The Biomechanics of Jumping

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Introduction

The main task for any level of coach is to construct a training program that will ensure continual progression of an athlete whilst avoiding injury. This is a particularly challenging task with athletes who have had several training years behind them. According to the principles of training, to ensure adaptation, overload in the form of manipulating frequency, volume and intensity must be applied. Furthermore, training exercises must be specific to the target task to ensure a carry over effect. Biomechanics is a sports science sub-discipline which is able to quantify the potential effect of training exercises, rather than leaving it to the coaches "gut feel".

In explosive events like the field events, athletes of all abilities require high levels of leg power to be successful. Power is a term that is used loosely by a number of coaches, therefore, a correct definition is necessary. Strictly speaking power is the product of force and velocity, thus, power is the expression of strength at speed.

Jumping ability may be improved via several methods as outlined by Baker (1996) in his review of types of strength training to improve the vertical jump. These methods may include:

* General strength exercises - These exercises are necessary to develop the force component of power. Squat exercises such as full squats, front squats, half squats, and splits squats, develop the jumping musculature to a large degree. Very few, if any, successful high level field event athletes would not have good squatting ability. Even in novice athletes, some form of squatting could be performed with medicine balls or shot puts to challenge the jumping musculature. Although there is great benefit in performing general strength exercises such as squats and its variants, one must be careful not to use the squat as an end in itself as these exercises are slow in nature thus do not replicate the exact demands of the power events.

* Special strength exercises - These exercises attempt to convert general strength to specific jumping strength. Some examples may include Olympic lifts and their variants and jump squats. There is some research (eg. Canavan et al., 1996) to suggest that the Olympic lifts are very similar in structure to a vertical jump. As jumping and throwing events have some component in the vertical direction the Olympic lifts are excellent exercises for these events.

* Specific strength exercises - These exercises are necessary to develop the velocity component of power and attempt to provide power improvement in a way which is specific to the required technique of an athlete. Examples of such exercises would include, bounding and hopping, weighted bounding and hopping in addition to single and double legged box jumps.
If you want to know more about methods to improve leg power, the reader is referred to the review by Baker (1996) pertaining to strength training methods to improve the vertical jump.

This article discusses why the field event athlete needs high levels of jumping ability, the research into specific jumping strength exercises and how they might fit into a periodised, field event athlete's program. I should outline that in this article I will not attempt to list every possible method to develop specific leg power in field event athletes as there already exists plenty of this type of information in the coaching literature. However, I will attempt to act as the "middle man" between the sports scientist and the coach and explain in layman's terms what the biomechanics research into jumping can potentially mean to the practising field event coach.

**Why is Jump Training is a Necessity for Field Event Athletes?**

Prior to discussing why jumps are necessary to the field event athlete, some preliminary discussion of the concepts of contact time, ground reaction force, impulse and momentum has to be undertaken.

Contact time is the period of time in which a foot, or feet, are in contact with the ground during an activity. This is of importance as the body cannot generate force to increase velocity or change direction without foot contact. The most specific exercises for an event are firstly, those in which the contact times approximate that of the event and secondly, whose demands on the neuromuscular system are similar to the event. This is why general strength exercises such as squats are not an end in themselves. They are an excellent exercise for developing the force component of power but the period of time in which force is generated in the relevant musculature (maybe a number of seconds for heavy squats) far exceeds the contact times for example, a hammer thrower. The velocity component of power needs to be trained via another method.

Ground reaction force is as it's name suggests, is the reaction force as a result of applying a force to the ground. Every action has an equal an opposite reaction. Impulse is a concept which is typically difficult to understand to those new to biomechanics. Put simply, it is the product of the ground reaction force and time. Momentum is the product of mass and velocity. For example, a ten pin bowling ball has a lot of momentum when it has firstly, a lot of weight and secondly, a lot of velocity.

The impulse-momentum relationship is expressed as follows:

\[
\text{Impulse} = \text{Change in Momentum}
\]

Which broken down into its components as outlined above results in the following:

\[
\text{Force} \times \text{Time} = \text{Mass} \times \text{Change in Velocity}
\]

When expressed this way, an athlete must apply a force over a time period (ie impulse) to change velocity. Change in velocity must be considered as not just a change in numerical value, but also as a change in direction. To place this in a field event coaches context, in the hop to step transition phase of the triple jump, just prior to foot contact, the athlete may have a horizontal velocity of 9.8 metres per second and a downward vertical velocity of 2.4 metres per second. After the step take-off the horizontal
velocity may be reduced to 8.6 metres per second and the vertical velocity is now an upward 2.0 metres per second, resulting in a take-off angle of 13 degrees. All of this may happen in 140 milliseconds (msec), that is 0.14 seconds.

During the hop-step transition a couple of things occurred. Firstly, horizontal velocity decreased in the direction of travel and secondly, vertical velocity decreased in value but changed direction from downwards to upwards. These changes occurred because of the ground reaction forces acting on the body. In the horizontal direction the athlete decreased speed because of what is termed a braking force which produces a force against the direction of travel. In the vertical direction, initially the accelerated downwards by gravity but the athlete then applies a force to the ground so that the reaction force is directed upwards, therefore the athlete produces velocity upwards to gain lift.

To illustrate how tough the triple jump is on the body, by assuming this triple jumper had a mass of 75kg it can be calculated that the average ground reaction force during the hop to step transition was 428 Newtons (N) (1kg = 9.8 Newtons) in the horizontal direction and 2357N in the vertical direction. When considering the body weight of the jumper, this is a force equivalent to 0.6 times body weight in the horizontal direction and 3.2 times body weight in the vertical direction. Whilst these figures may not seem excessive at first glance, consider that the peak vertical force could be expected to be up to approximately 15 times body weight and the peak horizontal force may be seven times body weight (Perttunen et al, 2000).

In both the horizontal jumps (long jump and triple jump) and the high jump, obviously jump training is a central part of training (Bianco et al, 1996). These jumps involve partial conversion of horizontal to vertical velocity as evidenced by the take-off angles involved in each of these events.

The need for jump training in the pole vault maybe a little less obvious. In the pole vault one of the key determinants of success is approach speed (McGinnis, 1989). Jump training such as bounding should be part of the training to develop speed. Furthermore, leg power is required to jump into the take-off. High level pole vault coaches talk about the pole vault take-off being similar in structure to that of the long jump. Examination of the biomechanical data from the 1988 Olympics supports this premise (Gros and Kunkel, 1990)

In the long jump the approach velocities are the fastest of all the jumps and contact times may range from 100-120 milliseconds. In the triple jump, pole vault and high jump these contact times may increase up to 0.18 of a second in the elite performer. The key to generating great distance in a jump, is to generate a high amount of ground reaction force within the very short period that the foot is on the ground.

As the angle of take-off increases, there is a greater need to convert horizontal velocity to vertical velocity, as the vertical velocity determines the height that someone an athlete will jump. Therefore, the foot needs to be on the ground long enough to generate sufficient ground reaction force to convert to vertical velocity. The contact time will depend upon the technique of the performer also. For example, there is some evidence that a triple jumper who utilises a single arm technique will have a shorter
contact time than someone who utilises a double arm technique. Further, the high jumper that utilises the speed flop technique will probably have a shorter contact time than that of a power flopper.

Tschiene (1988) outlined the extremely high level of jumping ability of elite throwers, for example, a standing long jump of 3.40-3.50m and 2.80-2.90m for males and females respectively. Hence to have developed this ability to such a level, a high emphasis in training must have been given to developing this jumping ability. This is supported by the discussions of high level coaches into training programs of throwers (eg. Abdelmalek et al., 1994; Agachi et al., 1997; Arbeit et al., 1997; Egger et al., 1994).

In the throwing events, we also must look at the demands of the activity to assess why such high levels of leg power are required to successfully undertake an activity. Firstly, from the data presented in Bartoneitz and Borgstrom (1995) and Bartoneitz et al. (1996), all the throws begin from the legs. Furthermore, the non-throwing side leg must effectively brace to so that non-throwing side of the body is stabilised (Bartoneitz and Borgstrom, 1995). Data from the abovementioned papers also outlines that the legs must be activated very quickly, for example, in the hammer throw, single support times range from 0.18 to 0.34 seconds and double support times range from 0.20 to 0.40 seconds. Furthermore, in the javelin, the duration between planting of the non-throwing leg and javelin release of selected women's finalists was 0.12 secs.

The Biomechanics of Jumping: The Application to Periodisation of Training

Manipulating intensity in a periodised program by altering exercise demands is an essential part of a correctly structured training program. To assess the demands of jumping exercises we need to examine a few biomechanical studies. The following is a discussion of selected papers from the biomechanics literature and how their findings might be applied in coaching.

Prior to discussing these papers however, a few concepts have to be outlined. When training out in the field, purely concentric strength (where the muscle shortens to overcome resistance) in the quadriceps may be developed by jumping up onto a box from a position where the knee is at 90 degrees. Conversely, eccentric strength (where a contraction involving muscle lengthening occurs) may be developed by jumping down from a box and finishing in a 90 degree position. Pure concentric or eccentric strength in field event athletes may also be developed via exercises in the weight room for example, concentric strength may be expressed in the quadriceps in the upward phase in the squat whereas eccentric strength would be expressed in the downward phase of the squat. The difference between the two methods of developing concentric and eccentric strength lies in the time of force application. Again, squats develop the force component of power and the box jumps develop the velocity component of power.

There is a place in most training programs for developing either concentric or eccentric strength however, it is a combination of these two forms of strength in varying proportions that is most commonly trained via jumping activities. For example, in alternate leg bounding, an eccentric contraction of the quadriceps assists in the body resisting collapse, whilst a concentric of the quadriceps assists in propelling the body off the ground. The combination of an eccentric action quickly followed by a concentric action develops elastic strength.
Research Study 1 Aura and Viitasalo (1989) High level male high jumpers (2.12m, 2.14m, 2.24m) and a triple jumper (16.74m) performed bounding and hopping exercises, drop jumps off a 52 cm box and a flop style high jump. These are typical exercises in a jumper’s training program. The study recorded the ground reaction forces, contact times of the activities and muscle activity (electromyography or EMG). This study showed that the most specific training for the high jump was the activity itself. The training exercises aimed at developing elastic strength did not replicate the contact times, ground reaction forces and EMG values recorded during the high jump.

The Application: If high jumping itself generates the maximal stimulus then why not high jump all the time? The fact that ground reaction forces are high and contact times are low, means that intensity is high, especially in the eccentric portion of the jump. Whilst quick progression will be probably occur due to repetitive high intensity activity, the athlete will more than likely get injured in a short space of time. Furthermore, the training effect will gradually decrease over time due to the lack of variety. Intensity could be adjusted by altering the length of the approach run or changing the jumping surface (if you shorten the run up, or change from an artificial track surface to grass, the ground reaction forces will also decrease). Various bounding and hopping activities provide a sound sub-maximal training stimulus for jumpers in general and specific preparation. In addition, these exercises are a very good power generation activity for throwers.

Research Study 2 Bobbert et al (1987a) Three types of jumps were examined in this study. They were a counter movement jump (CMJ), a counter drop jump off a 20cm box (CDJ) and a bounce drop jump off a 20cm box (BDJ). In the CDJ, the bend in the knees was exaggerated during the downward phase (ie. exaggerating the length of the eccentric phase) and in the BDJ the downward movement was reversed as quickly as possible. Results from this study were that the highest ground reaction force values were achieved by the BDJ as were the shortest contact times.

The Application: At first glance, the choice of the best training exercise seems obvious. The BDJ has the highest force demands in the shortest time period. However, a closer examination of the data revealed that most of the power output was from the ankle joint musculature, which would have been, in part, transferred to the ankle from higher up the kinetic chain ie from the hip and knee joint muscles (Jacobs et al., 1996). If the field event in question involves a large vertical component (for example, in the high jump) or requires ankle plantarflexion (for example, in the javelin cross steps) then the BDJ could be used in training. A cautionary note however, on excessive use of the BDJ in training. The anatomical structures of the lower limbs are heavily loaded in this form of jump which would cause an increased predisposition to injury. If high volume training is required, such as in the triple jump, a CDJ would be a better choice.

Research Study 3 Bobbert et al (1987b) This study compared power outputs of the ankle joint, knee joint and hip joint musculature in the drop heights from 20,40 and 60 cms in six physical education students. It was found that the optimal drop height was between 20 and 40 cms.
The Application: The applicability of this research for athletes who require high levels of elastic strength such as jumpers, is low as Young (1995) showed that untrained people and athletes who don't require elastic strength display lower optimal drop heights (the optimal drop height was 75 cms for an experienced high jumper). These results could be transferred however, to novice athletes with low levels of elastic strength. In short, if you are wanting to develop elastic strength in novice athletes, keep the drop height low for the best results.

Research Study 4 van Soest et al (1985) Biomechanical data was collected on well trained volleyball players who performed one-legged and two-legged vertical countermovement jumps. Jumping height in one-legged was approximately 58% of that reached in two-legged jumps. Therefore, in the one-legged jump more work was produced per leg during push-off.

The Application: A high degree of overload can be achieved in one-legged jumping exercises. In correctly periodised programs when a lower intensity is required, double-legged exercises such as repeat double leg jumps may be used. Conversely, closer to competition time, single legged bounding may be utilised. Be careful however with heavier athletes performing an extensive amount of single legged jumps. Because they are heavier they will generate high ground reaction forces which could cause injury.

Research Study 5 Stefanyshyn and Nigg (1998) Five male basketballers and four male long jumpers (7.05m - 7.53m) performed running vertical and running long jumps respectively. An examination of the lower limb energetics revealed that the movement pattern is quite similar. The ankle was the largest energy generator and absorber for both jumps. The percentage contribution of the ankle decreased in running long jumps (because they are more horizontally directed) whilst the hip musculature contribution increased.

The Application: Due to the high demands on the ankle joint according their analysis, the authors suggested that attention should be given to the gastroc-soleus complex in the training of jumpers. When interpreting this data however, one needs to examine the research of Jacobs et al. (1996) who stated that power output from the hip and knee joints via one joint muscles was transferred to the lower extremities by the two joint muscles (muscles that cross two joints such as a portion of the quadriceps). This suggests that these researchers may have overstated the importance of the ankle joint in horizontal jumpers. The main finding is that the ankle joint is more important as the take-off angle increases.

Conclusions

With the abovementioned research in mind, the process of deciding what exercises to place in a periodised program becomes somewhat easier. The progression of exercises for an field event athlete therefore, might be:

* General Preparation - Choose jumping exercises that have larger contact times and develop both concentric and eccentric strength, the components of elastic strength. You may develop eccentric strength via jumping down from obstacles such as a steeplechase hurdle or boxes and concentric strength may be developed via incline bounding and stair jumps. Jumps with a weighted jacket may also develop eccentric and concentric strength. As the volume of jumping continually increases in this phase,
most of these exercises could be done grass rather than an artificial track surface. Also, two-legged jumps are less stressful on the body than one-legged jumps, so a greater volume of these could be done.

* Specific Preparation - This is the period of the year where most athletes get injured as both volume and intensity are relatively high. Faster one-legged jumping exercises such as bounding and hopping would decrease contact times. This could be done by increasing the approach speed into the series of jumps. Box jumps emphasising fast rebound would be a good option in this phase of training. The athlete also needs to think about start progressing to harder surfaces. Ground reaction forces are higher so volume has to start decreasing. The amount of double-legged jumps may also decrease.

* Competition Season - The main emphasis in training should be on exercises that produce the most specific adaptations. For example, the proportion of technical jumps by all jumpers should at their highest. For throwers, the contact times should be decreased so that the exercises meet the demands of their specific event.

References


