generate a good level of horizontal force (Mero and Komi, 1994a). During CMJ the horizontal force is too low and this characteristic have a low level of specificity.

It is well proved that a change of technique when performing drop jumps changes a lot of different kinematic and kinetic variables (Young et al, 1995;

Bobbert et al, 1987a; Kovacs et al, 1999; Arampatzis et al, 2001b). This was proved during hopping too (Farley and Gonzalez, 1996). Mainly muscular power and rate of force development is affected.

Coaches can use the knowledge of which type of jumps are more powerful to optimize training. Thus, coaches might use the exercises that have a major specificity during competition or in the cases of the university sport ruled as the NCAA where it has a limited training time. However, as it was said before there is limited information about plyometric drills and its kinematics and kinetics variables.

1.3 Definitions

Plyometric: exercises characterized by rapid stretch-shortening cycle (SSC) muscle actions (Potach and Chu, 2008).

Ballistic movement: action that circumvents the deceleration phase by requiring athletes to accelerate throughout the entire range of motion to the point of projection (takeoff or release) (Cormie et al, 2011b).

Drop or depth jump: jump performed after dropping from a height using the mass of the athlete as a resistive force (Wilt, 1978; Potach and Chu, 2008; Komi and Bosco, 1978b).

Hurdle jump: jump performed over an obstacle, specifically a hurdle. Typically hurdle jumps drills use several obstacles in order to provide a repetitive stimulus.

Rate of force development: the rate of rise in contractile force at the onset of contraction (Aagaard et al, 2002). It is generally calculated as the slope in the force time curve (Delta force / Delta time).

Leg Stiffness: the relationship between the deformation of an object with a specific level of force. Stiffness can be measured in different ways. This concept can be applied to a microscope structure like muscle fiber or to a macroscopic structure like human leg. Stiffness is often defined as the resistance of an object or a body to a change in length (McMahon and Cheng, 1990).

Flat foot jump: landing technique which uses the entire sole of the foot to strike the ground.

Fore foot jump: landing type technique which uses the fore foot to strike the ground.

1.4 Bibliography

Reference List

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002). Increased rate of force dvelopment and neural drive of human skeletal muscle following resistance training. *J Appl Physiol, 93,* 1318-1326.

Arampatzis, A., Schade, F., Walsh, M., & Bruggemann, G. P. (2001a). Influence of leg stiffness and its effect on myodynamic jumping performance. *J Electromyogr.Kinesiol., 11,* 355-364.

Arampatzis, A., Schade, F., Walsh, M., & Bruggemann, G. P. (2001b). Influence of leg stiffness and its effect on myodynamic jumping performance. *J Electromyogr.Kinesiol., 11,* 355-364.

Aura O & Viitasalo J (1989). Biomechanical characteristics of jumping. *Int J Sport Biomech, 1989,* 89-98.

Barr, M. J. & Nolte, V. W. (2011). Which measure of drop jump performance best predicts sprinting speed? *J Strength Cond.Res., 25,* 1976-1982.

Behm, D. G. & Sale, D. G. (1993). Velocity specificity of resistance training. *Sports Med., 15,* 374-388.

Bobbert, M. F., Huijing, P. A., & van Ingen Schenau, G. J. (1987a). Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. *Med.Sci.Sports Exerc., 19,* 332-338.

Bobbert, M. F., Huijing, P. A., & van Ingen Schenau, G. J. (1987b). Drop jumping. II. The influence of dropping height on the biomechanics of drop jumping. *Med.Sci.Sports Exerc., 19,* 339-346.

Brughelli, M., Cronin, J., & Chaouachi, A. (2011). Effects of running velocity on running kinetics and kinematics. *J Strength Cond.Res., 25,* 933-939.

Chelly, M. S., Ghenem, M. A., Abid, K., Hermassi, S., Tabka, Z., & Shephard, R. J. (2010). Effects of in-season short-term plyometric training program on leg power, jump- and sprint performance of soccer players. *J Strength Cond.Res., 24,* 2670-2676.

Cissik J (2009). Plyometrics fundamentals. *NSCA Performance Training Journal, Volume 3 Number 2,* 9-13.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2011a). Developing maximal neuromuscular power: part 2 - training considerations for improving maximal power production. *Sports Med., 41,* 125-146.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2011b). Developing maximal neuromuscular power: part 2 - training considerations for improving maximal power production. *Sports Med., 41,* 125-146.

Debnam M (2007). Plyometric training. *Modern athlete and coach, 45,* 5.

Ebben, W. P., Simenz, C., & Jensen, R. L. (2008). Evaluation of plyometric intensity using electromyography. *J.Strength Cond.Res., 22,* 861-868.

Farley, C. T. & Gonzalez, O. (1996). Leg stiffness and stride frequency in human running. *J.Biomech., 29,* 181-186.

Flanagan E & Comyns T (2009). The use of contact time and the reactive strength index to optimize fast stretch-shortening cycle training. *Strength Cond, 30,* 32-38.

Komi P & Gollhofer, A. (1997). Stretch reflexes can have an important role in force enhacement during SSC exercise. *J Appl Biomech, 13,* 451-460.

Komi, P. V. & Bosco, C. (1978a). Utilization of stored elastic energy in leg extensor muscles by men and women. *Med.Sci.Sports, 10,* 261-265.

Komi, P. V. & Bosco, C. (1978b). Utilization of stored elastic energy in leg extensor muscles by men and women. *Med.Sci.Sports, 10,* 261-265.

Kovacs, I., Tihanyi, J., Devita, P., Racz, L., Barrier, J., & Hortobagyi, T. (1999). Foot placement modifies kinematics and kinetics during drop jumping. *Med.Sci.Sports Exerc., 31,* 708-716.

Leukel, C., Taube, W., Lorch, M., & Gollhofer, A. (2011). Changes in predictive motor control in drop-jumps based on uncertainties in task execution. *Hum.Mov Sci.*.

Lockie, R. G., Murphy, A. J., Knight, T. J., & de Jonge, X. A. (2011). Factors that differentiate acceleration ability in field sport athletes. *J Strength Cond.Res., 25,* 2704-2714.

Mcbride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (2002). The effect of heavy- vs. light-load jump squats on the development of strength, power and speed. *J Strength Cond.Res., 16,* 75-82.

McMahon, T. A. & Cheng, G. C. (1990). The mechanics of running: how does stiffness couple with speed? *J Biomech., 23 Suppl 1,* 65-78.

Mero A & Komi P (1994a). EMG, force and power analysis of sprint-specific strength exercises. *J Appl Biomech,* 1-13.

Mero A & Komi P (1994b). EMG, Force, and Power Analysis of Sprint-Specific Strength Exercises. *J Appl Biomech, 10,* 1-13.

Miller, M., Herniman, J., Ricard, M., Cheatham, C., & Michael, T. (2006). The effects of a 6-week plyometric training program on agility. *J Sport Sci Med, 5,* 459-465.

Potach D & Chu D (2008). Plyometrics training. In Baechle T & Earle R (Eds.), *Essentials of strength training and conditioning - third edition* (3 ed., Human Kinetics Publisher.

Ronnestad, B. R., Kvamme, N. H., Sunde, A., & Raastad, T. (2008). Short-term effects of strength and plyometric training on sprint and jump performance in professional soccer players. *J Strength Cond.Res., 22,* 773-780.

Ruben, R. M., Molinari, M. A., Bibbee, C. A., Childress, M. A., Harman, M. S., Reed, K. P. et al. (2010). The acute effects of an ascending squat protocol on performance during horizontal plyometric jumps. *J Strength Cond.Res., 24,* 358-369.

Schmidtbleicher, D. (1992). Training for power events. In P.V.Komi (Ed.), *Strength and Power in Sport* (First Edition ed., pp. 381-395). Oxford, U.K.: Blackwell Publishers.

Schmidtbleicher, D. & Haralambie, G. (1981). Changes in contractile properties of muscle after strength training in man. *Eur J Appl Physiol Occup.Physiol, 46,* 221-228.

Verkhoshansky Y & Siff M (2006). *Supertraining.*

Viitasalo, J. T., Hamalainen, K., Mononen, H. V., Salo, A., & Lahtinen, J. (1993). Biomechanical effects of fatigue during continuous hurdle jumping. *J Sports Sci., 11,* 503-509.

Wilt F (1978). Plyometrics - What it is and how it works. *Modern athlete and Coach, 16,* 9-12.

Young, W., Pryor, J. F., & Wilson, G. (1995). Effect of instructions on characteristics of countermovement jump and drop jump performance. *J Strength Cond.Res, 9,* 232-236.

Young, W., Wilson, G., & Byrne, C. (2000). A comparison of drop jump training methods: Effects on leg extensor strength qualities and jumping performance. *Int J Sport Med, 20,* 295-203.

Young, W. B., MacDonald, C., & Flowers, M. A. (2001). Validity of double- and single-leg vertical jumps as tests of leg extensor muscle function. *J Strength Cond.Res, 15,* 6-11.

Chapter 2 - Review of literature

2.1.1 Introduction

Maximal muscular power is an important factor for sport success. Common sport movements such as sprinting, jumping, change of directions, throwing, hopping, kicking and striking need to be trained to increase the performance during the competition. Cormie et al (2011a) states that "maximal power represents the greatest instantaneous power during a single movement performed with the goal of producing maximal velocity at takeoff, release or impact". These types of movements are performed in a very short time (typically less than 250 msec). Generally, the higher power movements are performed with only the body as an overload. Examples of these are the long jump and the sprint which have been reported to produce the highest power movements.

While technique is very important when performing jump training, the literature to substantiate the most optimal technique is not expansive. Hence coaches must often design training program based only on anecdotal evidence and/or observation. Concerning jump technique, it is important to understand the type of jump that generates the highest power. Specifically is there a particular foot strike technique that is optimal for jump height versus maximal power versus contact time or other variables? This review explores the relevant scientific literature about jump training technique, musculotendinous characteristics, elastic force, neuromuscular activation and muscular stiffness. Furthermore, this review attempts to relate these variables to functional athletic activities such as cover running, sprinting, acceleration and change of direction techniques to better understand how jump training influences performance of these activities.

2.1.2 Mechanisms of Plyometrics

Plyometric movements are represented by activities that enable a muscle to reach maximal force with maximal velocity (Verkhoshansky and Siff, 2006; Potach and Chu, 2008; Wilt, 1978). Typically, jumps, rebounds, throws and hits are examples of plyometric actions. The main objective of plyometric exercise training is to transfer the strength and power adaptations gained into sport actions like sprinting and change of direction (Young, 2006). Plyometric actions utilize the mechanism of the stretch shortening cycle (SSC). A short duration prestretch, which involves an eccentric or braking phase allows a potentiation of the concentric phase when compared with an isolated concentric action (Nicol et al, 2006). This potentiation is derived from two different mechanisms: mechanical (musculotendinous) and neural.

The mechanical model attempts to explain the role of elastic energy within the musculotendinous components (Bosco et al, 1981; Komi and Bosco, 1978). Muscle and connective tissue can be stretched during the eccentric phase of muscle contraction. The viscoelastic characteristic of these tissues allow the possibility for the storage of elastic energy (Proske and Morgan, 1984; Hill, 1950). This energy can be used later during the concentric phase of contraction to potentiate muscular power. Simulation studies have demonstrated the importance of SSC, however there is less understanding of the contribution of stored elastic energy during explosive sport movements (Bobbert et al, 1986). According to Hill (1970), tendinous tissue and cross-bridges of the fibres represent the series elastic component and gives the muscle the possibility to store energy during human dynamic movements (Morgan, 1977). The typical experiment used to explain the energy recoil during the concentric muscle phase of contraction is the comparison between squat jump and countermovement jump (CMJ) (Komi and Bosco, 1978; Bosco et al, 1981). This experiment compared the jump height reached during only a concentric muscle action and a concentric action preceded by a CMJ (stretch). Male physical education students obtained approximately 13% more height during CMJ than squat jump. This difference is attributed to the utilization of the elastic energy (Komi and Bosco, 1978). The velocity of the eccentric contraction is a determining factor in the recoil associated with the elastic energy. If there is a delay between eccentric and concentric contraction the energy can be lost as heat (Wilson et al, 1994). Not all the plyometric exercises have the same characteristics in relation to the eccentric phase velocity. CMJ have been extensively studied but since they exhibit a slow eccentric phase they are not widely used in training programs. Plyometric training is normally performed with several continuous repetitions and not just a single action (Radcliffe and Farentinos, 1999). As the preponderance of information published deals with single jumps, more research is necessary concerning fast continuous plyometric exercises.

The neurophysiological model explains the potentiation of force and power during the muscle concentric phase with the contribution of the stretch reflex (Komi and Gollhofer, 1997) and muscle preactivation prior to ground contact (Schmidtbleicher and Gollhofer, 1982). Stretch reflex is an involuntary response of the skeletal muscle generated by a stretch stimulus which is sensed by the muscle spindles and plays an important role during the SSC potentiation (Komi and Gollhofer, 1997).

During activities with a high eccentric velocity such as running and hopping, the characteristics of the stretch reflex can be easily identified with electromyography (EMG). The great number of motor units receiving Ia afferent stimuli from the eccentric stretch of the muscle would provide a strong contribution to the rapid increase (peak) in EMG. This reflex response cannot be seen during slow passive dorsiflexion ($0.4\ rad \cdot s^{-1}$) (Nicol and Komi, 1998). As a typical stretch reflex response is approximately 40 ms, this event will occur during the eccentric phase of the muscular contraction. The reflex amplitude is augmented with increases in movement velocity (Duysens et al, 1991). This high EMG activity shows a high correlation with muscular stiffness. In addition, elite sprinters develop more eccentric force during a maximum sprint compared with non-elite sprinters (Mero and Komi, 1986). Therefore it is possible that the reflex potentiation initiated in the eccentric phase can augment the force or power output of the concentric phase.

The main objective of the plyometric actions is to develop more power during sport specific movements. However, using the aforementioned Komi results, it is important to recognize that there are substantial differences between CMJ and other types of athletic movements. CMJ utilizes a longer contact time, lower force and greater knee angle than the fastest sport or training movements like sprinting, jumping drills and change of direction. CMJ does not exhibit a pre-activation. Furthermore, during the eccentric portion of CMJ contraction the reaction force decreases to less than the subject´s mass (unloading phase). This response indicates that the muscle has minimal absorption functions. However with a drop jump (DJ), the eccentric phase shows an increasing reaction force greater than the subject´s mass due to the acceleration of the body during the flight phase. These results indicate that the muscle is being strongly activated (Komi and Bosco, 1978). This muscle behaviour can change the fibre recruitment pattern (Nardone et al, 1989) and concentric phase performance. Nardone et al (1989) showed that fast fibers are preferably activated during fast eccentric contractions. Thus in addition to mechanical characteristics, neuromuscular responses can also contribute to the plyometric action. However, what type of plyometric jump should be used to guarantee increases in power and solve athletes' needs is still an open question.

In actions like sprinting, running and hopping the short latency stretch reflex component can be clearly observed by a sharp increase of the integrated EMG signal after the foot contacts the ground (Voigt et al, 1998; Gollhofer et al, 1992a). This sharp response can originate from the motor cortex during hopping (Zuur et al, 2010). The author used an innovate method to change the ground level up or down 2.5 cm with a moving force platform. Results suggest that sensory feedback and descending drive from the motor cortex combine to perform repetitive hopping movements. It is possible that the reflex response is not the same during DJs and hurdle jumps. There is very little information comparing the neural and mechanical responses between DJ and hurdle jumps and thus further investigations are necessary in this area.

The stretch reflex is very sensitive to loading conditions. Excessive drop height can inhibit reflexes. When untrained subjects performed DJs from 1.1 m, EMG activity decreased prior to ground contact and during the eccentric phase of the movement (Schmidtbleicher and Gollhofer, 1982; Gollhofer and Schmidtblecher, 1988). This response is important to keep in mind when coaches use boxes to design plyometric drills. There is a great possibility that excessive drop jump height during continuous drop or hurdle jumps will generate a reflex inhibition in the next landing (figure 2.1).

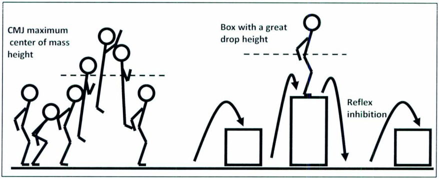

Figure 2.1. Box plyometric drill and possible reflex inhibition

Coaches should test their athletes to find the optimal drop height and use this data to design proper plyometric training drills (Komi, 1984). Komi and colleagues (1997) proposed three important characteristics of a SSC: a) a well-timed muscle preactivation before eccentric phase started, b) a short and fast eccentric phase and c) a short amortization period between eccentric and concentric phase. These characteristics will ensure high reflex activity. However not all jumps include these characteristics. For example, the CMJ is not a good example of a SSC action. The eccentric phase of a CMJ or a jump to box, typically persist more than 500 ms (Meylan et al, 2011; Cappa and Behm, 2011). EMG activity and movement velocity during the eccentric phase is very low compared with hopping or DJs. For these reasons CMJ belongs to a long SSC according to the Schmidtbleicher classification which represents a low power exercise (Schmidtbleicher, 1992). It is very important to remember that stretch reflexes contribute to the muscle stiffness which is another contributing factor. This is a very important muscle characteristic for high power SSC actions.

2.1.3 Stiffness

Stiffness can be defined as the relationship between the deformation of an object with a specific level of applied force and can be described by Hooke's law (McMahon and Cheng, 1990). Hooke's law is defined by the following equation:

$Fe = 2\ k\ x$

where Fe is elastic force, k is spring stiffness, and x is the amount of stretch or length. The external force which stretches or compresses a body could generate elastic force in the body. This force can be stored and then return the elastic energy.

Cavagna et al (1964,1988) and Heglund (1982) reported that mammals and birds store and recover energy like a bouncing ball during basic motor actions like running, hopping, trotting and galloping. Part of the gravitational and kinetic energy of the body is absorbed and restored by the muscles as with an elastic rebound. It can be said that human legs can act as a pogo stick, a ball or a spring-mass. The leg-spring stiffness model is highly representative of some human movements as running and hopping and provides researchers a good method (but not perfect) to analyze lower limb performance (Arampatzis et al, 2004). During a vertical movement, stiffness can be calculated by dividing the change in force produce during the movement by the change in length of the leg length (Δ force / Δ length). During running, stiffness of a particular joint is calculated with the change in moment divided by the change in joint angle during the braking phase (McMahon and Cheng, 1990).

There are four major components for muscular stiffness: passive (anatomical) stiffness, muscle stiffness, muscular stretch reflexes and muscular co-contraction. All these components contribute significantly to joint stiffness and allow humans to run, jump and sprint effectively. However there is a basic difference between humans and springs. A spring absorbs energy because of its special spiral form and material (typically metal) that stretches or compresses when a force is applied and this condition never changes unless the material experiences a modification. The force absorbed and restored during the compressing and lengthening movement is the same. This is not the case with human muscle because this behavior is strongly related to the action and movement velocity. Farley et al (1991,1999) showed that human leg stiffness does not perfectly behave like a spring, especially when subjects perform hopping at a low frequency. Figure 2.2 shows the relationship between the force and the center of mass displacement during normal hopping.

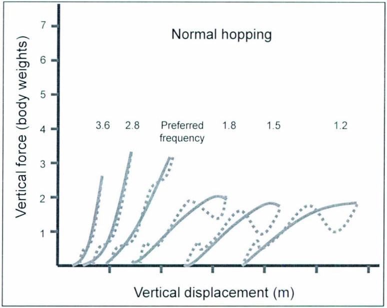

Figure 2.2. Vertical force and vertical displacement during hopping at different frequencies.

The dashed line represents the eccentric phase and the bold line the concentric phase. During slow hopping frequencies (1.8-1.5-1.2 Hz) a double peaked force can be seen during the braking period. During landing there is a high peak force when the subject contacts the ground (25 - 100 ms approximately). Then, the force decreases when the center of mass is moving downward (approaching the lowest point) and finally the force increases again (second force peak) which represents the concentric phase. This is a clear deviation from the behavior of a simple spring model because in a mechanical model, the force never falls while it is being stretched (Blickhan, 1989). These two peak force curves indicate a pause between the termination of the eccentric phase and the start of the concentric phase when hopping, hurdle or DJs are performed at slow velocity or by landing with the entire foot in a flat style (Kovacs et al, 1999). As hopping frequency increases (above the human preferred frequency) the two force lines overlap and this indicates that the muscle is behaving like a real spring (figure 2.2). It is important to point out that when hopping is performed at a higher frequency than the preferred frequency (minimizing contact time), the soleus and medial gastrocnemius EMG activity and leg stiffness are higher than lower frequencies (Hobara et al, 2007).

Cavagna et al (1977) proposed another way to explain this two force peak curve, that elastic energy during muscle lengthening is not converted into kinetic energy during muscle shortening. McMahon et al (1987) proposed that this first peak was related to the knee angle when running using the Groucho style. Groucho style is a particular style of walking adopted by Groucho Marx, hence the name: Groucho running. When a subject utilizes a greater knee angle during the stance phase, the first force peak is greater than in normal running. During this experiment the subjects ran normally and with the Groucho style at 4 $m \cdot s^{-1}$. Results showed that when a Groucho running style was used, stiffness decreases. This is a clear example of how leg stiffness can change due to coach´s instructions during the movement. It can be argued that the increase in the knee angle during some sport actions have a specific rationale.

There are more factors that may influence muscle and leg stiffness:

a) Coach technique instructions during exercise (Arampatzis et al, 2001).
b) Type and intensity of plyometric drill used (Cappa and Behm, 2011).
c) Athlete cannot reverse the downward movement due to a lack of force or power (Schmidtbleicher and Gollhofer, 1982).
d) Muscle is fatigued (Horita et al, 1996; Avela et al, 2002).
e) Subjects are still physically maturing (Lazaridis et al, 2010).
f) Athletes have different type of training background (Skurvydas et al, 2002).
g) Athletes training status (Hobara et al, 2010).

It is important to understand that leg stiffness during a plyometric exercise has a major influence on various athletic variables like the force curve, peak eccentric force, rate of force development, elastic energy storage and utilization (Brughelli and Cronin, 2008). However, in contrast, Seyfarth et al (2000) reported that there is an optimal stiffness for long jumping and that an increased stiffness would not increase jump performance. It is very important for coaches to understand this concept to design plyometric drills that achieve an athlete´s objective. Studies are needed to provide a better understanding of the type of landing that generates different types of force curves and leg stiffness.

2.1.4 Muscle preactivation

To generate a high level of leg stiffness it is extremely important to contact the ground after the flight phase with high muscle preactivation. This was shown during DJs (Ruan and Li, 2010; Ishikawa and Komi, 2004; Taube et al, 2011), hopping (Hobara et al, 2007), several jumping drills (Aura and Viitasalo, 1989) and maximum sprinting (Mero and Komi, 1987). Athletes develop an optimal strategy to pre-activate muscles for different type of activities. However this EMG activity can be changed with specific instructions (Arampatzis et al, 2001). In the Arampatzis study the author asked the athletes to perform DJs from different drop heights (20-40-60 cm). The decathletes jumped with the following instructions: "jump as high as you can". Then, the contact time was manipulated in relation to the optimal jump. The following instructions were used: a) "jump high a little faster (with relation to ground contact time) than your optimal jump" and b) jump high a little slower (with relation to ground contact time) than your optimal jump". With this concept 2 slower and 2 faster groups were established compared with the optimal DJ (group1= 210 ms, group2= 182 ms group3= 163 ms group4= 152 ms group5= 136 ms). Muscle pre-activity was higher in groups 3, 4 and 5 compared with group 1 and this higher muscle activation increased leg stiffness for all the drop heights. This change also increased the maximum ground reaction forces and decreased the vertical downward displacement of the center of mass during the eccentric phase. These results illustrate that minimal ground contact time during plyometric training drills should be employed when the objective is to increase pre-activation muscle capability, leg stiffness and potentiate concentric muscle contraction (Potach and Chu, 2008).

Muscle pre-activity was also analyzed by Aura and Viitasalo (1989) in several types of plyometric movements (standing 5 jumps, standing 5 hops, running 5 jumps, running 5 hops, hurdle hopping, DJs with unilateral foot contact, DJs with two approaching steps and flop-style high jump. The author reported maximal activation during a flop-style high jump takeoff. The total force produced was 6950 ± 1519 N representing 9 times body weight. This performance was accompanied with the highest EMG during pre-activity and eccentric phase and the highest average knee angular velocity. However EMG activity was average compared with the others jumps during the concentric contraction. This means the stretch reflex and muscle stiffness potentiate the concentric phase generating the highest mechanical power. It is probable that the flop-style high jump takeoff generates the highest mechanical power because it uses an uncontrolled and maximal velocity during takeoff meanwhile during the other jumps the athlete must think about the next landing. Therefore, it is possible that DJs generate a high muscular power because it is a ballistic movement without a pre-determined subsequent landing point and the athlete is requested to perform their maximal effort without concern for the following landing. Meanwhile hurdle jumps are repetitive jumps and the athlete must care about the hurdle by balancing their body during the flight. This action can produce a different pre-activation.

2.1.5 Force and power production during SSC exercises

Hill´s study (1938), is the traditional experiment to explain the relation between force and velocity. The author experimented with a large sartorii muscle of a frog at 0° C and found that force and concentric velocity have an inverse relationship. This means that when force (load in a resistance exercise) increases, velocity decreases. As the time for cross-bridges to attach and detach is a fixed time, the total number of cross-bridges attached decreases with increasing velocity of muscle concentric contraction. Later, Edman et al (1988) described the eccentric velocity relationship since Hill only experimented with shortening velocity. The author showed that eccentric contraction and velocity have a direct relationship in frog isolated muscle.

By using Hill´s data, mechanical power has been calculated during resistance training exercises. The results indicated that maximal power was produced when the load was at 30% of maximum isometric strength (Faulkner et al, 1992) or 30 – 45% of 1 repetition maximum (Newton et al, 1997; Moss et al, 1997). Training studies showed that the force-velocity curve can be modified by using the specific loads mentioned (Osteras et al, 2002). It is important to note that all these studies used traditional resistance exercise like bench press or squat. The nature of the exercise is when the bar reaches both extremes of the movement, the velocity is zero. Furthermore, the bar never loses contact with the body (bar and body form one system). This biomechanical characteristic prevents the development of the highest force and power compared with exercises that project an element or the body in space. It is important to remember that Hill´s and Edmans´s experiments were done with isolated preparations. Movements classified as SSC do not have the same force-velocity relationship (Komi, 1992). The author published a different force curve for SCC actions. In this experiment a buckle or E-form force transducer was used attached direct to the Achilles tendon. Figure 2.3 shows the results of the force velocity relationship.

Figure 2.3 data correspond to athletes running at 5.78 and 9.02 m·s-1 (solid lines). Dashed line represents Hill´s – Edman´s traditional curves. It can be seen that the force of a SSC is very different from isolated data. Probably the most important data is the great force generated during the eccentric phase which potentiates the concentric values compared with Hill´s data.

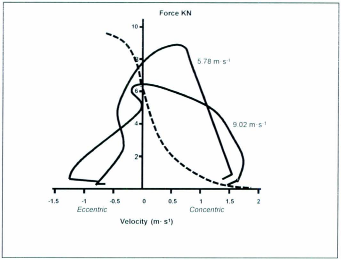

Figure 2.3. Force and velocity during running.

Several authors have investigated the force generated in other types of training movements such as weightlifting exercises, loaded squat jumps and plyometric drills (Ebben et al, 2008; Cormie, 2007a; Kawamori et al, 2005). Values of 3000, 3800, 4000 and 8000 N have been recorded during hopping, hurdle jumps, DJs and long jumps, respectively (Farley et al, 1991; Ruben et al, 2010; Luhtanen and Komi, 1979; Gollhofer, 1992b). Meanwhile Cormie et al (2007a) found only 2700 N during a squat utilizing 85% of the maximum repetition. To understand this concept better, the following figure shows data from a squat and a hurdle jump.

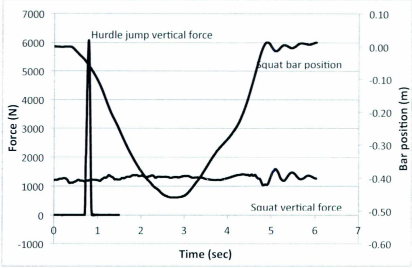

Figure 2.4. Force production during a squat and hurdle jump.

Figure 2.4 shows data from squat and hurdle jump performed by a national level rugby player, tested at the Jorge E. Coll laboratory Mendoza Argentina. Athlete mass was 98.3 kg and squat load was 170 kg. Hurdle height was set at 100% of the height reached during CMJ. During the squat, force had an initial decrease and then was maintained almost at the same level (1200 N) independently of the linear position during the 5 s of exercise duration. However during the hurdle jump the athlete produced more than 6000 N in only 180 ms. When RFD was calculated the hurdle jump showed higher values compared with squat movement. These data illustrate that plyometric exercises produce a high level of force and power.

The high level of force that can be produced during plyometric exercise is not common knowledge for all coaches. Some coaches think that the strongest exercise an athlete can perform would be a squat or dead lift.

Why is this perception widespread with coaches? Probably, because when squats are performed they generate a high level of fatigue by using a great resistive load. However it is clear that a squat generates less reaction force than a hurdle jump. Clearly, there is insufficient information about force production in plyometric exercises. Little information is published regarding the importance of movement pattern specificity, for generating muscular force and power with plyometric actions.

However, are all the plyometric actions similarly powerful? The answer is no; and to examine this concept two popular plyometric exercises were compared: a) cyclic split squat jump and b) double-leg zig zag hop (Potach and Chu, 2008). The cyclic split squat jump is a traditional modified CMJ with low velocity and muscle pre-activity and with a pronounced knee angle. Meanwhile the hop has a longer flight phase with significant EMG pre-activity which generates high leg stiffness. Perhaps plyometric intensity can be classified based on the previous flight phase and eccentric velocity controlled by the amplitude of knee angle.

2.2 Sport specific movements' characteristics

2.2.1 Running

It is very important to know about the biomechanics of running if a coach wants to develop optimal plyometric training programs. Running forward is the most common type of running in sport representative of jogging to sprinting. However athletes also need to run laterally or backwards as well. Several studies have published characteristics of ground running (Mann et al, 1986; Cavagna et al, 1964; Nigg et al, 1987) or treadmill running (Nigg et al, 1995; Nelson et al, 1972). Soccer players can cover more than 10 k during a match at different velocities (Randers et al, 2010; DiSalvo et al, 2009). More than 90% of the distance is covered below maximal aerobic speed which can differentiate between running and sprinting. Running refers to a movement with only one support. A gait cycle is the period from initial contact of one foot to the next initial contact of the same foot. The running gait cycle can be divided into three phases: stance, swing, and flight (Novacheck, 1998b; Dugan and Bhat, 2005). The first part of the stance phase represents the force absorption with a prone foot, the second half represents propulsion with a supine foot and finally the toe-off with a plantar flexion. The part of the sole which strikes the ground first was studied and generally athletes strike the ground with either the heel (rear foot strikers), with the midsole (mid foot strikers) or with the fore part of the sole (forefoot strikers) (Cavanagh and

Lafortune, 1980). Approximately between 70-85% of the runners are rear strikers, 20-25% are mid strikers and only 1-2% are fore strikers (Cavanagh and Lafortune, 1980; Munro et al, 1987; Hasegawa et al, 2007). Swing phase during running can be divided into an initial swing and terminal swing. After toe-off, the first flight phase begins and the body is in the air progressing forward until the opposite leg strikes the ground. After the opposite leg toe-off, the second flight phase occurs. During this action, the swinging limb is preparing to contact the ground again.

The necessary force to run forward at different velocities was analyzed in several studies (Cavanagh and Lafortune, 1980; Munro et al, 1987; Ruano et al, 2009; Brughelli, Cronin and Chaouachi, 2011; Ruano et al, 2009). Vertical force curves are related to the strike style. Rearfoot strikers have a double peak curve and midfoot strikers have only one force peak (Cavanagh and Lafortune, 1980; Nilsson and Thorstensson, 1989). The table 2.1 shows a summary of the vertical and horizontal forces during running at different velocities.

		Vertical forces (body weight)		Horizontal forces (body weight)	
Velocity $m \cdot s^{-1}$	Contact time ms	First peak	Second peak	Braking force	Propulsion force
3	270	1.57	2.51	-0.15	0.14
4	229	1.95	2.72	-0.21	0.20
5	199	2.32	2.83	-0.25	0.25

Table 2.1. Ground reaction forces during rear striker runners

Generally, in rear striker runners the first peak represents the weight acceptance or absorption and generates less force than the second peak. The force level exhibits moderate values such as ~ 1.5 – 2.5 times body weight. The second peak can typically be higher than the first peak and represent between 2 - 3 times body weights.

Plyometric training has been reported to increase running performance (Spurrs et al, 2003). However the interactions of different landing techniques and leg stiffness related to running performance have not been extensively studied.

2.2.2 Sprinting

Sprinting characteristics differ from running. In general, running is related to longer distance and sprinting with shorter distances (Dugan and Bhat, 2005). Sprinting is the fastest form of human locomotion. Probably the most important sprinting concept is that during the first part of ground contact, horizontal velocity decreases (braking phase) and this velocity decrement must be regenerated during the propulsion phase (Mann & Sprague, 1980). In relation to the foot strike during sprint running, Dugan and Bhat (2005), Mann and Sprague (1980) and Novachek (1988a) proposed that the sprint athletes do not contact the ground with the heel. However Bates et al (1978) based on Mason PhD thesis proposed that some runners are able to stay up on the ball of the foot and showed no impact force spike (first peak) indicating that the forces were being absorbed by the muscles and connective tissue. This can be seen during fast and slow DJs as well (Lockie et al, 2011). Nett (1964) studied the foot strike during sprinting and reported that the foot strike started with the 5th metatarsophalangeal joint in the forefoot. However as velocity decreases the contact point shifts towards the heel.

To clarify this topic Kanaoka (2005) discovered that all the athletes used a heel contact in a 30 m maximal sprint. A ground contact characterized by contact with the ball of the foot or flat foot was used by 56% of the runners and only 6% showed a ball of the foot contact only. The author did not mention if these athletes were the fastest or not and thus it is not known if the caliber of the athlete influences the foot placement during sprinting. In summary it is not clear what type of contact will induce a better sprint performance. Longitudinal plyometric studies are necessary to understand what type of ground contact is better when athletes use plyometric training to increase sprint velocity.

To elucidate the force applied during sprinting, Brughelli et al (2011) analyzed Australian Rules football players on a nonmotorized force treadmill. Athletes wore a harness around their waists, which was connected to a load cell that measured horizontal force. Vertical force was measured by four individual vertical load cells that were mounted under the treadmill. Table 2.2 shows the results.

% maximum velocity	60%	80%	100%
Vertical force N	1922	1942	1983
Horizontal force N	240	290	360
Contac time ms	280	248	209

Table 2.2. Ground reaction forces during maximal sprinting on a treadmill

Vertical force increased only 3.1% between 60 to 100% meanwhile horizontal force increased 50%. Pearson correlation coefficients were 0.24 and 0.47 for vertical and horizontal force respectively. This means that the horizontal force component was more important for increasing sprint velocity. This results contrast with the Weyand study (Weyand et al, 2000) who reported that the vertical force and maximal velocity have a direct relationship (0.62) until reaching maximum values. An important point in the Brughelli study was the shortest contact time occurred at 100% sprint (209 ms). This time is longer compared with those published in the literature: Weyand (107 ms) and Mero (102 ms) (Weyand et al, 2000; Mero and Komi, 1986). More studies are needed to elucidate this concept, which could help to understand if a plyometric training program needs a greater emphasis on horizontal or vertical jumps to improve sprinting speed. However there is a growing use and investigation of the weighted sledge or resisted velocity with sport training.

This type of training has been shown to change running biomechanics when attempting to generate more horizontal force (Lockie et al, 2003).

Limb movements during the flight phase may be an important aspect for generating higher velocities in sprinters (Cissik, 2004). However Murphy studied the joint velocity in field sport athletes and demonstrated that there was no difference between the faster and the slower group during the aerial phase. The greatest difference was found when the athletes were on the ground performing force. Fast athletes had shorter contact time (Murphy et al, 2003).

The force curve during a maximum sprint can be different from running. During running at slow velocities (3-5 $m\ s^{-1}$) there is an initial peak force which is generally lower than the second peak. However during maximal velocities (7-9 $m \cdot s^{-1}$) the first peak is greater than the second (Mero et al, 1992). Sometimes force curves with a single peak are evident (Kuitunen et al, 2002; Lockie et al, 2011). In addition, Mero and Komi (1986) reported that the best sprinters have a higher eccentric force compared with less skilled athletes. EMG activity also increased in concordance with velocity (Mero and Komi, 1987). Both pre-activity and braking phase showed an increase and this is in agreement with the necessity to develop a high muscular stiffness.

Another important aspect in sprinting is the different training background (technique) used when running at the same velocity between a sprinter and a long distance athlete. Bushnell analyzed this topic and found differences in minimum hip angle, centre of mass at touchdown and recovery knee at touchdown when running at 5.81 m s^{-1} (Bushnell and Hunter, 2007). There are no studies which compared sprint technique between a sprinter or distance athlete with a team sport athlete.

Finally there is evidence in the literature about improving sprint velocity with plyometric training (Chelly et al, 2010; Rimmer and Sleivert, 2000). However other authors found that sprint velocity remain unchanged with plyometric training (Markovic et al, 2007; Thomas et al, 2009). It is important to mention that Chelly study used a specific landing technique: "Jump with maximal effort". Each jump must be performed to reach the maximal possible height with a minimal ground contact time. Both hurdle and drop jumps were performed with small angular knee movements and the ground was touched with the balls of the feet only. Half of the plyometric training used jumps over hurdles which contain a high horizontal force component. In contrast, Thomas used only DJs and CMJs and could not get a significant increase in sprint velocity. Further research is necessary to help to clarify the importance, differences and appropriate applications for CMJ, DJ, hurdle jumps and other similar plyometric training activities to enhance sprint performance.

2.2.3 Acceleration

The analysis of maximal 100 m velocity results in three phases: acceleration, maximal velocity and maintained or decrease velocity. Tellez published that during a 100 m sprint, 64% of the athlete's total time can be determined by the block start and acceleration phase alone (Tellez, 1984). This underlies the importance of analyzing what type of predominant efforts should be emphasized during training. If field sports are considered, maximal sprint efforts last only 2 s and high velocity running 3 s (Docherty et al, 1988; Bangsbo et al, 1991; Spencer et al, 2004). By comparing field sports times with the 100-meter sprint, the fastest velocities in field sports reside within the acceleration phase. When an athlete accelerate there are some differences compared with maximal velocity phase: a) athlete cannot reach the maximum velocity b) during the first steps the center of gravity is forward of the stance point c) during early acceleration phase, vertical force is lower than constant running tested at the same speed and d) high vertical ground reaction force is counterproductive for forward acceleration because vertical force vector will induce a longer aerial phase.

As Brughelli et al (2011) states, horizontal velocity is highly important to increase sprint velocity. For acceleration, horizontal force is a major determinant for a fast athlete. Lockie et al (2011) reported that the fastest field sport athlete applied more than double the horizontal velocity during the first two steps. Mero and Komi (1990) discovered that sprint athletes generate more horizontal than vertical force during the first step after a block start (788 N vs 739 N respectively). With this information it is clear that horizontal force is a primary determinant for acceleration. This is very important because plyometric exercises can prioritize horizontal or vertical force production (Mero and Komi, 1994). This should be important to reach specific goals in training process.

Starting position can influence acceleration performance as well. There is abundant information regarding start from blocks in sprinters (Mero and Komi, 1990; Maulder et al, 2008; Cronin et al, 2007); however in field sports a natural standing position or a running start is used more frequently. Several starting positions have been studied. These included a parallel start (movement is initiated with a forward step), a false start (movement is initiated with a step back), a split start (movement is initiated from a split stance) and a thumb start (feet split with a hand on the floor). Some authors state that a step back before the start gives an advantage to accelerate (Frost and Cronin, 2011; Kraan et al, 2001) based on the horizontal impulse generated. Kraan et al (2001) compared the force and power at push-off between 3 starting styles (a staggered stance, a parallel stance, and a parallel stance whereby movement was initiated with a step backwards). It was concluded that using a backwards step to accelerate forwards could be beneficial because of the natural SSC at push-off phase.

In summary, plyometric drills should possess similar specific characteristics as the action such as a significant horizontal component to increase acceleration in all starting possible positions.

2.2.4 Changes of direction

The ability to change directions (cutting task) quickly is very important in sports where the athlete must elude other athletes to succeed (Young and Farrow, 2006; Farrow et al, 2005; Sheppard and Young, 2006). Often this change of direction must be performed at near maximal velocity. Frequently this movement action is classified as agility because according to Bloomfield agility has classically been defined as simply the ability to change direction rapidly (Bloomfield et al, 2007). The most investigated topics during cutting task are the differences between men and women, angle of change, preplanned and unanticipated conditions and anterior cruciate ligament injury prevention (Beaulieu et al, 2008; Besier et al, 2003; Besier et al, 2001; Benjaminse and Otten, 2011).

Change of direction during a game is not always anticipated. It may occur as a result of a sudden movement trying to stop an adversary or catch a ball. These are labeled as unanticipated conditions. In this case the neuromuscular response is different if the movement is preplanned (Besier et al, 2001; Farrow et al, 2005). Highly skilled athletes have a greater ability compared with less skilled athletes in decision-making time. Highly skilled players have a greater ability to anticipate the intended pass direction as a result of reduced decision time. These athletes respond 77 ms earlier than other less skilled athletes and hence complete the sprint component of the test with greater speed. During preplanned conditions, the EMG response is sport specific. However during unanticipated conditions the EMG response is of general activation (Besier et al, 2003). Thus employing different directions during the plyometric training would be an important consideration.

2.2.5 Muscular power adaptation with plyometric training

Cormie et al (2011a) observed that: "A fundamental relationship exists between strength and power, which dictates that an individual cannot possess a high level of power without first being relatively strong". Plyometric exercises produce or require a great level of vertical force, normally in the order of 3 or more times body weight (Cormie et al, 2007b). However, it has been demonstrated several times that traditional maximal strength training can also increase force and power too (Behm and Sale, 1993; Cormie et al, 2010).

Baseball players need a high level of upper limb power for throwing. Typically, athletes use resistance training to develop muscular power. Normally, high intensities are used with resistance exercises (e.g. bench press) that stress the specific muscles. Then, it is recommended to use more power-related exercises such as chest throws (Cormie et al, 2011b). However this progression is not the same for athletes with compared to athletes without resistance training experience. Newton and McEvoy (1994) studied training adaptations generated from low velocity and high intensity exercise (bench press and pullover) versus exercises with high velocity and high intensity (overhead and chest medicine ball throwing). Subjects did not have experience training with resistance exercise. The control test was baseball throwing velocity. It would be expected that the medicine ball throw training would develop more power during the ball throw. However the group who trained with resistance exercise improved throwing velocity by 4.1% meanwhile the medicine ball group improved only 1.6%. This is indicative that athletes need a minimum initial level of force in order to build a foundation for a high level of muscular power. But one important question arises: should this initial type of training be performed at slow or high velocity? For example, is it necessary to begin with a squat or the loaded squat jump exercise in order to gain this specific force? There are not precedents in the literature for comparing studies of these two types of training methods.

However the muscular power increase is only appreciable in untrained or moderately trained subjects. When high intensities are used with slow velocity exercise as a squat or bench press, changes in maximal strength and power can be seen during the first months but this relationship will plateau if the untrained subject progresses to a highly trained athlete. The figure 2.5 represents the process.

These specific adaptations during the first part of the training process are based on the basic neural modifications: increase of motor unit firing rate, motor unit recruitment and inhibition of the antagonist muscle (Sale, 1988). If similar intensity and type of training is used for a prolonged period these training adaptations cease. One of the reasons is that this type of training will not generate further neural adaptations.

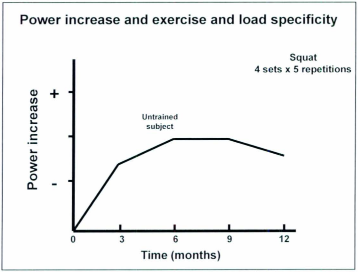

Figure 2.5. Relationship between power increase and specific low velocity training

The training is similar to a powerlifter training system. These athletes were studied and showed a low capacity to jump vertically compared with sprinters and weightlifters (McBride et al, 1999). Weightlifters and sprinters jumped 21% and 25% higher than powerlifters, respectively. This is very interesting because the training intensities used by powerlifters and weightlifters are similar (80-100% of one maximum repetition). Both types of athletes were extremely strong in the squat exercise (more than 2.8 times body weight). Why cannot extremely strong athletes jump as high? Part of answer was stated by Cormie et al (2007a). According to the author the ability to produce maximal muscular power during whole body movements is dependent on the nature (type) of movement. Type of movement is a very important topic in plyometrics because (as it was previously mentioned) not all the jumps or movements have the same characteristic in relation to reflex responses, velocity, ground reaction force, rate of force development or leg stiffness. As an example two exercises can be planned using the same external load, equal volume, intensity and density and the produced mechanical power could be very different. An example of this is when comparing a jerk and a squat movement with 100 kg of external load. The jerk generates approximately 5000 watts and the squat just 1500 watts (Garhammer, 1980).

3. Summary and conclusions

In summary it is clear that maximal muscular power is influenced by a wide variety of neuromuscular factors including the type of jump and the jump technique. Besides elastic energy storage, leg stiffness, stretch reflex and force direction play a determinant role in the process to recognize the optimal type of jump to use during training. In order to maximize the transfer of specific training to sport performance, training should involve plyometric activities with flat, heel-toe and forefoot landings with specific coaches' technique instructions. In preparation for this training process, athletes must develop a high level of general strength/force prior to using advanced plyometric techniques.

4. Bibliography

Reference List

Arampatzis, A., Schade, F., Walsh, M., & Bruggemann, G. P. (2001). Influence of leg stiffness and its effect on myodynamic jumping performance. *J Electromyogr.Kinesiol., 11,* 355-364.

Arampatzis, A., Stafilidis, S., Morey-Klapsing, G., & Bruggemann, G. P. (2004). Interaction of the human body and surfaces of different stiffness during drop jumps. *Med.Sci.Sports Exerc., 36,* 451-459.

Aura, O. & Viitasalo, J. (1989). Biomechanical characteristics of jumping. *Int. J. Sport Biomec, 1989,* 89-98.

Avela, J., Kyrolainen, H., Nicol, C., & Komi, P. V. (2002). Acute and prolonged reduction in joint stiffness in humans after exhausting stretch-shortening cycle exercise. *Eur J Appl Physiol, 88,* 107-116.

Bangsbo, J., Norregaard, L., & Thorso, F. (1991). Activity profile of competition soccer. *Can.J Sport Sci., 16,* 110-116.

Bates B, Mason B, & James S (1978). Lower extermity Function During the Support Phase of Running. In E.Asmussen & Jorgensen J (Eds.), *Biomechanics VI* (pp. 30-39). *Baltimore: University Park Press.*

Beaulieu, M. L., Lamontagne, M., & Xu, L. (2008). Gender differences in time-frequency EMG analysis of unanticipated cutting maneuvers. *Med.Sci.Sports Exerc., 40,* 1795-1804.

Behm, D. G. & Sale, D. G. (1993). Intended rather than actual movement velocity determines velocity-specific training response. *J.Appl.Physiol, 74,* 359-368.

Benjaminse, A. & Otten, E. (2011). ACL injury prevention, more effective with a different way of motor learning? *Knee.Surg.Sports Traumatol.Arthrosc., 19,* 622-627.

Besier, T. F., Dloyd, D. G., & Ackland, T. R. (2003). Muscle activation strategies at the knee during running and cutting maneuvers. *Med.Sci.Sports Exerc., 35,* 119-127.

Besier, T. F., Lloyd, D. G., Ackland, T. R., & Cochrane, J. L. (2001). Anticipatory effects on knee joint loading during running and cutting maneuvers. *Med.Sci.Sports Exerc., 33,* 1176-1181.

Blickhan, R. (1989). The spring-mass model for running and hopping. *J Biomech,* 1217-1227.

Bloomfield, J., Polman, R., O'Donoghue, P., & McNaughton, L. (2007). Effective speed and agility conditioning methodology for random intermittent dynamic type sports. *J Strength Cond.Res., 21,* 1093-110.

Bobbert, M. F., Huijing, P. A., & van Ingen Schenau, G. J. (1986). A model of the human triceps surae muscle-tendon complex applied to jumping. *J Biomech., 19,* 887-898.

Bosco, C., P.V.Komi, & Ito, A. (1981). Prestretch potentiation of human skeletal muscle during ballistic movement. *Acta Physiol Scand, 111,* 135-140.

Brughelli, M. & Cronin, J. (2008). A review of research on the mechanical stiffness in running and jumping: methodology and implications. *Scand.J Med.Sci.Sports, 18,* 417-426.

Brughelli, M., Cronin, J., & Chaouachi, A. (2011). Effects of running velocity on running kinetics and kinematics. *J Strength Cond.Res., 25,* 933-939.

Bushnell, T. & Hunter, I. (2007). Differences in technique between sprinters and distance runners at equal and maximal speeds. *Sports Biomech., 6,* 261-268.

Cappa, D. F. & Behm, D. G. (2011). Training Specificity of Hurdle vs. Countermovement Jump Training. *J Strength Cond.Res.25,10,* 2715-2720.

Cavagna, G. A., Franzetti, P., Heglund, N. C., & Willems, P. (1988). The determinants of the step frequency in running, trotting and hopping in man and other vertebrates. *J Physiol, 399,* 81-92.

Cavagna, G. A., Heglund, N. C., & Taylor, C. R. (1977). Mechanical work in terrestrial locomotion: two basic mechanisms for minimizing energy expenditure. *Am.J.Physiol, 233,* R243-R261.

Cavagna, G. A., Saibene F.P., & Margaria, R. (1964). Mechanical work in running. *J.Appl.Physiol, 19*, 249-256.

Cavanagh, P. R. & Lafortune, M. A. (1980). Ground reaction forces in distance running. *J Biomech., 13,* 397-406.

Chelly, M. S., Ghenem, M. A., Abid, K., Hermassi, S., Tabka, Z., & Shephard, R. J. (2010). Effects of in-season short-term plyometric training program on leg power, jump- and sprint performance of soccer players. *J Strength Cond.Res., 24,* 2670-2676.

Cissik J (2004). Means and methods of speed training, Part 1. *Strength Cond J, 26,* 24-29.

Cormie, P., McCaulley, G. O., Triplett, N. T., & Mcbride, J. M. (2007a). Optimal loading for maximal power output during lower-body resistance exercises. *Med.Sci.Sports Exerc., 39,* 340-349.

Cormie, P., McCaulley, G. O., Triplett, N. T., & Mcbride, J. M. (2007b). Optimal loading for maximal power output during lower-body resistance exercises. *Med.Sci.Sports Exerc., 39,* 340-349.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010). Adaptations in athletic performance after ballistic power versus strength training. *Med.Sci.Sports Exerc., 42,* 1582-1598.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2011a). Developing maximal neuromuscular power: Part 1--biological basis of maximal power production. *Sports Med., 41,* 17-38.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2011b). Developing maximal neuromuscular power: part 2 - training considerations for improving maximal power production. *Sports Med., 41,* 125-146.

Cronin, J. B., Green, J. P., Levin, G. T., Brughelli, M. E., & Frost, D. M. (2007). Effect of starting stance on initial sprint performance. *J Strength Cond.Res., 21,* 990-992.

Di, S., V, Gregson, W., Atkinson, G., Tordoff, P., & Drust, B. (2009). Analysis of high intensity activity in Premier League soccer. *Int.J Sports Med., 30,* 205-212.

DiSalvo, V., Gregson, W., Atkinson, G., Tordoff, P., & Drust, B. (2009). Analysis of high intensity activity in Premier League soccer. *Int.J Sports Med., 30,* 205-212.

Docherty D, Wenger H, & Neary P (1988). Time-motion analysis related to the physiological demands of rugby. *J hum mov stud, 14,* 269-277.

Dugan, S. A. & Bhat, K. P. (2005). Biomechanics and analysis of running gait. *Phys.Med.Rehabil.Clin.N.Am., 16,* 603-621.

Duysens, J., Tax, A. A., van der Doelen, B., Trippel, M., & Dietz, V. (1991). Selective activation of human soleus or gastrocnemius in reflex responses during walking and running. *Exp.Brain Res., 87,* 193-204.

Ebben, W. P., Simenz, C., & Jensen, R. L. (2008). Evaluation of plyometric intensity using electromyography. *J.Strength Cond.Res., 22,* 861-868.

Edman, K. A. P., Reggiani, C., Schiaffino, S., & Te Kronnie, G. (1988). Maximum velocity of shortening related to myosin isoform composition in frog skeletal muscle fibres. *J Physiol, 395,* 679-694.

Farley, C. T., Blickhan, R., Saito, J., & Taylor, C. R. (1991). Hopping frequency in humans: a test of how springs set stride frequency in bouncing gaits. *J.Appl.Physiol, 71,* 2127-2132.

Farley, C. T. & Morgenroth, D. C. (1999). Leg stiffness primarily depends on ankle stiffness during human hopping. *J.Biomech., 32,* 267-273.

Farrow, D., Young, W., & Bruce, L. (2005). The development of a test of reactive agility for netball: a new methodology. *J Sci.Med.Sport, 8,* 52-60.

Faulkner, J. A., Claflin, D. R., & McCully, K. K. (1992). Power output of fast and slow fibers from human skeletal muscles. In *Strength and Power in Sport* (pp. 81-91).

Frost, D. M. & Cronin, J. B. (2011). Stepping back to improve sprint performance: a kinetic analysis of the first step forwards. *J Strength Cond.Res., 25,* 2721-2728.

Garhammer, J. (1980). Power production by Olympic weightlifters. *Med.Sci.Sports Exerc., 12,* 54-60.

Gollhofer, A. & Schmidtblecher, D. (1988). Muscle activation patterns of human leg extensors and force-time characteristics in jumping exercises under increased stretching loads. In (pp. 143-147). *Free university Press Amsterdam*.

Gollhofer, A., Strojnik, V., Rapp, W., & Schweizer, L. (1992a). Behaviour of triceps surae muscle-tendon complex in different jump conditions. *Eur J Appl Physiol Occup.Physiol, 64,* 283-291.

Gollhofer, A., Strojnik, V., Rapp, W., & Schweizer, L. (1992b). Behaviour of triceps surae muscle-tendon complex in different jump conditions. *Eur J Appl Physiol Occup.Physiol, 64,* 283-291.

Hasegawa, H., Yamauchi, T., & Kraemer, W. J. (2007). Foot strike patterns of runners at the 15-km point during an elite-level half marathon. *J Strength Cond.Res., 21,* 888-893.

Heglund, N. C., Cavagna, G. A., & Taylor, C. R. (1982). Energetics and mechanics of terrestrial locomotion. III. Energy changes of the centre of mass as a function of speed and body size in birds and mammals. *J.exp.Biol., 97,* 41-56.

Hill AV (1938). The Heat of Shortening and the Dynamic Constants of Muscle. *Proceedings of the Royal Society of London, 126,* 136-195.

Hill A.V. (1970). *First and last experiment in mucle mechancis.* Cambridge: Cambridge University Press.

Hill, A. V. (1950). The series elastic component of muscle. *Proc.R.Soc.Lond B Biol.Sci., 137,* 273-280.

Hobara, H., Kanosue, K., & Suzuki, S. (2007). Changes in muscle activity with increase in leg stiffness during hopping. *Neurosci.Lett., 418,* 55-59.

Hobara, H., Kimura, K., Omuro, K., Gomi, K., Muraoka, T., Sakamoto, M. et al. (2010). Differences in lower extremity stiffness between endurance-trained athletes and untrained subjects. *J Sci.Med.Sport, 13,* 106-111.

Horita, T., Komi, P. V., Nicol, C., & Kyröläinen, H. (1996). Stretch shortening cycle fatigue: interactions among joint stiness, reflex, and muscle mechanical performance in the drop jump. *Eur J Appl Physiol, 73,* 393-403.

Ishikawa, M. & Komi, P. (2004). Effects of different dropping intensities on fascicle and tendinous tissue behavior during stretch-shortening cycle exercise. *J Appl Physiol, 96,* 848-852.

Kanaoka T (2005). *Foot placement during sprinting and its effects on biomechanics of sprint performance in NCAA division-1 female track and field runners.* University of Hawai.

Kawamori, N., Crum, A. J., Blumert, P. A., Kulik, J. R., Childers, J. T., Wood, J. A. et al. (2005). Influence of different relative intensities on power output during the hang power clean: identification of the optimal load. *J Strength Cond.Res., 19,* 698-708.

Komi P (1992). Stretch-Shortening Cycle. In Komi P (Ed.), *Strength and Power in Sport* (First ed., pp. 169-179). Blackwell Scientific Publications.

Komi P & Gollhofer, A. (1997). Stretch reflexes can have an important role in force enhacement during SSC exercise. *J Appl Biomech, 13,* 451-460.

Komi, P. (1984). Physiological and biomechanical correlates of muscle function:effects of muscle structure and stretch-shortening cycle on force and speed. *Exercise sport sc, 12,* 81-121.

Komi, P. V. & Bosco, C. (1978). Utilization of stored elastic energy in leg extensor muscles by men and women. *Med.Sci.Sports Exerc., 10,* 261-265.

Kovacs, I., Tihanyi, J., Devita, P., Racz, L., Barrier, J., & Hortobagyi, T. (1999). Foot placement modifies kinematics and kinetics during drop jumping. *Med.Sci.Sports Exerc., 31,* 708-716.

Kraan, G. A., van Veen, J., Snijders, C. J., & Storm, J. (2001). Starting from standing; why step backwards? *J Biomech., 34,* 211-215.

Kuitunen, S., Komi, P. V., & Kyrolainen, H. (2002). Knee and ankle joint stiffness in sprint running. *Med.Sci.Sports Exerc., 34,* 166-173.

Lazaridis, S., Bassa, E., Patikas, D., Giakas, G., Gollhofer, A., & Kotzamanidis, C. (2010). Neuromuscular differences between prepubescents boys and adult men during drop jump. *Eur J Appl Physiol, 110,* 67-74.

Lockie, R. G., Murphy, A. J., Knight, T. J., & de Jonge, X. A. (2011). Factors that differentiate acceleration ability in field sport athletes. *J Strength Cond.Res., 25,* 2704-2714.

Lockie, R. G., Murphy, A. J., & Spinks, C. D. (2003). Effects of resisted sled towing on sprint kinematics in field-sport athletes. *J Strength Cond.Res., 17,* 760-767.

Luhtanen, P. & Komi P.V. (1979). Mechanical power and segmental contribution to force impulses in long jump take-off. *Eur J Appl Physiol,* 267-274.

Mann, R. & Sprague, P. (1980). A kinetic analysis of the ground leg during sprint running. *Res.Q.Exerc.Sport, 51,* 334-348.

Mann, R. A., Moran, G. T., & Dougherty, S. E. (1986). Comparative electromyography of the lower extremity in jogging, running, and sprinting. *Am.J Sports Med., 14,* 501-510.

Markovic, G., Jukic, I., Milanovic, D., & Metikos, D. (2007). Effects of sprint and plyometric training on muscle function and athletic performance. *J Strength Cond.Res., 21,* 543-549.

Maulder P, Bradshaw E, & Keogh, J. (2008). Kinematics alterations due to different loading schemes in early acceleration sprint performance from starting blocks. *J Strength Cond.Res., 22,* 1992-2002.

McBride J, Triplett-McBride, T., Davie A, & Newton R (1999). Comparison of Strength and Power Characteristics Between Power Lifters, Olympic Lifters, and Sprinters. *J Strength Cond.Res., 13,* 58-6.

McMahon, T. A. & Cheng, G. C. (1990). The mechanics of running: how does stiffness couple with speed? *J Biomech., 23 Suppl 1,* 65-78.

McMahon, T. A., Valiant, G., & Frederick, E. C. (1987). Groucho running. *J Appl Physiol, 62,* 2326-2337.

Mero A & Komi P (1986). Force-, EMG- and elasticity-velocity relationships at submaximal, maximal and supramaximal running speed in sprinters. *Eur J Appl Physiol,* 553-561.

Mero A & Komi P (1994). EMG, force and power analysis of sprint-specific strength exercises. *J Appl Physiol Biomech,* 1-13.

Mero, A. & Komi, P. V. (1986). Force-, EMG-, and elasticity-velocity relationships at submaximal, maximal and supramaximal running speeds in sprinters. *Eur J Appl Physiol Occup.Physiol, 55,* 553-561.

Mero, A. & Komi, P. V. (1987). Electromyographic activity in sprinting at speeds ranging from sub-maximal to supra-maximal. *Med.Sci.Sports Exerc., 19,* 266-274.

Mero, A. & Komi, P. V. (1990). Reaction time and electromyographic activity during a sprint start. *Eur J Appl Physiol Occup.Physiol, 61,* 73-80.

Mero, A., Komi, P. V., & gregor, R. J. (1992). Biomechanics of sprint running. A review. *Sports Med., 13,* 376-392.

Meylan, C. M., Nosaka, K., Green, J., & Cronin, J. B. (2011). The effect of three different start thresholds on the kinematics and kinetics of a countermovement jump. *J Strength Cond.Res., 25,* 1164-1167.

Morgan, D. L. (1977). Separation of active and passive components of short-range stiffness of muscle. *Am.J Physiol, 232,* C45-C49.

Moss, B. M., Refsnes, P. E., Abildgaard, A., Nicolaysen, K., & Jensen, J. (1997). Effects of maximal effort strength training with different loads on dynamic strength, cross-sectional area, load-power and load-velocity relationships. *Eur J Appl Physiol Occup.Physiol, 75,* 193-199.

Munro, C. F., Miller, D. I., & Fuglevand, A. J. (1987). Ground reaction forces in running: a reexamination. *J Biomech., 20,* 147-155.

Murphy A, Lockie R, & Coutts A (2003). Kinematic determinants of early acceleration in field sport athletes. *J Sport Sci Med,* 144-150.

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

Nelson, R. C., Dillman, C. J., Lagasse, P., & Bickett, P. (1972). Biomechanics of overground versus treadmill running. *Med.Sci.Sports, 4,* 233-240.

Nett T (1964). Foot plant in running. *Track Technique,* 462-463.

Newton R & McEvoy K (1994). Baseball throwing velocity: a comparison of medicine ball training and weight training. *J Strength Cond.Res., 8,* 198-203.

Newton, R. U., Murphy, A. J., Humphries, B. J., Wilson, G. J., Kraemer, W. J., & Hakkinen, K. (1997). Influence of load and stretch shortening cycle on the kinematics, kinetics and muscle activation that occurs during explosive upper-body movements. *Eur J Appl Physiol Occup.Physiol, 75,* 333-342.

Nicol, C., Avela, J., & Komi, P. V. (2006). The stretch-shortening cycle : a model to study naturally occurring neuromuscular fatigue. *Sports Med., 36,* 977-999.

Nicol, C. & Komi, P. V. (1998). Significance of passively induced stretch reflexes on achilles tendon force enhancement. *Muscle Nerve, 21,* 1546-1548.

Nigg, B. M., Bahlsen, H. A., Luethi, S. M., & Stokes, S. (1987). The influence of running velocity and midsole hardness on external impact forces in heel-toe running. *J Biomech., 20,* 951-959.

Nigg, B. M., De Boer, R. W., & Fisher, V. (1995). A kinematic comparison of overground and treadmill running. *Med.Sci.Sports Exerc., 27,* 98-105.

Nilsson, J. & Thorstensson, A. (1989). Ground reaction forces at different speeds of human walking and running. *Acta Physiol Scand., 136,* 217-227.

Novacheck, T. F. (1998a). Running injuries: a biomechanical approach. *Instr.Course Lect., 47,* 397-406.

Novacheck, T. F. (1998b). The biomechanics of running. *Gait.Posture., 7,* 77-95.

Osteras, H., Helgerud, J., & Hoff, J. (2002). Maximal strength-training effects on force-velocity and force-power relationships explain increases in aerobic performance in humans. *Eur J Appl Physiol, 88,* 255-263.

Potach D & Chu D (2008). Plyometrics training. In Baechle T & Earle R (Eds.), *Essentials of strength training and conditioning - third edition* (3 ed., Human Kinetics Publisher.

Proske, U. & Morgan, D. L. (1984). Stiffness of cat soleus muscle and tendon during activation of part of muscle. *J Neurophysiol., 52,* 459-468.

Radcliffe, J. C. & Farentinos RC. High powered plyometrics. 1999. Human Kinetics Publishers.

Randers, M. B., Mujika, I., Hewitt, A., Santisteban, J., Bischoff, R., Solano, R. et al. (2010). Application of four different football match analysis systems: a comparative study. *J Sports Sci., 28,* 171-182.

Rimmer E & Sleivert G (2000). Effects of a plyometric intervention program on sprint performance. *J Strength Cond.Res., 14,* 295-301.

Ruan, M. & Li, L. (2010). Approach run increases preactivation and eccentric phases muscle activity during drop jumps from different drop heights. *J Electromyogr.Kinesiol., 20,* 932-938.

Ruano C, Powell D, Chalambaga E, & Renshaw D (2009). The Effects of Tempur Insoles on Ground Reaction Forces and Loading Rates in Running. *Int J Exer Sci, 2,* 186-190.

Ruben, R. M., Molinari, M. A., Bibbee, C. A., Childress, M. A., Harman, M. S., Reed, K. P. et al. (2010). The acute effects of an ascending squat protocol on performance during horizontal plyometric jumps. *J Strength Cond.Res., 24,* 358-369.

Sale, D. G. (1988). Neural adaptation to resistance training. *Med Sci Sport Exer, 20,* 135-145.

Schmidtbleicher D & Gollhofer, A. (1982). Neuromuskulare untersuchungen zur bestimmung individueller belastunggrossen fur ein teifsprungtraining. *Leistungssport, 12,* 298-307.

Schmidtbleicher, D. (1992). Training for power events. In P.V.Komi (Ed.), *Strength and Power in Sport* (First Edition ed., pp. 381-395). Oxford, U.K.: Blackwell Publishers.

Seyfarth, A., Blickhan, R., & Van Leeuwen, J. L. (2000). Optimum take-off techniques and muscle design for long jump. *J Exp.Biol., 203,* 741-750.

Sheppard, J. M. & Young, W. B. (2006). Agility literature review: classifications, training and testing. *J Sports Sci., 24,* 919-932.

Skurvydas, A., Dudoniene, V., Kalvenas, A., & Zuoza, A. (2002). Skeletal muscle fatigue in long-distance runners, sprinters and untrained men after repeated drop jumps performed at maximal intensity. *Scand.J Med.Sci.Sports, 12,* 34-39.

Spencer, M., Lawrence, S., Rechichi, C., Bishop, D., Dawson, B., & Goodman, C. (2004). Time-motion analysis of elite field hockey, with special reference to repeated-sprint activity. *J.Sports Sci., 22,* 843-850.

Spurrs, R. W., Murphy, A. J., & Watsford, M. L. (2003). The effect of plyometric training on distance running performance. *Eur J Appl Physiol, 89,* 1-7.

Taube, W., Leukel, C., Lauber, B., & Gollhofer, A. (2011). The drop height determines neuromuscular adaptations and changes in jump performance in stretch-shortening cycle training. *Scand.J Med.Sci.Sports*.

Tellez T (1984). Sprinting from start to finish. *Track Technique,* 2802-2805.

Thomas K, French D, & Hayes P (2009). The effect of two plyometric training techniques on muscular power and agility in youth soccer players. *J Strength Cond.Res., 23,* 332-335.

Verkhoshansky Y & Siff M (2006). *Supertraining*.

Voigt, M., Dyhre-Poulsen, P., & Simonsen, E. B. (1998). Modulation of short latency stretch reflexes during human hopping. *Acta Physiol Scand., 163,* 181-194.

Weyand, P., Sternlight D, Bellizzi M, & Wright S (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol,* 1991-1999.

Wilson, G. J., Murphy, A., & Pryor, J. F. (1994). Musculotendinous stiffness: its relationship to eccentric, isometric and concentric performance. *J Appl Physiol, 76,* 2714-2719.

Wilt F (1978). Plyometrics - What it is and how it works. *Modern athlete and Coach, 16,* 9-12.

Young, W. & Farrow, D. (2006). A review of agility: Practical applications for strength and conditioning. *Strength Cond J, 28,* 24-29.

Young, W. B. (2006). Transfer of strength and power training to sports performance. *Int.J.Sports Physiol Perform.*, *1*, 74-83.

Zuur, A. T., Lundbye-Jensen, J., Leukel, C., Taube, W., Grey, M. J., Gollhofer, A. et al. (2010). Contribution of afferent feedback and descending drive to human hopping. *J Physiol*, *588*, 799-807.

Chapter 3 - co-authorship statement

I will address my contributions to this thesis in four statements:

1) This project was one of many ideas about training problems that Dr. David Behm and I discussed. Really Dr. Behm showed to me a world of new ideas in relation to the application of the electromyography to training drills. Together we designed the experimental methodology about the plyometric drills. All the equipment was provided by Dr. Behm or by laboratories of the School of Human Kinetics and Recreation – Memorial University of Newfoundland and Labrador.

2) All the athletes tested in this thesis were recruited thanks to the help of: Justin Murphy, Jacques Marais, Michelle Healey, Peter Benoitte and Scott Betts. The experimental methodology required two researchers at all times.

3) Raw data was collected by Tim Alkanani and Mike Harding and myself. With the guidance of Dr. Behm, I performed all data analysis procedures.

4) With the guidance of Dr. Behm, I prepared the manuscript.

Chapter 4 – Research study

4.1 Title: Neuromuscular characteristics of drop and hurdle jumps with different types of landings

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Original investigation

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Running Title: Drop Jump, Hurdle Jump, forefoot, flatfoot

4.2 Abstract

The objective of this study was to compare drop jumps (DJ) and hurdle jumps using a preferred (preferred), flat foot (FLAT) and fore foot (FORE) type of landing technique. Countermovement jump height was used to establish the hurdle and the DJ height. Subjects performed forward hurdles and vertical DJs on a force plate. The following variables were analyzed: vertical ground reaction force (VGRF), contact time, vertical stiffness and average rate of force development (RFD). Electromyographic (EMG) activity was measured in rectus femoris, biceps femoris, tibialis anterior and gastrocnemius during 3 phases: pre-activity, eccentric phase and concentric phase. All the kinetic variables showed a significant difference in favor of hurdles over DJs. Furthermore, hurdle preferred and FORE exhibited the shortest contact time and DJ FLAT the longest. The VGRF was higher in hurdle preferred and FORE than DJ preferred, FLAT and FORE. For stiffness and RFD, hurdle preferred and FORE were higher than DJ preferred and FLAT. Hurdle jumps showed higher rectus femoris EMG activity than DJ during pre-activity and eccentric phases but lower activity during concentric. Considering the type of landing, FLAT demonstrated the greatest activity. During the concentric phase, DJ exhibited the higher rectus femoris EMG activity. Biceps femoris activity was higher with hurdles in all phases. Gastrocnemius showed the highest EMG activity during concentric phase and during the eccentric phase hurdle

preferred and FORE showed the highest results. In conclusion, the hurdle FORE technique was the more powerful type of jump.
Key Words: plyometric, stretch-shortening cycle, electromyography, reaction forces, landing technique.

4.3 Introduction

Lower limb plyometric exercises combine speed and strength to produce an explosive-reactive movement (Debnam, 2007; Verkhoshansky and Siff, 2006). These exercise involve a cycling of eccentric (stretch) and concentric (shortening) muscle contractions cycle generally using the body as an overload stress (Schmidtbleicher, 1992; Cormie et al, 2011). Plyometric exercises use accumulated elastic energy during the eccentric phase of the contraction to help augment the concentric phase (Komi and Bosco, 1978). Furthermore the rapid stretch shortening cycle (SSC) plyometric activity is purported to cause an excitation of the muscle reflexes (Komi and Gollhofer, 1997). The flight phase in repeated jumps is characterized by an electromyographic pre-activity in the muscle (Ruan and Li, 2010). These exercises are utilized to increase the velocity of other specific sport movements such as change of direction, jumps, running and sprinting to increase the possibility of athletic success.

Although there are a great number of plyometric exercises, little is known about quantifying drill intensity and the optimal technique for an effective plyometric training program (Ebben et al, 2008). Plyometric activities can include drop jumps (DJ), hops, jumps over hurdles, bounding, countermovement jumps (CMJ) and others. These various activities may involve different movement speeds, electromyographic (EMG) activity, rate of force development, ground contact times, leg stiffness and reaction forces.

Generally, power training programs use a variety of plyometric exercises which may exceed more than 20 types a year (Miller et al, 2006). For this reason, it is important to know which exercises have the greatest power output or what landing technique must be used to induce changes in specific sport actions.

Coaches utilize jump drill training with a short contact time and maximal height or maximal velocity to induce changes in muscular power performance (Young et al, 2000; Young et al, 2001; Flanagan and Comyns, 2009; Bobbert et al, 1987a; Chelly et al., 2010; Ronnestad et al, 2008; Mcbride et al, 2002). Some examples of a short SSC are jumps over low to moderately high obstacles, sprinting, lateral hopping or drop jumps from low or optimal drop heights.

The current plyometric classifications do not recommend an appropriate or optimal landing technique for plyometric drills. However research has shown that landing on different parts of the foot can generate various amounts of power (Mero and Komi, 1994b; Bobbert et al, 1987a; Kovacs et al, 1999). Bobbert (1987a) showed that when a DJ was performed with a rebound technique (using just the fore foot) the force generated (4099 N) was higher than a DJ with a slow countermovement technique (2649 N) or a traditional CMJ jump (2094 N) (Bobbert et al, 1987a).

Accordingly, an optimal explosive-ballistic training exercise is a movement that uses similar contact time and force production as specific sport actions. In sports like soccer, tennis, rugby and others these actions are: maximal sprinting, running, change of direction, rapid decelerations, run-up and jump and jumping from a stationary position. With plyometric techniques coaches' attempt to increase explosive power, jump height and shorten contact time, in the hope that this training will be sport specific. This principle is called training specificity and the concept states that athletes must train similarly to the competitive environment (Behm and Sale, 1993).

It has been shown that a change of technique when performing drop jumps and hopping alters many kinematic and kinetic variables (Bobbert et al, 1987b; Kovacs et al, 1999; Young et al, 1995; Young et al, 1995; Arampatzis et al, 2001; Farley and Gonzalez, 1996). Jumps over obstacles are one of the most common types of plyometric drills used to increase power (Viitasalo et al, 1993a; Ruben et al, 2010a; Ronnestad et al, 2008; Aura and Viitasalo, 1989).

However, it is not known if a change of landing technique can generate changes in other variables in a similar form to those observed during DJs. Maybe it is possible with a simple technique instruction to positively modify training quality or specificity.

Thus, the main objective of this study was to compare the neuromuscular characteristics of two types of jumps: hurdle and DJ. In addition three types of landing techniques were investigated: preferred, flat foot and fore foot technique. It was hypothesized that hurdle jumps would be more powerful than DJs and that the flat foot technique would diminish mechanical power.

4.4 Methods

Subjects: Twenty five male athletes from Memorial University (9 volleyball players, 5 soccer players, 5 basketball players and 6 well trained recreational athletes) were assessed. Age, weight, height and years of training were the following 21.1 ± 4.5 yrs, 83.4 ± 10.9 kg, 184.4 ± 8.1 cm and 6.3 ± 4.1 yrs respectively. The data were collected during the athletes' competitive season. They refrained from performing any type of exercise 24 hours prior to the testing sessions. All participants provided written consent to participate in this study in accordance with the Memorial University of Newfoundland Human Investigation Committee. Subjects were informed of the all procedures. All the athletes (including the recreational) were accustomed to performing multiple plyometric drills. The typical volume of plyometric drills training performed by the athletes was over 100 repetitions per session and drills were generally performed as fast as possible minimizing contact time. The plyometric drills included different directions and were performed unilaterally and bilaterally. However none of the athletes had experience performing DJs. As the athletes were not familiar with DJs this test was the first assessed jump to avoid fatigue. The participant´s regular training also included resistance exercises. Exclusion criteria were any musculoskeletal injuries and any pain which did not allow the athlete to jump properly.

Experimental Approach to the Problem

Three landing techniques (preferred, flat foot, and fore foot technique) were performed during DJs and hurdle jumps and reaction forces, contact time, rate of force development and lower limb electromyographic (EMG) activity were measured. The first visit to the laboratory included general anthropometric measurements and an orientation to the jumps and tests procedures. The second visit to the laboratory was to assess jumps. During the experimental testing period, a general warm-up was followed by two trials of a maximum countermovement jump (CMJ) on a force platform. After calculating the maximum height reached during CMJ, the athletes randomly performed a series of drop jumps and jumps over hurdles bilaterally. The athletes performed drop jumps from a box and landed on the force platform. The athletes also jumped forward over two hurdles without stopping with the force plate positioned between the two hurdles. The height of the DJ and the hurdle height were set at 100% of the maximum height reached with the CMJ.

Protocol

All experimental sessions were performed late morning to early afternoon (between 10.00 and 14.00 hours). Athletes were hydrated ad libitum prior and during the test and wore their regular training shoes. All the jumps were assessed with the arms akimbo. The warm up consisted of 10 minutes of cycling at an intensity of 75 watts – 60 rpm followed by five sets of five submaximal hopping, five single submaximal CMJ and two maximal CMJ. Only dynamic stretching exercises were allowed during the warm up to avoid muscular power deficits associated with static stretching (Behm et al, 2001; Turki et al, 2011).

Then the subjects stood on the force platform and were asked to perform a maximal CMJ. Subjects did not receive any specific instructions about leg position or knee movement during the jump. Two trials were tested with one minute rest to avoid fatigue. The maximum CMJ height was used to establish DJ and hurdle jump height. The average flight time of the two trials of each jump was used to calculate jump height.

Since recently published data reported that CMJ does not involve a rapid stretch shortening cycle (SSC) movement, which is different than the hurdle jump (Cappa and Behm, 2011), the analyses did not consider differences between CMJ and the other two jumps. The order of DJ and hurdle jump tests was randomized. Five minutes of rest was allocated between DJ and hurdle jumps.

For the DJ the athletes stood on the edge of a box. Athletes were instructed to start the drop by leaning forward at takeoff and land bilaterally with both feet at the same time. For the preferred technique, the athletes received the following instructions: "jump as quickly and as high as possible". Subjects used the technique they believed was their best to reach the objective (quickly and high).

For the FLAT technique athletes were asked to perform the same DJ but land on the entire or flat foot (DJFLAT), with the same objective as before. Finally the athlete was asked to land just with the forefoot (DJFORE). The subjects were not allowed to touch the floor with the heel during this technique. Landing technique was strictly observed by two evaluators.

The athletes jumped forward over two hurdles with the force plate positioned between hurdles. Hurdles were spaced apart as the athletes requested. For all type of landings, the athletes were instructed to jump with two legs as fast as possible with no hesitation (feet shoulder width apart). For the preferred technique athletes repeated the same procedure as during the DJ. Athletes performed a flat foot landing touching the heel to the floor (HJFLAT) and as well as a fore foot landing technique with no heel supporting (HJFORE). The instruction for the hurdle jumps was to jump as fast as possible but not as high as possible. The take-off was strictly monitored with no intermediate jumps or delays during the eccentric-concentric transition phases. Two trials for each jump type were assessed.

Data collection

An AMTI force platform (400x600 x83 mm, model BP400600 HF-2000 - Watertown, MA02472-4800 USA) was used to evaluate the different jumps utilizing 2 axes. The force platform was connected to an amplifier (AMTI Miniamp MSA-6 – Gain 2000). NIAD software was used to collect data with a sample frequency of 2000 Hz. Force platform was calibrated by using the shunt technique provided by the company.

EMG surface electrodes (MediTrace 133, Kendall, 1-cm silver/silver chloride – Budlow Technical products ONT Canada) were placed on the mid-belly of the rectus femoris, biceps femoris, tibialis anterior and gastrocnemius. EMG activity was monitored and collected at 2000 Hz, amplified (bipolar differential amplifier, input impedance = 2 MΩ, common-mode rejection ratio >

110 dB min [50/60 Hz], gain ×1000, noise > 5μV), and analog-to-digitally converted with a 12 bit acquisition and analysis system (Biopac Systems, Santa Barbara, CA). The skin surface was prepared by shaving the zone, cleaning with alcohol and removing dead epithelial cells with abrasive sandpaper. The EMG signal was analyzed in three segments. It was analyzed 100 ms prior to the start of the jump (PRE), during the entire duration of the eccentric and concentric phases.

Data analysis

Contact time (ms) was defined as the sum of the eccentric and concentric phase time. Velocity was calculated by the following formula and was used to define the eccentric and concentric phases.

$$\text{Velocity m}\cdot\text{seg}^{-1} = F_z \cdot \Delta t / m$$

where F_z is the vertical ground reaction force, Δt is the time period and m is the athletes' mass. The eccentric phase was considered as a negative velocity and concentric phase as a positive velocity. Peak vertical ground reaction force (PVGRF) was the maximal force produced during the jump. Flight time was defined as the time the athlete stayed in the air after the jump.

Different analytical methods were used to identify the eccentric and concentric phases for the DJ s and hurdle jump. The same formula used for CMJ analysis cannot be implemented for DJ, since DJs do not start with a zero velocity. Therefore, the Voigt method was used to calculate velocity and determine eccentric and concentric phases (Voigt et al, 1995). Take-off velocity was estimated from flight time with the following equations:

1 - Δ height = 0.125 $g \cdot t^2$

2 – Velocity take-off = $\sqrt{2\, g\, \Delta \text{ height}}$

During the following integration of force the order of the movements that actually happened was reversed corresponding to a backwards integration with respect to time. Finally the following equation was used

$$3 - \text{Velocity m sec}^{-1} = -\int_{\text{Take-off}}^{\text{Touch-down}} (Fz / BM - g)\, \Delta t + \text{velocity take-off}$$

The touch-down represented the time when the toes touched the ground and take-off when the toes left the ground. F_z represents the vertical ground reaction force, g is the acceleration due to gravity and BM is the athletes' mass.

Sometimes DJs or hurdle jumps displays two separate force peaks. A two-peak force curve is typical of a FLAT landing technique. This curve is similar to other motor actions reported in the literature (Cavanagh and Lafortune, 1980; Cormack et al, 2008; Bencke et al, 2000). Since the hurdle jump method in the present study did not have the subject land on the force platform after the initial contact, the Voigt method was not applied. Alternatively the Cormack method (Cormack et al, 2008) which considers the end of the eccentric phase as the minimum vertical ground reaction force after the first peak force was used. This point can be found after the first force peak which is considered the weight absorption and is represented by a high frequency and passive force (Nigg et al, 1981).

Single peak force curves were the typical shapes for the FORE and preferred landing techniques. During the single peak curve the maximal value represents the separation of eccentric and concentric phases. This condition was controlled later with a goniometry (PS2137 Roseville, CA 95747 USA) during these types of jumps (data not published).

EMG

The data were offline analyzed with BIOPAC software. The raw EMG signals were amplified (1000) and bandpass-filtered (Blackman 62dB 10–500 Hz). The signal was integrated and root mean square was calculated. To analyze EMG activity during DJ and hurdle jump three periods were taken into account. One hundred milliseconds before contact time was considered the pre-landing phase. The full duration of the eccentric and concentric phase's time were analyzed.

Rate of force development

Average rate of force development (ARFD) was considered as the peak force developed during the concentric portion of the contraction divided by the time employed ($N \cdot sec^{-1}$) (McLellan et al, 2010).

Average rate of force development $N \cdot sec^{-1}$ = (AFCON – body weight (N) / CCT where AFCON is the average force applied during concentric phase and CCT was the time during concentric phase of all jumps.

Vertical stiffness

Another important variable used to understand differences in jump performance was vertical stiffness (McMahon et al, 1987). The following formula was used:

Vertical Stiffness $kN\ m^{-1}$ = body mass x w^2

where w is the natural frequency of oscillation

4.5 Statistical Analysis

The statistical analyses were completed using SPSS 17.0 for Windows (SPSS, Inc., Chicago, IL). A 3 way ANOVA 2x3x3 with repeated measure was employed to test for main effects between type of jump (DJ and hurdle jump), landing (preferred, FLAT and fore) and time phase (pre-landing, eccentric, concentric) during the jump. Significant main effects were further analyzed with Bonferroni adjusted pairwise comparison of within-subject differences among the variables. The criterion for significance was set at a level of F-ratios of $p \leq 0.05$. Effect sizes (ES = mean change / standard deviation of the sample scores) were also calculated and reported (Cohen, 1988). Cohen applied qualitative descriptors for the effect sizes with ratios of <0.41, 0.41-0.7, and >0.7 indicating small, moderate and large changes respectively. All data are reported as mean ± sd.

4.6 Results

Table 4.1 shows descriptive statistics and significant interactions for jump height, contact time, eccentric phase, concentric phase and VGRF for each type of jump.

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Insert table 4.1

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Contact time

There was a significant main effect for contact time. The hurdle jump had 36.9% shorter contact time compared with DJ ($p < 0.001$, F= 75.8, Effect size (ES) = 2.94). There was also a significant main effect for type of landing. The preferred technique had 29.1% shorter contact time than FLAT ($p < 0.001$, F= 28.5, ES = 1.51). Preferred technique had 9.6% longer contact time than FORE technique ($p < 0.05$, F= 28.5, ES = 2.06). Finally, FLAT type of landing had 25.9% longer contact period than FORE ($p < 0.001$, F= 28.5, ES = 2.5). Jump and landing type interactions showed a significant 23.8% shorter ground contact time for DJ FORE vs FLAT ($p<0.001$, F= 48.5, ES=2.3).

Eccentric contact time

A main effect for the type of jump indicated that hurdle jump had a 56.5% shorter contact period than DJ ($p < 0.001$, F= 119, ES = 4.16). Moreover, DJ FLAT showed a 21.4% longer eccentric contact time than DJ FORE ($p<0.01$, F= 124, ES=2.24).

Concentric contact time

For the concentric contact time, main effects for type of jump revealed that all hurdle jumps averaged 19.0% shorter contact period compared with DJ ($p < 0.001$, F= 14.6, ES = 2.27). Main effects for the type of landing showed that preferred technique had a 35.9% shorter, but a 12.0% longer concentric contact time than the FLAT technique ($p<0.001$, F= 53.5, ES=1.35) and FORE technique ($p<0.01$, F= 53.5, ES=2.10) respectively. Furthermore, FLAT technique had a 35.3% longer concentric contact time compared to the FORE technique ($p<0.001$, F= 48.5, ES=2.87). Significant interactions demonstrated that DJ preferred technique had a 29.0% shorter concentric contact time than

DJ FLAT ($p<0.001$, F= 46.4, EF=1.35). DJ FLAT had the longest concentric contact time of all techniques. It was 39.2%, 61.0% longer than DJ FORE ($p<0.001$, F= 46.4, EF=2.92). Table 4.2 shows significant interactions between DJ and hurdle jumps for concentric contact time during the all phases.

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Insert table 4.2

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Vertical Ground Reaction Forces

Main effect differences were found between types of jumps for the average vertical ground reaction force. Hurdle jump forces were 11.0% higher than DJ ($p < 0.001$, F= 18.0, ES = 1.71). The type of landings revealed main effect differences as well. FLAT technique showed 30.8% less reaction force than preferred technique ($p < 0.001$, F= 64.9, ES = 1.33) and 40.9% less than FORE techniques ($p < 0.001$, F= 64.9, ES = 1.44). Meanwhile, significant interactions showed that, DJ preferred technique had a significantly higher force (14.9%) than DJ FLAT ($p<0.05$, F= 69.5, EF=2.14). Moreover, DJ FLAT showed the lowest force level and had substantial differences with all the other jump categories. DJ FLAT was 25.9% lower than DJ FORE ($p<0.001$, F= 69.5, EF=1.35). Table 4.3 shows significant interactions between DJ and hurdle jumps for vertical ground reaction force.

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Insert table 4.3

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In order to illustrate more clearly which variables had the best performance during different jumps, the differences can be appreciated by viewing table 4.4 which shows the optimal result as 100% (bold font) in every variable (column) with the remaining variables relative (percentage of) to the optimal condition.

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Insert table 4.4

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Electromyography (EMG) results

Table 4.5 shows descriptive statistics for rectus femoris, biceps femoris, tibialis anterior and gastrocnemius during pre, eccentric and concentric contact phase.

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Insert table 4.5

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Rectus femoris

Main effects for rectus femoris EMG activity were found for type of jump, landing and contact phase. Hurdle jump showed a 30.0% higher EMG activity than DJ ($p<0.001$, $F=28.2$, $ES=2.49$). For the type of landing, it was found that the preferred technique had 18.4% lower activity than FLAT ($p<0.01$, $F=11.9$, $ES=1.46$). Meanwhile, FLAT technique had 47.0% higher activity than the FORE technique ($p<0.01$, $F=11.9$, $ES=2.14$).

Main effects for the contact phase showed that pre-landing had 275% and 204% less activity than eccentric ($p<0.01$, $F=95.4$, $ES=0.46$) and concentric phases ($p<0.001$, $F=95.4$, $ES=0.57$) respectively. Finally, the eccentric phase showed 18.8% more EMG activity than concentric phase of contraction ($p<0.01$, $F=95.4$, $ES=2.12$). Table 4.6 shows significant interactions between DJ and hurdle jumps for the EMG activity of the rectus femoris during all contact phases.

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Insert table 4.6

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Biceps femoris

Main effects for the biceps femoris EMG activity were analyzed and statistical differences were found for type of jump, landing and contact phase. DJ had 68.8% less EMG activity than hurdles ($p<0.001$, $F=24.0$, $ES=0.89$). Moreover, for the type of landing, it was found that preferred technique had 18.9% more EMG activity than FLAT ($p<0.01$, $F=23.0$, $ES=1.90$). Finally, pre-landing contact phase showed 135% and 212% less activity than eccentric (p<0.01, F=23.0, ES=0.65) and concentric phases (p<0.001, F=23.0, ES=0.49) respectively. Eccentric phase showed 32.7% lower EMG activity than concentric phase of contraction (p<0.001, F=23.0, ES=1.16). Table 4.7 shows significant interactions between DJ and hurdle jumps for the EMG activity of the biceps femoris during all contact phases.

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Insert table 4.7

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Tibialis anterior

Main effects for tibialis anterior were found for type of landing and contact phase. Preferred technique landing technique had a 36.4% less EMG activity than FLAT (p<0.001, F=23.0, ES=1.24) but 21.1% higher activity than FORE technique (p<0.001, F=23.0, ES=2.18). Finally, pre-landing contact phase showed 54.5% less activity than eccentric phase (p<0.01, F=23.0, ES=1.08). The eccentric phase exhibited 22.2% higher activity than CON (p<0.05, F=23.0, ES=2.12). Table 4.8 shows significant interactions between DJ and hurdle jumps for the EMG activity of the tibialis anterior during all contact phases.

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Insert table 4.8

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Gastrocnemius

Main effects for gastrocnemius showed statistical differences for the type of landing and the contact phase. Preferred technique had 26.3% more activity than FLAT ($p<0.001$, $F=29.8$, $ES=2.27$). In addition FLAT technique demonstrated 47.0% lower activity than FORE ($p<0.001$, $F=29.8$, $ES=1.13$). When the phases were analyzed, pre-landing showed 54.6% and 73.3% less activity than eccentric ($p<0.01$, $F=17.9$, $ES=1.09$) and concentric phases ($p<0.001$, $F=17.9$, $ES=0.99$) respectively. Table 4.9 shows significant interactions between DJ and hurdle jumps for the EMG activity of the gastrocnemius during all contact phases.

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Insert table 4.9

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Muscular Power

By analyzing DJ and hurdle jump results for the muscular power variables, the condition of sphericity was met in all conditions. Table 4.10 shows the descriptive statistics and significant interactions.

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Insert table 4.10

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Main effects for hurdle jump demonstrated 46.3% higher RFD than DJ ($p < 0.001$, F= 44.4, ES = 1.21). When type of landing was considered, FORE technique had the best result and was 11.3% higher than preferred technique ($p < 0.001$, F= 60.1, ES = 2.03) and 45.0% higher than FLAT ($p < 0.001$, F= 60.1, ES = 3.24). Furthermore, preferred technique was 38.0% higher than FLAT as well ($p < 0.001$, F= 60.1, ES = 2.85). Analyzing all jump categories, DJ preferred technique had a RFD 35% greater than DJ FLAT ($p<0.05$, F= 41.4, EF=2.21). However showed a 40.9% lower RFD than HJ preferred technique ($p<0.001$, F= 41.4, ES=1.00) and 43.6% lower than HJ FORE ($p<0.001$, F= 41.4, ES=0.96). DJ FLAT was the lower value of RFD representing 41.6% DJ FORE ($p<0.001$, F= 41.4, ES=0.98), 56.4% hurdle jump preferred technique ($p<0.001$, F= 41.4, ES=0.75) and 58.4% hurdle jump FORE ($p<0.001$, F= 41.4, ES=0.72). Finally, RFD during DJ FORE was 25.3% lower than hurdle jump preferred technique ($p<0.001$, F= 41.4, ES=1.31) and 28.7% lower than hurdle jump FORE ($p<0.001$, F= 41.4, ES=1.25).

Stiffness

Concerning leg stiffness, main effects for types of jumps and landing techniques were discovered. Hurdle jump were 64.0% stiffer than DJ ($p < 0.001$, F= 131, ES = 4.8). Preferred technique was 42.4% higher that FLAT ($p < 0.001$, F= 96, ES = 3.00). Significant interactions for all the jump categories showed that DJ preferred technique was 32.8% stiffer than DJ FLAT ($p<0.05$, F= 138, ES=2.39) but was 204%, 66.4% and 221% less stiff than hurdle jump preferred technique ($p<0.001$, F= 138, ES=0.55), hurdle jump FLAT ($p<0.05$, F= 138, ES=0.96) and hurdle jump FORE ($p<0.001$, F= 138, ES=0.52) respectively. DJ FLAT exhibited the least stiff technique. DJ FLAT was 76.0%, 354%, 147.9% and 379% less stiff than DJ FORE ($p<0.001$, F= 138, ES=0.94), hurdle jump preferred technique ($p<0.001$, F= 138, ES=7.75), hurdle jump FLAT ($p<0.001$, F= 138, ES=4.03) and with hurdle jump FORE ($p<0.001$, F= 138, ES=8.2) respectively.

Acceleration

Average acceleration results behaved in a similar manner as RFD. HJ were 17.4% higher than DJ ($p < 0.001$, F= 15.9, ES=1.58). When type of landing was considered, FLAT technique had the lowest acceleration and was 17.4% lower than preferred technique ($p < 0.001$, F= 27.0, ES = 1.57) and 22.3% lower than FORE ($p < 0.001$, F= 27.0, ES=1.53). When all jump interactions were analyzed, DJ PT had a 24.0% less acceleration than hurdle jump preferred technique ($p<0.001$, F= 15.6, ES=1.46) and 22.6% less than hurdle jump FORE ($p<0.05$, F= 15.6, ES=1.47). DJ FLAT was the lowest value of acceleration being 27.6%, 43.0%, 19.5% and 41.5% lower than DJ FORE ($p<0.001$, F= 15.6, ES=1.44), hurdle jump preferred technique ($p<0.001$, F= 15.6, ES=1.29), hurdle jump FLAT ($p<0.05$, F= 15.6, ES=1.54) and hurdle jump FORE ($p<0.001$, F= 15.6, ES=1.29) respectively.

4.7 Discussion

The most important finding in this study was that the FORE and preferred hurdle jump techniques were more powerful plyometric activities than DJ (all landing techniques). The second major finding was that the type of landing during a jump drill significantly influences muscular power. FORE and preferred landing technique provided the best results for all mechanical power variables.

Drop jump vs. hurdle jump

Hurdle jumps and DJ are two of the most popular plyometric training activities. Preferred and FORE hurdle jumps developed the greatest mechanical power. The literature provides conflicting findings with a number of publications in agreement with the results of the present study (Kovacs et al, 1999; Bobbert et al, 1987a; Young et al, 1995; Ebben et al, 2008; Aura and Viitasalo, 1989) while others recommended DJ as the highest intensity type of jump (Potach and Chu, 2008; Verkhoshansky, 1995).

The conflict in the literature may be related to the differing methodologies. In several studies, the drop height established was arbitrary. For example, drop heights of 20-60cm were employed even when the subjects had different training backgrounds (Kovacs et al, 1999; Bobbert et al, 1987a; Young et al, 1995). It is clear that the drop height condition affects the results (Walsh et al, 2004; Peng, 2011). The present study used an average drop height of 34.4 cm corresponding to 100% of maximal height reached in CMJ. The literature shows several studies with DJ heights higher than the maximal height reached by the athlete in a CMJ (Taube et al, 2011; Komi and Bosco, 1978; Leukel et al, 2011; Ruan and Li, 2010; Voigt et al, 1995). It is important to remember that such heights can generate reflex inhibition (Schmidtbleicher and Gollhofer, 1982; Gollhofer and Schmidtblecher, 1988). For example, a given drop height that induce a reflex inhibition for one athlete, could be the optimal training height for another.

To plan and implement DJ training, it is important to determine the optimal drop height. Two common methods are: the DJ maximum height (Komi, 1984) and the reactive strength index (Wilson et al, 1991; Flanagan and Comyns, 2009). If maximal jump height is the objective, the method applied in this study would not be recommended for moderately trained athletes as they may not able to reach the same height as their maximal CMJ. However if high muscle activation is the objective, Ishikawa showed that when the optimal height is decreased by 10 cm the gastrocnemius and vastus medialis show higher activation (Ishikawa et al, 2005).

Landing techniques

The force curves obtained in the present study were similar to the studies from the Kovac's laboratory (Kovacs et al, 1999; Mero and Komi, 1994a). When comparing heel-toe and FORE landing techniques Kovacs concluded that the heel-toe landing technique was- typical of long, triple and high jump meanwhile the forefoot landing represents other activities that must attenuate the shock force. This attenuation of shock force allows the athlete to develop more power in the following jump. Kovacs described a two-peak force curve for heel-toe landing technique and a single peak force curve for the forefoot landing. In the single peak force curve the author reported a small peak at the beginning of the foot contact (25 ms) which was also reported previously with forefoot landings during hurdle jumps (Cappa and Behm, 2011). This peak is small and can be seen at approximately 25-50% of the maximal peak force with a subsequent decrease of approximately 500-1000 N. The peak represents just the small knee flexion to perform the jump, the center of mass passing above the support point or the body accommodating searching for balance.

Bobbert et al (1987a) demonstrated a single peak force curve even with FLAT and FORE techniques. As the drop height was very low (20 cm) for volleyball players they could more easily reverse the eccentric force (i.e. the force impact was low) even with a FLAT technique. The contact times in Bobbert and present study were similar (364 - 400 ms). This long contact time has been attributed to the researcher´s instructions that generated a greater knee angle. In general the fast decrease of the center of mass is produced by the difficulty of the musculotendinous system to reverse the force. This was illustrated by Arampatzis et al (2001) when the center of mass descended from -10.5 to -16.5 cm increases when the drop height increased from 20 to 60 cm.

In another study Bobbert et al (1987b) changed the dropping height to 60 cm. The results showed a typical 2 peak force curve when dropping from 60 cm. The subjects were physically active with DJ experience but this height was probably too high for this type of training background.

Young analyzed the DJ from three different drop heights and gave the subject different instructions to jump: maximum height, minimum contact time and maximum height/minimum contact time (Young et al, 1995). As the drop height increased the percentage of the heel used during contact increased as well. This represents the difficulty of the plantar flexors muscles to absorb and reverse the descending force, especially in the 60 cm drop height.

Hurdle jump preferred and FORE techniques demonstrated higher RFD than all DJ techniques. Only the hurdle jump FLAT showed lower values than DJ preferred and FORE technique. The rationale for these results could be that when contacting the ground first with the heel or with a flat foot, there is an impediment for high mechanical power production due to the necessity of balancing the body (by flexing the knees) and this action increase the contact time and diminishes gastrocnemius and rectus femoris activation. A functional benefit of the FORE strategy is to minimize contact time and produce high mechanical power. In DJs the FORE strategy is effective if the optimal drop height is implemented. The increased mechanical power could be attributed to the elastic energy accumulated in the stretched plantar flexors during eccentric phase.

However, not all jumps which use a FLAT or heel-toe technique have low mechanical power. For example during a long jump Luthanen and Komi (1979) reported that a non-elite athlete generated 2001 N (126 watts$\cdot$kg^{-1}) whereas an elite athlete generated 3508 N (160 watts$\cdot$kg^{-1}) at the take-off even when they used a heel-toe technique. Perttunen et al (2000) assessed the vertical force during a triple jump and reported 7945, 10624 and 9056 N for the braking forces and 2535, 2680 and 2491 N for the propulsion forces during the hop, step and jump respectively. These braking forces generate a great high first peak in the force curve.

How was it possible to produce a high level of mechanical power when the present study established that the FLAT technique diminished the RFD? The horizontal velocity during these jumping techniques is extremely high. In the long jump the take-off release velocity was 8.40 and 7.09 m$\cdot$s^{-1} for elite and average athletes respectively and for the triple jump Perttunen et al (2000) reported 8.65 m$\cdot$s^{-1} for the last 5 m. With this horizontal velocity the athlete´s center of mass passes over the center of gravity very quickly and allows the system to behave like a spring (Farley and Gonzalez, 1996). The same principle can be applied for the difference between hurdle jump and DJ in this study.

There are far fewer studies investigating hurdle jumps versus DJs. Hurdle jumps are widely used in training but has received little attention in the literature. Furthermore, even less is known about the effects of repeated forward jumps over hurdles. To my knowledge, only four studies have investigated variables associated with this type of jump (Viitasalo et al, 1993b; Ruben et al, 2010b; Smith et al, 2011; Cappa and Behm, 2011). None of these investigations studied different type of landings. This study is the only study to demonstrate decreased power when employing a FLAT style landing technique with hurdle jumps.

Ruben et al (2010a) reported an average of 3373 N for hurdle jumps without clarifying the landing technique. As he used the instruction to "jump as fast as possible", it is likely the subjects used the FORE technique. The present study generated an average of 4880 N when using the FORE technique. The difference may be based on the concept that when the hurdle height is too high the force and power decreases while the contact time increases (Cappa and Behm, 2011). Ruben´s study set the hurdle height at 5.1 cm above the patella which correspond to 65.2 cm.

In this study DJ FORE showed the highest vertical force of all DJ landing techniques (3633 N). This force is less than those produced by all hurdle landing techniques even though the objective of the DJ is vertical height compared to forward hurdle jumps which must combine vertical and horizontal forces. Hurdle jumps showed more vertical force when using FORE and preferred landing technique even when part of the force is produced in a horizontal direction.

The degree of muscle stiffness is an important factor when performing powerful movements such sprints, jumps and changes of directions. Gollhofer et al (1992) reported that during the first 40 ms of the DJ ground contact, length muscle changes were not controlled by neuronal activation. Therefore during this early phase the muscle stiffness must be controlled by muscle pre-activation. Dietz et al (1979) showed that the EMG activity prior to ground contact represents an action with a central command as well. Other than the CMJ which does not have a previous flight phase, the FLAT technique had the least pre-landing gastrocnemius EMG activity. It is possible that during a FLAT landing style the supraspinal centers anticipate that the objective of the landing was not to produce the greatest amount of force in anticipation of another movement. This is supported by the EMG pre-activation level of tibialis anterior where DJ and HJ FLAT techniques showed the highest level. Hence, the FLAT technique is the most optimal for the absorption of force.

Meanwhile hurdle jump FORE and preferred and DJ FORE and preferred showed at least 50% higher EMG pre-activity than FLAT techniques. Dietz et al (1984) and Gollhofer and Schmidtbleicher (1989) have reported that if an activated muscle is stretched forcefully high stretch reflex activation should be expected. To increase mechanical power in activities which show a flight phase prior to contact, the plyometric training should include activities with a FORE landing technique.

As biceps femoris is a hip extensor that helps in the forward movement and rectus femoris is a knee extensor, all the hurdle jumps showed the highest EMG level and again this confirms the importance of pre-activity to generate muscle stiffness.

EMG analysis during eccentric and concentric phase

Comparing EMG plyometric results between studies can be difficult as the various studies use different normalization procedures. For example Bobbert et al (1987a) used results from CMJ to normalize DJ FORE and FLAT while Peng et al (2011) normalized EMG signal with a maximal isometric voluntary contraction.

In the present study the rectus femoris during CMJ showed the lowest activation during the eccentric phase but the highest during concentric phase. However, all DJs showed similar results during the concentric phase but exhibited greater eccentric activation. This response can be attributed to the higher activation of the stretch reflexes with SSC during the absorption of the landing. All hurdle jumps showed less activation than DJ for the eccentric phase because of the forward direction of the jump. In contrast during hurdle jumps the biceps femoris as a hip extensor showed the highest values when moving the center of mass forward. There is a growing interest in the analysis of horizontal jumps since typical sport movements require muscle preloading, horizontal as well as vertical forces and unilateral propulsion (Holm et al, 2008; Maulder and Cronin, 2005; Stalbom et al, 2007).

To my knowledge, there are no studies that have assessed horizontal DJ and EMG. However Ruan and Li (2010) tested an horizontal approach to dropping. This type of approach increased the EMG activity during the push-off phase for the gastrocnemius and rectus femoris due to the horizontal force component.

In the present study the tibialis anterior exhibited unique behavior compared to the rectus femoris and biceps femoris since with all techniques there was an increase in activation from pre-activity to the eccentric phase except for the hurdle jump FORE. All the hurdle jumps presented the highest levels during the concentric phase. Since only with hurdle jumps were necessary to overcome a subsequent obstacle the athlete must dorsiflex when jumping over the next hurdle to pass clearly. Hence increased tibialis anterior activity would be expected in these instances.

The gastrocnemius increased muscle activity from the pre-activity to the eccentric phase for all jumps. However, the CMJ exhibited the lowest values compared with hurdle and DJs. During the concentric phase all the hurdle jumps and DJs increased the activation above the CMJ due to the augmentation associated with the prior SSC.

Conclusion

The results showed that hurdle jumps FORE technique generated the highest mechanical power compared with all the DJ and hurdle techniques. This high muscular power was possible because this technique had the highest muscle pre-activation prior to land and the highest muscular stiffness during the eccentric phase. This was corroborated with the EMG activity during pre and eccentric phases. In addition hurdle FORE generated the highest RFD and average acceleration. This means that jumping forward over hurdles landing with the forefoot seems to be one of the best techniques to develop muscular power. FORE technique was better than preferred technique and therefore it is demonstrated that a coach instruction can change the power production during training.

4.9 Bibliography

Reference List

Arampatzis, A., Schade, F., Walsh, M., & Bruggemann, G. P. (2001). Influence of leg stiffness and its effect on myodynamic jumping performance. *J. Electromyogr. Kinesiol., 11,* 355-364.

Aura, O. & Viitasalo, J. (1989). Biomechanical characteristics of jumping. *Int. J. Sport Biomec, 1989,* 89-98.

Behm, D. G., Button, D. C., & Butt, J. C. (2001). Factors affecting force loss with prolonged stretching. *Can.J.Appl.Physiol, 26,* 261-272.

Behm, D. G. & Sale, D. G. (1993). Velocity specificity of resistance training. *Sports Med., 15,* 374-388.

Bencke, J., Naesborg H, Simonsen, E., & Klausen K (2000). Motor pattern of the knee joint muscles during side-step cutting in European team handball. *Scand. J. Med. Sci. Spor,* 68-77.

Bobbert, M. F., Huijing, P. A., & van Ingen Schenau, G. J. (1987a). Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. *Med.Sci.Sports Exerc., 19,* 332-338.

Bobbert, M. F., Huijing, P. A., & van Ingen Schenau, G. J. (1987b). Drop jumping. II. The influence of dropping height on the biomechanics of drop jumping. *Med.Sci.Sports Exerc., 19,* 339-346.

Cappa, D. F. & Behm, D. G. (2011). Training Specificity of Hurdle vs. Countermovement Jump Training. *J Strength Cond.Res.* 25, 10, 2715-2720.

Cavanagh, P. R. & Lafortune, M. A. (1980). Ground reaction forces in distance running. *J Biomech., 13,* 397-406.

Chelly, M. S., Ghenem, M. A., Abid, K., Hermassi, S., Tabka, Z., & Shephard, R. J. (2010). Effects of in-season short-term plyometric training program on leg power, jump- and sprint performance of soccer players. *J Strength Cond.Res., 24,* 2670-2676.

Cormack S, Newton R, McGuigan M, & Doyle T (2008). Reliability of measurements obtained during single and repeated countermovement jumps. *Int. J. Spor. Phys. Perf.,* 131-144.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2011). Developing maximal neuromuscular power: part 2 - training considerations for improving maximal power production. *Sports Med., 41,* 125-146.

Debnam, M., (2007). Plyometric training. *Modern athlete and coach, 45,* 5.

Dietz, V., Quintern, J., & Berger, W. (1984). Corrective reactions to stumbling in man: functional significance of spinal and transcortical reflexes. *Neurosci.Lett., 44,* 131-135.

Dietz, V., Schmidtblecher, D., & Noth, J. (1979). Neuronal Mechanisms of Human Locomotion. *J. Neurophysiol., 42,* 1212-1222.

Ebben, W. P., Simenz, C., & Jensen, R. L. (2008). Evaluation of plyometric intensity using electromyography. *J.Strength Cond.Res., 22,* 861-868.

Farley, C. T. & Gonzalez, O. (1996). Leg stiffness and stride frequency in human running. *J.Biomech., 29,* 181-186.

Flanagan E & Comyns T (2009). The use of contact time and the reactive strength index to optimize fast stretch-shortening cycle training. *Strength Cond., 30,* 32-38.

Gollhofer, A. & Schmidtblecher, D. (1988). Muscle activation patterns of human leg extensors and force-time characteristics in jumping exercises under increased stretching loads. In (pp. 143-147). Free university Press Amsterdam.

Gollhofer, A. & Schmidtbleicher, D. (1989). Stretch reflex responses of the human M. Triceps surae following mechanical stimulation. In Gregor R J, Zernicke RF, & Whiting WC (Eds.), *University of California, Los Angeles* (pp. 219-220).

Gollhofer, A., Strojnik, V., Rapp, W., & Schweizer, L. (1992). Behaviour of triceps surae muscle-tendon complex in different jump conditions. *Eur J Appl Physiol Occup.Physiol, 64,* 283-291.

Holm, D. J., Stalbom, M., Keogh, J. W., & Cronin, J. (2008). Relationship between the kinetics and kinematics of a unilateral horizontal drop jump to sprint performance. *J Strength Cond.Res., 22,* 1589-1596.

Ishikawa, M., Niemela, E., & Komi, P. V. (2005). Interaction between fascicle and tendinous tissues in short-contact stretch-shortening cycle exercise with varying eccentric intensities. *J Appl Physiol, 99,* 217-223.

Komi P & Gollhofer, A. (1997). Stretch reflexes can have an important role in force enhacement during SSC exercise. *J.Appl Biomec, 13,* 451-460.

Komi, P. (1984). Physiological and biomechanical correlates of muscle function:effects of muscle structure and stretch-shortening cycle on force and speed. *Exercise sport sc, 12,* 81-121.

Komi, P. V. & Bosco, C. (1978). Utilization of stored elastic energy in leg extensor muscles by men and women. *Med.Sci.Sports Exerc., 10,* 261-265.

Kovacs, I., Tihanyi, J., Devita, P., Racz, L., Barrier, J., & Hortobagyi, T. (1999). Foot placement modifies kinematics and kinetics during drop jumping. *Med.Sci.Sports Exerc., 31,* 708-716.

Leukel, C., Taube, W., Lorch, M., & Gollhofer, A. (2011). Changes in predictive motor control in drop-jumps based on uncertainties in task execution. *Hum.Mov Sci.*.

Luhtanen, P. & Komi P.V. (1979). Mechanical power and segmental contribution to force impulses in long jump take-off. *Eur J Appl Physiol,* 267-274.

Maulder, P. & Cronin, J. (2005). Horizontal and vertical jump assessment: reliability, symmetry, discriminative and predictive ability. *Phys.Ther.Sport, 6,* 74-82.

Mcbride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (2002). The effect of heavy- vs. light-load jump squats on the development of strength, power and speed. *J Strength Cond.Res, 16,* 75-82.

McLellan C, Lowell D, & Gass G (2010). The role of the rate of force development during a countermovement jump performance. *J Strength Cond.Res, 23.*

McMahon, T. A., Valiant, G., & Frederick, E. C. (1987). Groucho running. *J Appl Physiol, 62,* 2326-2337.

Mero A & Komi P (1994a). EMG, force and power analysis of sprint-specific strength exercises. *J Appl Physiol,* 1-13.

Mero A & Komi P (1994b). EMG, Force, and Power Analysis of Sprint-Specific Strength Exercises. *J Appl Physiol, 10,* 1-13.

Miller, M., Herniman, J., Ricard, M., Cheatham, C., & Michael, T. (2006). The effects of a 6-week plyometric training program on agility. *J. Sport Sci Med, 5,* 459-465.

Nigg B, Denoth J, & Neukomm P (1981). Quantifying the load on the human body: problems and some possible solutions. In Morecki A, Fidelus K, Kedzior K, & Wit A (Eds.), *Biomechanics VII* (pp. 88-99). Baltimore: University Park Press.

Peng, H. T. (2011). Changes in biomechanical properties during drop jumps of incremental height. *J Strength Cond.Res., 25,* 2510-2518.

Peng, H. T., Kernozek, T. W., & Song, C. Y. (2011). Quadricep and hamstring activation during drop jumps with changes in drop height. *Phys.Ther.Sport, 12,* 127-132.

Perttunen, J. O., Kyrolainen, H., Komi, P. V., & Heinonen, A. (2000). Biomechanical loading in the triple jump. *J Sports Sci., 18,* 363-370.

Potach D & Chu D (2008). Plyometrics training. In Baechle T & Earle R (Eds.), *Essentials of strength training and conditioning - third edition* (3 ed., Human Kinetics Publisher.

Ronnestad, B. R., Kvamme, N. H., Sunde, A., & Raastad, T. (2008). Short-term effects of strength and plyometric training on sprint and jump performance in professional soccer players. *J Strength Cond.Res., 22,* 773-780.

Ruan M & Li L (2010). Approach run increases preactivation and eccentric phases muscle activity during drop jumps from different drop heights. *J Electromyogr Kin, 20,* 932-938.

Ruben, R. M., Molinari, M. A., Bibbee, C. A., Childress, M. A., Harman, M. S., Reed, K. P. et al. (2010a). The acute effects of an ascending squat protocol on performance during horizontal plyometric jumps. *J Strength Cond.Res., 24,* 358-369.

Ruben, R. M., Molinari, M. A., Bibbee, C. A., Childress, M. A., Harman, M. S., Reed, K. P. et al. (2010b). The acute effects of an ascending squat protocol on performance during horizontal plyometric jumps. *J Strength Cond.Res., 24,* 358-369.

Schmidtbleicher D & Gollhofer, A. (1982). Neuromuskulare untersuchungen zur bestimmung individueller belastunggrossen fur ein teifsprungtraining. *Leistungssport, 12,* 298-307.

Schmidtbleicher, D. (1992). Training for power events. In P.V.Komi (Ed.), *Strength and Power in Sport* (First Edition ed., pp. 381-395). Oxford, U.K.: Blackwell Publishers.

Smith, J. P., Kernozek, T. W., Kline, D. E., & Wright, G. A. (2011). Kinematic and kinetic variations among three depth jump conditions in male NCAA division III athletes. *J Strength Cond.Res., 25,* 94-102.

Stalbom M, Holm D, Cronin J, & Keogh J (2007). Reliability of kinematics and kinetics associated with Horizontal Single leg drop jump assessment. A brief report. *J. Sport Sci Med, 6,* 261-264.

Taube, W., Leukel, C., Lauber, B., & Gollhofer, A. (2011). The drop height determines neuromuscular adaptations and changes in jump performance in stretch-shortening cycle training. *Scand.J Med.Sci.Sports.*

Turki, O., Chaouachi, A., Drinkwater, E. J., Chtara, M., Chamari, K., Amri, M. et al. (2011). Ten minutes of dynamic stretching is sufficient to potentiate vertical jump performance characteristics. *J Strength Cond.Res., 25,* 2453-2463.

Verkhoshansky Y (1995). Means and methods: resistance exercises. In *Special Strength Training: Practical Manual for Coaches* (First ed., pp. 15-31). Rome: Verkhoshansky.

Verkhoshansky Y & Siff M (2006). *Supertraining.*

Viitasalo, J. T., Hamalainen, K., Mononen, H. V., Salo, A., & Lahtinen, J. (1993a). Biomechanical effects of fatigue during continuous hurdle jumping. *J Sports Sci., 11,* 503-509.

Viitasalo, J. T., Hamalainen, K., Mononen, H. V., Salo, A., & Lahtinen, J. (1993b). Biomechanical effects of fatigue during continuous hurdle jumping. *J Sports Sci., 11,* 503-509.

Voigt, M., Simonsen, E. B., Dyhre-Poulsen, P., & Klausen, K. (1995). Mechanical and muscular factors influencing the performance in maximal vertical jumping after different prestretch loads. *J Biomech., 28,* 293-307.

Walsh, M., Arampatzis, A., Schade, F., & Bruggemann, G. P. (2004). The effect of drop jump starting height and contact time on power, work performed, and moment of force. *J.Strength Cond.Res., 18,* 561-566.

Wilson, G. J., Wood, G. A., & Elliot, B. C. (1991). Optimal stiffness of series elastic component in a stretch-shorten cycle activity. *J Appl Phys, 70,* 825-833.

Young, W., Pryor, J. F., & Wilson, G. (1995). Effect of instructions on characteristics of countermovement jump and drop jump performance. *J.Strength Cond.Res., 9,* 232-236.

Young, W., Wilson, G., & Byrne, C. (2000). A comparison of drop jump training methods: Effects on leg extensor strength qualities and jumping performance. *Int J Sport Med, 20,* 295-203.

Young, W. B., MacDonald, C., & Flowers, M. A. (2001). Validity of double- and single-leg vertical jumps as tests of leg extensor muscle function. *J.Strength Cond.Res., 15,* 6-11.

Table 4.1: Descriptive statistics for jump height, total contact time, eccentric contact time, concentric contact time and ground reaction force.

The following symbols represent the following significant differences:

A percentage sign (%) represents significant difference from CMJ $p<0.01$, an asterisk (*) represents significant difference from the drop jump preferred technique $p<0.001$, double asterisk (**) represents significant difference from the drop jump preferred technique $p<0.05$, addition symbol (+) represents significant difference from drop jump FLAT $p<0.001$ and the number symbol (#) represents significant difference from drop jump FORE $p < 0.001$.

	Height cm	Contact time ms	Eccentric contact time ms	Concentric contact time ms	Concentric Peak ground reaction force N
CMJ	34.4 ± 4.2	852 ± 153.2	576 ± 107.6	273 ± 56.2	2040 ± 451
DJ preferred	32.2 ± 4.4 %	323.3 ± 91.5	153.5 ± 43.9	169.2 ± 55.0	3167 ± 806.8
DJ FLAT	33.3 ± 4.2	364.4 ± 85.9 #	171.0 ± 58.4	193.4 ± 43.8 * +	2693 ± 524.7 **
DJ FORE	32.2 ± 3.9 %	277.6 ± 66.8 +	134.3 ± 40.1 +	143.2 ± 34.8 +	3633 ± 945.9 +
HJ preferred	----	181.0 ± 22.3 * + #	67.8 ± 14.8 * + #	113.1 ± 17.6 *+ #	4730 ± 762.4 *+#
HJ FLAT	----	250.2 ± 61.7 ** +	59.6 ± 21.5 * + #	190.5 ± 59.9 +	3345 ± 545.2 +
HJ FORE	----	177.9 ± 25.5 * + #	72.1 ± 19.1 * + #	105.7 ± 14.5 *+#	4880 ± 731.5 *+#

Table 4.2: Statistically significant interactions for total, eccentric and concentric contact times. The percentage differences reported, represent the change between the vertical column as compared to the horizontal column. For example, DJ preferred had a 44% longer total contact time than hurdle preferred technique. Increasing arrows represent a longer contact time whereas the decreasing arrows represent a shorter contact time. ES= effect size

Total Contact Time			
	Hurdle Preferred	Hurdle FORE	Hurdle FLAT
DJ Preferred	↑ 44% $p<0.001$ F= 48.5 ES=3.29	↑ 44.9% $p<0.001$ F= 48.5 ES=3.33	↑ 22.6% $p<0.05$ F= 48.5 ES=2.32
DJ FORE	↑ 34.7% $p<0.001$ F= 48.5 ES=2.85	↑ 35.9% $p<0.001$ F= 48.5 ES=2.88	
DJ FLAT	↑ 50.3% $p<0.001$ F= 48.5 ES=3.74	↑ 51.1% $p<0.001$ F= 48.5 ES=3.79	↑ 31.3% $p<0.001$ F= 48.5 ES=2.64
Eccentric Contact Time			
DJ Preferred	↑ 55.6% $p<0.001$ F= 124 ES=4.09	↑ 52.8% $p<0.001$ F= 124 ES=3.81	↑ 61% $p<0.001$ F= 124 ES=4.53
DJ FORE	↑ 46.3% $p<0.001$ F= 124 ES=3.57	↑ 55.6% $p<0.001$ F= 124 ES=3.32	↑ 49.5% $p<0.001$ F= 124 ES=3.95
DJ FLAT	↑ 60.3% $p<0.001$ F= 124 ES=4.50	↑ 57.8% $p<0.001$ F= 124 ES=4.20	↑ 65.1% $p<0.001$ F= 124 ES=4.98
Concentric Contact Time			
DJ Preferred	↑ 49% $p<0.001$ F= 46.4 ES=3.5	↑ 52.7% $p<0.001$ F= 46.4 ES=3.82	

DJ FORE	↑ 46.3% p<0.001 F= 124 ES=3.57	↑ 55.6% p<0.001 F= 124 ES=3.32	↑ 49.5% p<0.001 F= 124 ES=3.95
DJ FLAT	↑ 61% p<0.001 F= 124 ES=4.50	↑ 63.5% p<0.001 F= 124 ES=4.20	↑ 34.3% p<0.001 F= 124 ES=4.98

Table 4.3: Statistically significant interactions for Vertical Ground Reaction Forces. The percentage differences reported, represent the change between the vertical column as compared to the horizontal column. For example, DJ preferred had a 14.9% higher force than DJ FLAT. Increasing arrows represent a higher ground reaction force whereas the decreasing arrows represent a lower ground reaction force. ES= effect size

Vertical Ground Reaction Forces			
	Hurdle Preferred	Hurdle FORE	Hurdle FLAT
DJ Preferred	↓ 33.0% p<0.001 F= 69.5 ES=1.2	↓ 35.0% p<0.001 F= 69.5 ES=1.19	
DJ FORE	↓ 23.0 % p<0.001 F= 69.5 EF=1.41	↓ 25.6% p<0.001 F= 69.5 EF=1.37	
DJ FLAT	↓ 43.1% p<0.05 F= 69.5 ES=1.06	↓1 9.5% p<0.001 F= 69.5 ES=1.03	↓ 44.8% p<0.001 F= 69.5 ES=1.49

Table 4.4: Table shows the optimal value as 100% for each variable with the other variables illustrated as a percentage of the optimal value. Optimal values for contact time were the shortest duration whereas the optimal value for reaction forces was the greatest values.

	Jump Height cm	Contact Time ms	Eccentric contact time ms	Concentric contact time ms	Concentric Peak ground reaction force N
CMJ	**100**	481	976	260	41
DJ preferred	93.6	182	259	160	64
DJ FLAT	96.8	205	289	183	55
DJ FORE	93.6	156	227	136	74
Hurdle jump preferred	----	102	113	107	96
Hurdle jump FLAT	----	141	**100**	180	68
Hurdle jump FORE	----	**100**	122	**100**	**100**

Table 4.5. Descriptive statistic of EMG activity for rectus femoris, biceps femoris, tibialis anterior and gastrocnemius during pre, eccentric and concentric phases. Data are in mV

Rectus femoris	**Pre-contact**	**Eccentric**	**Concentric**
DJ Preferred	0.037 ± 0.005	0.179 ± 0.017	0.226 ± 0.018
DJ FLAT	0.045 ± 0.005	0.174 ± 0.018	0.242 ± 0.018
DJ FORE	0.031 ± 0.004	0.181 ± 0.02	0.208 ± 0.019
Hurdle Preferred	0.057 ± 0.005	0.172 ± 0.016	0.042 ± 0.006
Hurdle FLAT	0.061 ± 0.007	0.2 ± 0.015	0.124 ± 0.021
Hurdle FORE	0.058 ± 0.006	0.173 ± 0.013	0.033 ± 0.005
Biceps Femoris			
DJ Preferred	0.031 ± 0.004	0.097 ± 0.034	0.117 ± 0.014
DJ FLAT	0.025 ± 0.004	0.061 ± 0.009	0.114 ± 0.011
DJ FORE	0.031 ± 0.005	0.09 ± 0.025	0.127 ± 0.022
Hurdle Preferred	0.082 ± 0.016	0.167 ± 0.021	0.17 ± 0.024
Hurdle FLAT	0.052 ± 0.009	0.11 ± 0.018	0.181 ± 0.04
Hurdle FORE	0.068 ± 0.01	0.151 ± 0.016	0.191 ± 0.041
Tibialis anterior			
DJ Preferred	0.075 ± 0.007	0.188 ± 0.03	0.119 ± 0.025
DJ FLAT	0.122 ± 0.018	0.248 ± 0.028	0.107 ± 0.012
DJ FORE	0.068 ± 0.007	0.14 ± 0.019	0.071 ± 0.012
Hurdle Preferred	0.086 ± 0.009	0.096 ± 0.015	0.145 ± 0.012
Hurdle FLAT	0.159 ± 0.017	0.184 ± 0.022	0.143 ± 0.015
Hurdle FORE	0.083 ± 0.007	0.064 ± 0.004	0.132 ± 0.014
Gastrocnemius			
DJ Preferred	0.17 ± 0.017	0.196 ± 0.098	0.265 ± 0.019
DJ FLAT	0.116 ± 0.015	0.177 ± 0.045	0.262 ± 0.022
DJ FORE	0.181 ± 0.017	0.259 ± 0.044	0.285 ± 0.022
Hurdle Preferred	0.162 ± 0.013	0.308 ± 0.027	0.265 ± 0.028

Hurdle FLAT	0.094 ± 0.012	0.128 ± 0.021	0.238 ± 0.025
Hurdle FORE	0.177 ± 0.016	0.323 ± 0.03	0.256 ± 0.028

Table 4.6: Statistically significant interactions for EMG rectus femoris during the pre-contact and concentric phase. The percentage differences reported, represent the change between the vertical column as compared to the horizontal column. For example, DJ preferred had a 35% lower EMG activity than hurdle preferred. Increasing arrows represent a higher ground reaction force whereas the decreasing arrows represent a lower EMG activity. ES= effect size

EMG Rectus femoris – Pre-contact phase			
	Hurdle Preferred	Hurdle FORE	Hurdle FLAT
DJ Preferred	↓ 35% $p<0.05$ F= 190 ES=2.53	↓ 36.2% $p<0.01$ F= 190 ES=2.53	↓ 39.3% $p<0.05$ F= 190 ES=2.63
DJ FORE	↓ 45.6% $p<0.001$ F= 190 ES=2.97	↓ 49.1% $p<0.05$ F= 190 ES=3.08	↓ 49.1% $p<0.01$ F= 190 ES=2.97
EMG Rectus femoris – Concentric contact phase			
DJ Preferred	↑ 81.4% $p<0.001$ F= 192 ES=8.66	↑ 85.3% $p<0.001$ F= 192 ES=10.9	↑ 45.1% $p<0.01$ F= 192 ES=2.86
DJ FORE	↑ 79.8% $p<0.001$ F= 192 ES=7.87	↑ 84.1% $p<0.001$ F= 192 ES=9.9	↑ 40.3% $p<0.05$ F= 192 ES=2.06
DJ FLAT	↑ 82.6% $p<0.001$ F= 192 ES=9.33	↑ 86.3% $p<0.001$ F= 192 ES=11.7	↑ 48.7% $p<0.001$ F= 192 ES=3.09

Table 4.7: Statistically significant interactions for EMG biceps femoris during the pre-contact and eccentric phase. The percentage differences reported, represent the change between the vertical column as compared to the horizontal column. For example, DJ preferred had a 62.1% lower EMG activity than hurdle preferred. Increasing arrows represent a higher ground reaction force whereas the decreasing arrows represent a lower EMG activity. ES= effect size

EMG Biceps femoris – pre-contact phase		
	Hurdle Preferred	Hurdle FORE
DJ Preferred	↓ 62.1% $p<0.01$ F=57.3 ES=3.77	↓ 54.4% $p<0.05$ F=57.3 ES=3.3
DJ FORE	↓ 69.5% $p<0.01$ F=57.3 ES=3.77	↓ 63.2% $p<0.01$ F=57.3 ES=3.31
DJ FLAT	↓ 62.1% $p<0.01$ F= 57.3 ES=3.66	↓ 54.4% $p<0.05$ F= 57.3 ES=3.22
EMG Biceps femoris – eccentric contact phase		
DJ FLAT	↓ 63.4% $p<0.001$ F=56.3 ES=4.17	↓ 59.6% $p<0.001$ F= 56.3 ES=3.85

Table 4.8: Statistically significant interactions for EMG tibialis anterior during the pre-contact, eccentric and concentric phases. The percentage differences reported, represent the change between the vertical column as compared to the horizontal column. For example, DJ preferred had a 52.8% lower EMG activity than hurdle FLAT. Increasing arrows represent a higher ground reaction force whereas the decreasing arrows represent a lower EMG activity. ES= effect size

EMG tibialis anterior – pre-contact phase			
	Hurdle Preferred	Hurdle FORE	Hurdle FLAT
DJ Preferred			↓ 52.8% $p<0.01$ $F=195$ ES=3.46
DJ FORE			↓ 57.2% $p<0.001$ $F= 195$ ES=3.78
EMG tibialis anterior – eccentric phase			
DJ Preferred		↑ 65.9% $p<0.01$ $F=96.7$ ES=4.6	
DJ FLAT	↑ 61.2% $p<0.001$ $F= 96.7$ ES=3.9	↑ 74.1% $p<0.001$ $F= 96.7$ ES=6.4	
EMG tibialis anterior – concentric phase			
DJ FORE	↓ 51.% $p<0.01$ $F=149$ ES=3.2	↓ 46% $p<0.05$ $F= 149$ ES=2.8	↓ 50.3% $p<0.01$ $F= 149$ ES=3

Table 4.9: Statistically significant interactions for EMG gastrocnemius during the pre-contact phase. The percentage differences reported, represent the change between the vertical column as compared to the horizontal column. For example, DJ preferred had a 35.9% higher EMG activity than DJ FLAT. Increasing arrows represent a higher EMG activity whereas the decreasing arrows represent a lower EMG activity. ES= effect size

EMG Gastrocnemius – pre-contact phase			
	Hurdle Preferred	Hurdle FORE	Hurdle FLAT
DJ Preferred			↑ 44.7% $p<0.01$ F= 186 ES=2.78
DJ FORE			↑ 48% $p<0.001$ F= 186 ES=3
DJ FLAT		↓ 34.4% $p<0.05$ F= 186 ES=2.45	
EMG Gastrocnemius – concentric phase			
DJ Preferred	↓ 36.3% $p<0.01$ F= 82.5 ES=2.5	↓ 39.3% $p<0.01$ F= 82.5 ES=2.6	
DJ FORE			↑ 50.5% $p<0.05$ F= 82.5 ES=2.88

Table 4.10: Table shows descriptive statistics for average acceleration, average rate of force development and stiffness for each type of jump. The following symbols represent the following significant differences: An asterisk (*) represents significant difference from drop jump preferred technique $p<0.001$, double asterisk (**) represents significant difference from drop jump preferred technique $p<0.05$, addition symbol (+) represents significant difference from drop jump FLAT $p<0.001$, double addition symbols (++) represents significant difference drop jump FLAT; $p<0.05$ and the number symbol (#) represents significant difference from drop jump FORE $p < 0.001$.

	Average acceleration $m\ s^{-2}$	Average rate force development $N\ s^{-1}$	Stiffness $kN\ m^{-1}$
CMJ	9.8 ± 2.14	1609 ± 227.4	5.2 ± 2.45
DJ preferred	15.0 ± 4.59	8292 ± 4490.0	14.3 ± 8.16
DJFLAT	13.0 ± 3.15	6120 ± 2745.8 **	9.6 ± 5.39 ** #
DJFORE	16.6 ± 3.48 +	10484 ± 4044.3 +	16.9 ± 7.46 +
Hurdle jump preferred	18.6 ± 3.38 *+	14031 ± 3266.1 * + #	43.6 ± 12.87 * + #
Hurdle jump FLAT	15.5 ± 3.43 ++	7708 ± 2646.4	23.8 ± 12.41 ** +
Hurdle jump FORE	18.4 ± 3.53 ** +	14700 ± 3419.1 * + #	46.0± 12.3 * + #