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Plyometric exercises: Optimizing the Transfer of Training Gains to Sport Performance

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ABSTRACT

Rapid force production and its transmission to the skeleton are important factors in movements that involve the stretch-shortening cycle. Plyometric exercises are known to augment this cycle and thereby improve the neuromechanical function of the muscle. However, the training exercises that maximize translation of these gains to sports performance are not well defined. We discuss ways to improve this transfer.

SUMMARY FOR TABLE OF CONTENTS: This perspective for progress article examines the most appropriate plyometric exercises and training modalities to optimize the transfer of training adaptations to sport performance.

KEY WORDS

Jump height; Explosive force; Stretch-shortening cycle; Rate of force development; Reactivity index; Tendon stiffness; Ground contact time

KEY POINTS

- Plyometric exercises are known to augment the efficacy of the stretch-shortening cycle and thereby improve the neuromechanical function of the muscle during fast "reactive-type" movements.
- The improvement in performance can be explained by adaptations within both the nervous system and the muscle-tendon complex after several weeks of plyometric training.

- In addition to the total training volume, the magnitude of these adaptations appears to be specific to the individual's characteristic and experience, the type of plyometric exercises, and the specific training modalities employed.
- In this perspective for progress paper, we highlight several gaps in the existing literature to be addressed in future studies, with particular focus on the transfer of training gains to specific sport disciplines.

INTRODUCTION

Plyometric exercises are commonly included in the training programs of athletes involved in sport activities as a means to increase "explosive" force (i.e., rate of force development or RFD) (1–3). These exercises are utilized to enhance the neuromechanical function of the muscle during the "stretch-shortening cycle". This cycle, which is involved in most fast and reactive movements and in particular in sport activities, comprises a rapid stretch of an active muscle-tendon unit before it performs a shortening contraction [see 4]. By increasing the magnitude of muscle-tendon loading during the stretching (lengthening) phase of the cycle and by improving the transition between this phase and the following shortening phase (5), plyometric exercises can acutely increase the amount of force, power, and RFD produced by the muscle compared with a shortening contraction alone (4,6,7).

Although review articles have documented that repeated workouts with plyometric exercises can improve athletic performance, such as sprinting and jumping events (1,2,8–10), contrasting results in performance gains and adaptations in both muscle activity and characteristics of the muscle-tendon unit have been reported between studies (1). Among other variables, the differing adaptations may depend on individual characteristics, jumping modalities, type of ground surface, training volume, and periodization (Figure 1). In addition, the type of exercise used to assess the improvement in performance (identical or different from sport-specific movements) and its combination with other training modalities can influence the magnitude and specificity of the adaptations (1,9). However, how isolated training gains translate into improved sports performance is currently not well known.

The primary objective of this perspective for progress article, therefore, is to discuss the most relevant plyometric exercises and training modalities that may optimize the transfer into enhanced sports performance.

DETERMINANTS OF EXPLOSIVE FORCE

The rate at which force is produced and transmitted to the skeleton (i.e., RFD) during isometric and shortening contractions is a major determinant of athletic performance (e.g., punches in boxing or karate, kicking, force impulse in sprinting, etc) in which the time to develop force is so brief (<200 ms) that only a fraction of the maximal force can be produced. The RFD is often used as an index of "explosive" force for such actions (11–13). The RFD is influenced by several factors such as the intensity of voluntary activation (12,14,15), the speed-related properties of the muscle (11,16,17) and the characteristics of the series elastic component of the muscle-tendon unit (18,19). The relative contribution of these variables to the instantaneous force produced vary during the time course of the contraction (11,17). Furthermore, in multi-joint actions, such as in jumps, the force produced results from the sequential involvement of synergistic muscles (i.e., coordination). In contrast, the RFD during longer duration actions (≥ 300 ms), such as for the leg extensor muscles during the squat jump (SJ), is not an exclusive predictor of vertical jump height (20) and it appears that the contribution of the maximal force capacity becomes increasingly more important than the other variables (20–23).

Most movements, however, typically involve an initial stretch of the muscle-tendon unit as muscle is activated before it shorten subsequently (i.e., stretch-shortening cycle); (4). A classic example of this action is the lengthening and then shortening of the muscle-tendon unit of the plantar flexors and knee extensors after foot strike in running. At initial foot contact with the ground (braking phase), the leg extensor muscles must resist to the impact and subsequent stretch, which is immediately followed by a shortening contraction (propulsive phase). The efficacy of this strategy was studied by Kawakami and colleagues (24) when they compared the behavior of muscle fascicles as measured by ultrasonography in the medial gastrocnemius during rapid plantarflexion performed against a load with or without countermovement of the ankle joint. Kawakami et al. (21) observed a gradual shortening of the gastrocnemius medialis fascicles throughout the extension of the ankle joints when the action was executed without countermovement (propulsive phase only). In contrast, the muscle fascicles experienced an initial stretch when the ankle was flexed during the start of the countermovement before remaining at a nearly constant length (isometric contraction) for most of the dorsiflexion phase, and finally performing active shortening as the ankle extended. Nonetheless, faster stretch-shortening actions (<200-250 ms; (25,26)) and higher impact load, such as during the ground contact phase in drop jumps, are characterized by brief isometric phase between the braking and propulsive phases, at least in mono-articular muscles fascicles [see 4, 22]. Indeed, different behaviors in fascicle length changes not only between mono (soleus) and biarticular (medial gastrocnemius) muscles but also drop jumps from different heights have been reported (22). These observations underline the task specificity of the changes in fascicle length and thereby, the adjustments that can be elicited in different types of the stretch-shortening cycle.

Several neuromuscular processes have been suggested to explain the superior muscle performance during the stretch-shortening cycle. First, the muscle becomes more fully activated after an initial lengthening due to the increase in time to develop force relative to a shortening contraction performed from a resting condition (27,28) and the potential benefit of residual force enhancement mechanism (29). As a consequence, the area under the force-length curve is greater during the stretch-shortening cycle due to the greater force generated at the onset of the stretching (lengthening) phase which in turn, allows greater storage of elastic energy in the muscle-tendon unit (21). Second, the energy stored in the series elastic components of the muscle-tendon unit during the stretch phase is reused, as in a spring, during the subsequent shortening contraction (4,24). Third, the stretch reflex elicited at the onset of the contact phase of a high impact load (e.g., drop jump) augments the excitatory synaptic input to motor neurons at the beginning of the propulsive phase (4,30–32). Although, the relative contribution of these neuromechanical factors to the enhanced performance of the stretch-shortening cycle is still under discussion, as it can vary between different types of actions (slow vs. fast stretch-shortening cycle; with or without impact, load intensity), muscle groups (mono vs. pluri-articular) and training status of individuals. Furthermore, for movements during which muscle pre-activation is present before ground contact (e.g. running, drop jump), its intensity can modulate joint stiffness at ground contact and thereby the relative contribution of these mechanisms during the subsequent stretch-shortening cycle (4).

CHARACTERISTICS OF PLYOMETRIC EXERCISES

Plyometric exercises were first introduced by Verkhosansky (33) in the training programs of athletes involved in power events as a means to increase "reactive" force production (34). These exercises appear to augment the efficacy of the stretch-shortening cycle and thereby the performance of athletes, by increasing muscle-tendon loading during the braking phase and by decreasing the duration of the transition between the braking and propulsive phases (i.e., coupling time; see below; 5).

Although plyometric exercises can target either lower or upper limb muscles, a classic exercise used to increase vertical jump height is the drop jump exercise. It involves a vertical jump that is performed immediately after a dropping down from an elevated surface. We will mainly focus on the vertical jump in this article because it has been studied frequently and is more easily standardized than other jump types.

Optimal jump height

Although jump height is increased when the drop height is increased, there is an optimum in the acute augmentation in performance. This can be easily observed by comparing drop jumps executed from increasing heights, which increases the mechanical load during the braking phase. The height of the vertical jump (rebound) after ground contact first increases with drop height, to reach a maximum, and then decline (breaking point) for higher drop heights (Figure 2A; (35–37)). In parallel, contact time increases gradually with increasing drop heights (Figure 2B; (36,37)) due to the longer time needed to resist (brake) the increasing vertical impact forces at ground contact and to produce maximal impulse (force-time integral) during the propulsive phase (38). These attributes are sometimes used to determine a “reactivity” index, which is computed as the ratio of the maximal jump height attained relative to the contact time (Figure 2C; (36,37)). This index characterizes the ability to produce high forces with the leg extensors during a brief period of time (i.e., reactive force production; (36,37)).

The optimal drop height for maximal jumping performance raises the question of which factors are responsible for the decline in performance beyond that height? A first explanation is the tolerance to high impact loads and thus the ratio between the individual resistive force capacity and the amount of mechanical load produced by both the impact force (peak vertical ground reaction force) and the intervention of the stretch reflex (4,31). It has been proposed that high mechanical loads during the braking phase can produce slipping or detachment of cross-bridges between myofilaments (4). Despite the limitation of the ultrasonographic method, this hypothesis is indirectly supported by recording the changes in fascicle length in the medial gastrocnemius under submaximal and extreme impact loads. In the latter condition, muscle fascicles showed a sudden increase in length immediately after ground contact but not with lower impact loads (39). This sudden increases in fascicle length is considered indicative of the critical stretch load beyond which muscle fascicles lose their capacity to utilize effectively muscle-tendon elasticity (4). Importantly, this response appears to differ slightly among synergistic muscles (e.g., increasing drop height may result in specific length change patterns of the fascicles of the bi-articular medial gastrocnemius but not of the mono-articular soleus; see (25)). Indeed, a slight increase in knee flexion due to increasing landing impacts can influence the fascicles length of the medial gastrocnemius but not of the soleus.

Another factor that can influence the optimal drop height is the variation in the neural control of the stretch-shortening cycle. It has been observed that the amplitude of the plantar flexor EMG activity increases gradually before ground contact (pre-activation phase) for drop jumps of increasing heights (~20-100 cm; see (40,41)). This modulation appears to be preprogrammed by the CNS (feedforward control) in anticipation of the expected ground reaction force, thereby controlling the compliance of the limbs at landing (42–44). This adjustment appears to differ across tasks and to depend on the individual's training status (see below; (31)). The observation of a decline in EMG activity during the pre-activation phase, just before ground contact of "extreme" drop jumps (>70 cm) in some studies (25,40) but not all (30) or in untrained individuals (40), may be indicative of a preventative strategy to limit the magnitude of stress forces on the muscle-tendon unit during landing.

During the braking phase, the EMG amplitude which is influenced by both central and short-latency stretch reflex differs between the training status of individuals. In untrained individuals, a high pre-activation EMG activity is often followed by a low EMG activity during the braking phase whereas in trained individuals, the opposite is observed (40). The first EMG peak after touch-down strongly relies on Ia-afferent feedback (short-latency stretch-reflex) as indicated by concurrent increases in Hoffmann-reflex amplitude (45). Furthermore, in trained individuals, soleus EMG amplitude in the first ~50 ms after ground contact increases with drop height (from 20 to 60 cm) but decreases at greater heights (80 cm) (see (30,36)). Regardless of the exact source of this decrease in EMG amplitude during the braking phase, these changes suggest either a decreased facilitation from muscle spindles or an increased inhibition acting at pre- and post-synaptic sites of the motor neuron pool (for more detailed explanations, see (31)).

In practical context, the optimal jump height and reactivity index can either occur at the same or different drop heights. More often, maximal jump performance peaks at higher drop heights than the reactivity index (Figure 2; (46)). Because the main objective of such drop jump exercises is to improve reactive force, training height that maximizes the reactivity index is often chosen. However, the adopted strategy can depend on the requirements of the sport discipline (see below). For example, peak jump height in elite track & field athletes is obtained at greater drop heights for triple jumpers (80-100 cm) than for sprinters (40-60 cm) (see (47)). This difference emphasizes the capacity of triple jumpers to optimize the stretch-shortening cycle performance relative to the mechanical loads encountered in their athletic discipline (~15 times body weight).

Landing technique

The type of jump performed, particularly the landing technique, can influence jump performance. For example, minimizing the amount of knee flexion during ground contact (i.e., bounce-type drop jump) increases the peak reaction forces at the knee and ankle joints and the force transmitted by the Achilles tendon relative to those observed during larger knee-flexion jumps [i.e. CMJ drop jump] (see (48)). It is likely that the stress force generated in the bi-articular gastrocnemius at ground contact during bounce-type drop jump is greater than during jumps with more knee flexion. For example, the gastrocnemii are stretched at a shorter length during the CMJ, thereby reducing the load on the Achilles tendon (37,49) but, however, increasing the stress on the patellar tendon at landing compared with bounce-type drop jump during which knee angle is nearly fully extended. Therefore, it is expected that these two landing techniques (bounce-type drop jump and CMJ-type drop jump) involve contrasting adaptations in Achilles and patellar tendon properties (see (37)).

Other jumping conditions

Coaches must also consider the type of stance (bilateral vs. unilateral) when the athlete is jumping and the direction of the applied vertical and horizontal forces according to the specificity of the sport discipline. Indeed, as the control of balance and coordination differ between one-legged and two-legged jumps and the direction of the applied forces, the intensity and the timing of activation of the involved muscles vary according to the type of stance (50). In addition to the potential effect of bilateral deficit (51), the greater load (body weight) applied on a single leg during unilateral compared with bilateral jumps likely influences the amount of stress exerted on the tendons.

The ground surface (athletic track, rubber floor, sprung surface, grass and sand) may further influence jumping performance. It was recently reported that drop jumps from 40 cm onto sand, for example, reduces jump height (~20%), vertical reaction force, and power output, but increases RFD, work, knee-joint range of motion, and peak ankle angular velocity during the downward phase (52). Due to the greater compliance of sand relative to a rigid surface, it can provide injury prevention under demands for large energy expenditure (53). Although training on a compliant surface can reduce injury risk, jumping on harder surfaces allow a more reactive jump and briefer contact time. Consequently, the preferred jump surface should depend on the objective of the training program and on the specific requirements of the sporting activity. Hard surfaces are preferred for most athletic disciplines, such as sprinting and jumping, whereas compliant surfaces (sand or foam mat) are better suited for training of beach volleyball players and some gymnastic activities, for example.

As indicated in Figure 1, these characteristics must be considered when attempting to optimize the transfer of plyometric training adaptations to sport performance (i.e., concept of specificity of the adaptations; (54,55)). This concept predicts that the closer the training routine mimics the desired outcome (i.e., a specific exercise task to match a performance criterion), the better will be the outcome (Hawley 2008). The next sections will illustrate some of these specific adaptations in response to plyometric training.

PLYOMETRIC TRAINING

A training program that includes plyometric exercises can improve vertical jump height (see (2,9,56)) and athletic performance (e.g., sprinting and jumping events; (1)). Although plyometric training can also reduce the incidence of injuries (57) and improve bone mineral content, density, and structural properties (58,59), at least during childhood and adolescence, our perspective article focuses on the neuromuscular characteristics that influence drop jump performance.

Drop jump performance

Many studies have reported that a few weeks (≥ 4 weeks) of plyometric training can increase vertical jump height substantially (up to ~30%) when assessed by drop jumps testing (for reviews, see (1,2,56)). The influence of plyometric training on ground contact time, however, is variable as found to be reduced (36,37,60), unchanged (37,61) or augmented (36) depending on the average drop height used during training, the height chosen for testing, and the landing technique (see below). For example, Laurent and colleagues (37) observed a reduction in contact time during a 20-cm drop jump but not during higher drop heights (40 and 60 cm), after 10 weeks of hopping and drop jump (from 30-40 cm) exercises. Similarly, Taube and colleagues (36) reported a reduction in contact time when all plyometric exercises during training were performed from a low and similar height as the testing conditions (30 cm), but an increased duration when training also included drop jumps from higher heights (50 and 75 cm). This effect was observed in both studies despite participants being instructed to minimize ground contact time during training. The results of these two studies indicate that drop jumps performed from low to moderate heights favor the reduction in contact time. In contrast, the reactivity index usually increases, regardless of the drop height utilized during training (Figure 3; 30,31). In addition, most studies have found that the RFD for the knee extensor muscles increased after jump training that included plyometric exercises (62–66). Collectively, these data indicate that plyometric training is an effective method to augment explosive force production.

Specificity of landing technique

Drop jumping technique strongly influences the mechanical output of muscles (67), the duration of the braking phase, and the contact time, which distinguishes between fast (<250 ms) or slow (>250 ms) stretch-shortening cycles (26). However, most studies rarely report whether participants performed slow (CMJ-type) or fast (bounce-type) drop jumps during training. This oversight likely explains why the classic meta-analysis of Markovic (56) found that the effects of plyometric training were slightly greater for the slow stretch-shortening cycle (pooled data: 8.7% and 7.5% in CMJ with or without arm swing, respectively) than for the drop jump (4.7%). Moreover, the meta-analysis concluded that the increase in jump height was similar for the SJ (4.7%) after plyometric training. Another study reported that 6 weeks of jump training (60 jumps/session, 2 sessions/week) comprising 80% of CMJ jumps was more effective than 80% of drop jumps in non-professional women volleyball players (61). Although both training protocols substantially increased jump height, the CMJ training was significantly more effective in all jump types (17% vs. 7% on average). The conclusion of this study was that CMJ training was more effective than DJ training in enhancing jump height in women volleyball players presumably because the slower stretch-shortening cycle during CMJs seems to be more specific for these players and tasks.

Based on the findings discussed in the preceding paragraph, it is obvious that training results must be discussed in terms of the specificity principle. It appears that the CMJ drop jump is more effective than the bounce drop jump at increasing CMJ jump height (49). In contrast, training with drop jumps appears more effective than CMJs or SJs at increasing the speed of the fast stretch-shortening cycle (1,68,69).

Few plyometric studies have compared the influence of the landing techniques on jumping performance. One exception was the study by Laurent and colleagues (37) in which they compared the influence of 10 weeks of training (200-400 jumps/session; 2 sessions/week) with either of two different jumping techniques. One group performed all jumping exercises (height of the boxes 30-40 cm) while minimizing knee flexion at landing and trying to minimize contact time (bounce-type drop jump). The second group executed the jumping exercises by braking the downward movement after ground contact by quickly flexing the knees to 80–90° and then jumping as high as possible (CMJ-type drop jump). This study indicates the two different jumping techniques stressed the Achilles tendon differently (43), which resulted in an increase in tendon stiffness for the group that performed the bounce drop jump. Moreover, the increase in jump height and decrease in contact time for the 20-cm drop jump was greater after the bounce drop jump compared with the CMJ drop jump (37). In contrast, there was no difference between the two techniques when drop jumps were performed from higher drop heights (40 and 60 cm). However, jump height during the CMJ increased to a greater extent after training with CMJ-type drop jump (17.5%) than bounce-type drop jump (11.8%).

Similarly, a 4-week training program (10 sets of 10 jumps, 3 sessions/week) compared the gains achieved by 19 young basketball players trained with either of the two techniques (bounce drop jump vs. CMJ drop jump; Pechlivanos et al. Unpublished data, 2023). The outcomes included jumping ability (SJ, CMJ, CMJ with arm swing, drop jumps from 20 cm and 40 cm) and the biomechanical characteristics of the knee extensors and plantar flexors. One group performed 50-cm drop jumps with the knee always flexed (knee angle ranged from 90° to 120°) at landing, and the other group performed 30-cm drop jumps with a more extended knee angle at landing (ranged from 130^{o} to 170^{o}). The group that trained with bounce drop jumps increased the maximal jump height during drop jumps from 20 cm (+10%) and 40 cm (+12%), but decreased during SJ height (-4%). In contrast, the group that trained with CMJ drop jump technique increased jump height in SJ (+10%) and CMJ (+11%), but decreased jump height during the 40-cm drop jump (-7%). The group that trained with the CMJ drop jumps did not improve isokinetic and isometric strength of the plantar-flexor muscles after training, whereas the group that trained with bounce drop jumps increased their force at some angular velocities and positions.

Together the findings of these two studies suggest that the jumping technique elicits specific adaptations in neuromuscular function of the involved muscle-tendon units and potentially in muscle synergies primarily involved in the exercise used during training.

Muscle-tendon length

Another aspect of the training specificity is the determination of the optimal joint angle at ground contact as an index of the length of the muscle-tendon unit. In sprinting, for example, modifying the ankle range of motion toward greater muscle lengths may increase the medial gastrocnemius contribution and thus the force developed during plantar flexion. Sprint start performance, for example, was improved by increasing the contribution of the medial gastrocnemius, without changing the duration of the pushing phase, when the initial muscle length was increased by lowering the front block angle from 70 to 30 degrees (70). In jumping, medial gastrocnemius produces a large proportion of the plantar flexors force when its length remains close to the optimum range (71). Thus, the amount of force produced by this muscle is greater when the muscle-tendon unit operates at a length close to its maximal force potential.

One way to train the plantar flexor muscles at longer length, closer to the optimal length for force production (i.e., knee fully extended and ankle dorsiflexed at 15-20 degrees (72) and to increase the excursion range of the muscle-tendon unit during drop jumps is to land on an inclined surface. To that end, Kannas and colleagues (73) compared two groups of active men performing a 4-week plyometric training (8 sets of 10 jumps/session; 4 sessions/week) with the instruction "to jump as fast and as high as possible", either on a level or an inclined surface. Ankle hopping on the inclined surface resulted in greater improvements in jump height during fast drop jump executed from heights of 20 cm (+17%) and 40 cm (+14%), compared with hopping on the level surface (5% for both heights) (73). These changes were accompanied by a greater EMG activity of the medial gastrocnemius during the propulsive phase of the drop jump. In addition, plyometric training on an inclined surface was associated with a greater strain of the aponeurosis and the tendon, with greater range of motion at the ankle joint and stretch of the muscle-tendon unit. As a previous biomechanical analysis of hopping in these two conditions demonstrated that the fascicle length of the medial gastrocnemius was longer during the initial contact with the ground but reached similar length at the end of the braking phase, these findings suggest that muscle fascicles operate at a more optimal length during the initial contact to resist the impact load (74). Based on these observations, inclined hopping may be more effective compared with hopping on a level surface, because of a more optimal muscle function and presumably an increased recoil of the elastic energy stored in the muscle-tendon unit.

Another way to train the plantar flexor muscles at their optimal length and to overload the Achilles tendon during plyometric training is to use specifically designed shoes (thick rubber platform of ~4 cm attached under the front of the soles; so-called strength shoes). The few studies that have tested the effects of a training program (8-10 weeks, 2-3 sessions/week) with these shoes have found no advantage over normal shoes in sprinting and jumping abilities (75,76); unpublished data from one of the authors). Nonetheless, more studies are needed to explore this feature more carefully and to further analyze the optimal length of adaptation for other muscles among the leg extensors with regard of plyometric training.

Type of ground surface

As already mentioned, training for sports performed on compliant surface (e.g., sand for beach volley) may benefit from matching the surface stiffness (53). Although few studies have investigated the differences in biomechanical adaptations between plyometric training performed on rigid and compliant surfaces (52), they have all indicated that jump-related performances can be increased after training on both surfaces (77–79). For example, the study of Ahmadi and colleagues (78) found that an 8-week plyometric program in women volley ball players increased drop jump height to a greater extent when the training exercises were done on a rigid surface than on sand, but the opposite was observed for the CMJ. Similarly, Ojeda-Aravena and colleagues (79) observed a greater improvement in jump and power performances by rugby players after a 4-week plyometric training performed on sand than on a rigid surface, but only for CMJ tested with arms swing. In contrast, no change was found for the other jump types (SJ and CMJ without arm swing) for different ground surfaces. This finding suggests that the increase in CMJ height may have reflected an improvement in jumping technique, as the contribution of arm swing is more important when jumps are performed on a compliant surface. Together, these studies suggest that plyometric training on compliant surfaces improves jump performance for slow stretch-shortening cycle exercises, such as CMJs, whereas training on a more rigid surface is more appropriate to increase performance of fast (high impact) stretch-shortening cycle exercises, such as drop jumps. However, the training effects were tested only on a rigid surface (force platform), with no evaluation of the training specificity on the two ground surfaces. Further work is needed to address this point.

Neuromechanical adaptations

Adaptations that occur in both the nervous system (spinal and supraspinal), including muscle synergies and intensity of activation, and the muscle-tendon complex can explain the specific increase in performance (jump height & reactivity index) in response to a training program that includes plyometric exercises (Figure 1). In some studies (36,62,65), but not all (80), part of the increase in drop jump height after several weeks of plyometric training has been attributed to neural adaptations, as estimated by surface EMG amplitude. As with training-related changes in contact time, the effect on muscle activation varies across the different phases of the jump. While most studies have reported no change in pre-activation EMG (pre-landing phase), contrasting changes were observed for the EMG activity recorded in the leg extensor muscles during ground contact. For example, findings for the plantar flexors have included: (1) no change in EMG activity during both the braking and propulsive phases (61); (2) no change during the braking phase but an increase during the propulsive phase (36,80); and (3) an increase during the braking phase with no change (36) or decrease (60) during the propulsive phase. Also, Hirayama et al. (60) found that the increase in EMG activity of the triceps surae during the braking phase was accompanied by a reduced EMG of the antagonist muscle (tibialis anterior). Although care should be taken when interpreting surface EMG signals (81), the findings nevertheless show, at least for the contact time, that the contrasting adaptations may depend on the average dropping height used during training (36). For example, in the study by Taube and colleagues (30), the soleus EMG activity increased mainly during the braking phase for training with drop jumps performed from a low height (30 cm) but during the propulsive phase when training incorporated also drop jumps from higher heights (50 and 75 cm). These divergent neural adaptations likely contribute to optimize jump performance specifically to the conditions encountered during training (30).

In addition to possible increases in muscle contractile kinetics (80), an increase in tendon stiffness after plyometric training has been reported by some (37,82–84), but not all studies (80,85). The contrasting findings are often explained by differences in the loading intensity (drop height) and the landing technique (degree of knee flexion), which can differently modulate the mechanical stress generated at the muscle-tendon complex (see below; (37,48)), but also the volume of jumps performed in each session and the total duration of the training program (86,87). As plyometric training for a few weeks (≤ 10 weeks) does not change the cross-sectional area (CSA) of the Achilles tendon, the increase in tendon stiffness likely arises from intrinsic structural changes in the tendon (84). Because a stiffer tendon recoils elastic energy and transmits force to the skeleton more quickly (18,60,82), such an adaption improves the efficacy of the stretch-shortening cycle and thereby drop jump performance. Tendon stiffness, together with changes in neuromuscular activity and optimization of muscle-tendon interaction (36,60,62,65), appear to be important factors for increasing the height of jumps with low impact forces (i.e. CMJ). Nevertheless, the lack of statistically significant association between the gains in Achilles tendon stiffness and jump height at higher drop heights (40 and 60 cm) after plyometric training (37), may be explained by differences in neural (31,45) and mechanical (39) adaptations or between muscle and tendon stiffness as a function of the drop height. In addition, as plyometric training can induce muscle hypertrophy (80,88), increase muscle pennation angle (89) and maximal force (37,62,64,80,83), at least in moderately trained individuals, these adaptations likely increase their capacity to resist high impact loads at landing and thus augment the efficacy of the stretch-shortening cycle [see 4].

The different adaptations elicited by plyometric exercise training using low and high impact loads underscore the specificity of the neuromuscular and tendon adaptations to the conditions in which the plyometric exercises are performed. This conclusion has important implications for the choice of plyometric exercises used during training and consequently the transfer of the training gains to different sport disciplines.

PERSPECTIVES FOR PROGRESS

Although the number of studies performed on plyometric training in the last 20 years has increased substantially (9), many variables still need to be investigated to determine how to maximize the gains and their transfer to specific sport disciplines. As several variables have been addressed in a recent meta-analysis (3), we focus on four fundamental and practical issues.

Index of reactivity

Many studies have mainly examined the influence of plyometric training on maximal jump height attained during classical jumps, such as SJ, CMJ with and without arm swing, and drop jump. Although this parameter is important in some sports for which maximal height reached during a vertical jump is a major determinant of the performance (e.g., volleyball, ski jumping), in many other sport disciplines (e.g., athletic events), athletes are required to maximize the vertical impulse (ground reaction force-time integral) in minimal time. For example, the contact time in elite athletes is ~100 ms when sprinting at maximal speed and ~120-130 ms during long jump take-off, which indicates that the time to produce force is less than that required to achieve maximal force (>300 ms; (9,10,83)). In sports that involve lesser velocities (tennis, basketball, etc.), a brief contact time (reactive force) during testing exercises is also an important factor for performance. Such performances can be characterized by the reactivity index (jump height/contact time), provided the athlete attempts to maximize jump height. Another key metric when jump performance is performed on a force platform is the RFD (10). These measures provide an index of explosive force and are more informative for monitoring training progress than maximal height attained during a vertical jump. In that context, augmented feedback (i.e., referring to feedback that originates from an external source such as jump height, contact time, etc), was shown to be beneficial to maximize drop jump performance, notably in elite athletes (91). Interestingly, this improvement, associated with a stimulating motivation and an external focus of attention, was observable in both acute and long-term training, but was not influenced by the amount of feedback provided during the training period (90).

Stance and jump direction

The type of stance (bilateral vs. unilateral) and direction of the plyometric jumps (vertical vs. horizontal) are additional factors to consider for training and testing. In most studies, training has been performed during two-legged exercises in a vertical direction. Although this training condition is relevant for some sports (e.g., volleyball, basketball, hopping during sparring in combat sports, gymnastics), other sporting activities involve one-legged actions with a significant horizontal component (e.g., sprinting and horizontal jumping in athletic) or a combination of the two (e.g., basketball, soccer, rugby, tennis, badminton). These jump conditions should be mimicked during training and tested to evaluate the magnitude of the transfer of training gains. We recognize that it is more difficult to test accurately the efficacy of a training program during one-legged exercises in horizontal directions due to the greater relative influence of technique. Such tests require a prolonged period of familiarization to identify the specific muscle synergies and neural adaptations (54,55,92), which depend on the type of action (bilateral vs. unilateral; see (93,94)), and changes in the muscle-tendon complex as a function of training duration (74,95) and level of mechanical stress (37,87,96). With regard to muscle synergies a particular attention should be paid on sex specificities as they appear to differ during locomotion (97).

Intensity

There is also some uncertainty over the influence of drop height on the gains in performance. Drop height manipulates the intensity of a plyometric exercise by influencing the stress generated on the involved muscles, connective tissue, and joints (98). Few studies have investigated the influence of the drop height used during training on the increase in jump performance (36,48,99). Among these studies, Taube and colleagues (36) reported a significant increase in jump height regardless of drop height (30, 50 and 75 cm) when plyometric exercises included drop jumps from these three heights, but not when all jumps were performed from the lowest height only (30 cm). Although, the average reactivity index increased similarly (14%)

after the two training programs, the ground contact time was reduced when drop jumps were executed from the lowest height (30 cm) only but increased when jumps were executed from the three different heights. These results indicate that a program of drop jumps performed from higher heights influence preferentially the increase in jump height but it is at the expense of an increased contact time. In contrast, in the study by Laurent and colleagues (31), the reactivity index was not changed significantly in moderately trained individuals (students in physical education) when drop jumps were assessed from higher drop height (40 and 60 cm), but this index increased more by training with jumps from lower heights and brief reactive landings that reduce contact time. Together, these studies indicate that the magnitude of the adaptations among the variables that characterize jump performance (jump height, contact time, reactivity index) are specifically influenced by the drop height used during plyometric training.

It should be noted, however, that some elite athletes (e.g., long and triple jumpers) achieve a maximal reactivity index at higher drop heights (Figures 2 and 3; see also (47)). Moreover, drop-jump training (2 sessions/week for 8 weeks) performed from the height that elicited the maximal reactivity index (60 cm), in combination with classical strength training, increased the reactivity index from drop heights of 20 to 80 cm with minimal change in contact time (Figure 3). In agreement with this specific training effect, a greater improvement was found for the drop height (60 cm) that was used during training (Figure 3). Although these data were acquired from a single athlete and he performed concurrent plyometric and strength training, the results nevertheless indicate specific adaptations based on the drop height used during training.

To accommodate the uncertainty over the optimal height to maximize neuromuscular and tendon adaptations, periodization of various type of plyometric exercises is often used by coaches. For example, they favor high ground impacts at the expense of relatively brief contact time during the general preparation period of a training season (38). In this instance, the objective is to generate a high-level of stress in the involved muscles during the braking phase of the jump. In the more specific preparation period (pre-competitive and competitive phases), the approach is to use drop jumps executed from heights equal or lower than the optimal height at which the reactivity index is obtained in sports involving brief contact times. In many sports, jump training is combined with other types of strength-related methods (classical strength training, eccentric or dynamic training, contrast loading, electrostimulation; Figure 1; (1,9)). Although some studies have investigated such combination programs (66,100,101), the effectiveness of these strategies warrants further investigations.

Additional studies are needed to define the plyometric exercises (type of jump) that maximize the gains for specific sport disciplines but also to personalize the training program (athlete vs. moderately trained individual; Figure 1). In addition to the type of ground surface (see above), the type of shoes, especially the recent running shoes that incorporate carbon-fiber plate and which appear to be helpful in improving athletic performance, should be also considered in future studies.

Dose-response

In addition to drop height, the training volume (number of jumps/session and total number of sessions) is also considered as an important stimulus for adaptations elicited by plyometric training but the optimal dose-response is uncertain (9). The meta-analysis conducted by de Villarreal and colleagues (102) led to the conclusion that individuals with more sporting experience achieve greater increases in vertical jump height than those in either good or poor physical condition. They also found that training programs of more than 10 weeks and 20 sessions performed at a frequency of ~2 sessions per week with high-intensity exercises and more than 50 jumps per session were most effective at improving performance. However, some studies reported that training frequency might not be as important as the overall training volume (8). Furthermore, a combination of jump types (SJ, CMJ, and drop jumps) is recommended to maximize jumping gains rather than using a single type of jump (102).

In many studies, the number of jumps per session appears relatively modest compared with the number performed by elite athletes (200-400 jumps/session). However, it is mainly jump coordination (neural adaptations) that improves jump height and reactivity index in novice individuals after a brief plyometric training program. As with strength training, the number of jumps per session should not be a major reason for early increases in performance. In contrast, structural adaptations, such as increases tendon stiffness, require a greater number of jumps. For example, both jump performance (maximal height & reactivity index) and Achilles tendon stiffness were increased after a total volume of ~6.000 - 7.000 jumps (37,83), whereas only jump height was augmented after ~ 4.800 jumps (80). Although additional studies are needed to determine the optimal dose-response relative to participant experience, structural adaptations can be considered as a marker of the minimal number of jumps necessary depending on the intensity of the drop jump (36) and the landing technique (37).

Conclusion

Although plyometric exercises are widely used in sport and a growing number of studies have examined the acute and long-term adaptations of this training method, much remains to be learned for optimizing the neuromechanical adaptations induced by plyometric training and to transfer performance gains into specific sport disciplines. In addition, more studies are also needed to evaluate the risks incurred by this training method and the conditions under which it is practiced.

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Figures

Figure 1. Diagram representing the main parameters to be taken into account to maximize the effect of plyometric training in a specific sport discipline. First, the movement-related characteristics of the sport discipline must be determined by analyzing the type of stretch-shortening cycle, ground surface and the individual level of expertise (NB: age is not considered in this article). Based on this analysis, training prescription should include the exercises characteristics (comprising their modalities of execution) and the training program (workload and its total volume, as well as the periodization and combination of plyometric training with other strength-related methods). This training process, if adequately planned, will produce specific neuromechanical adaptations that will result in specific improvements of sport performance.

Figure 2. Vertical jump height (A), ground contact time (B) and reactivity index (jump height/ground contact time; C) during bounce-type drop jumps performed from heights ranging from 20 to 100 cm in an elite pole vaulter (best performance 5m 70). Note that peak jump height was achieved at a greater drop height (60 cm) than the reactivity index (40 cm).

Figure 3. Change in the reactivity index as a function of the drop height in a young long jumper (best performance of ~7 m) after an 8-week training program consisting in bounce-type drop jumps (~100 jumps per session; 2 sessions/week) performed mostly from the same height (60 cm). Although this index increased regardless of the drop height (from 20 to 80 cm), a greatest increase was obtained at the same drop height (60 cm) than the one used during training (shown by the arrow). Note that regardless of drop height, the increased reactivity index after training results mainly from an increased jump height with minimal change in contact time. This result emphasizes the specificity of the adaptation as a function of the drop height.

Figure 1

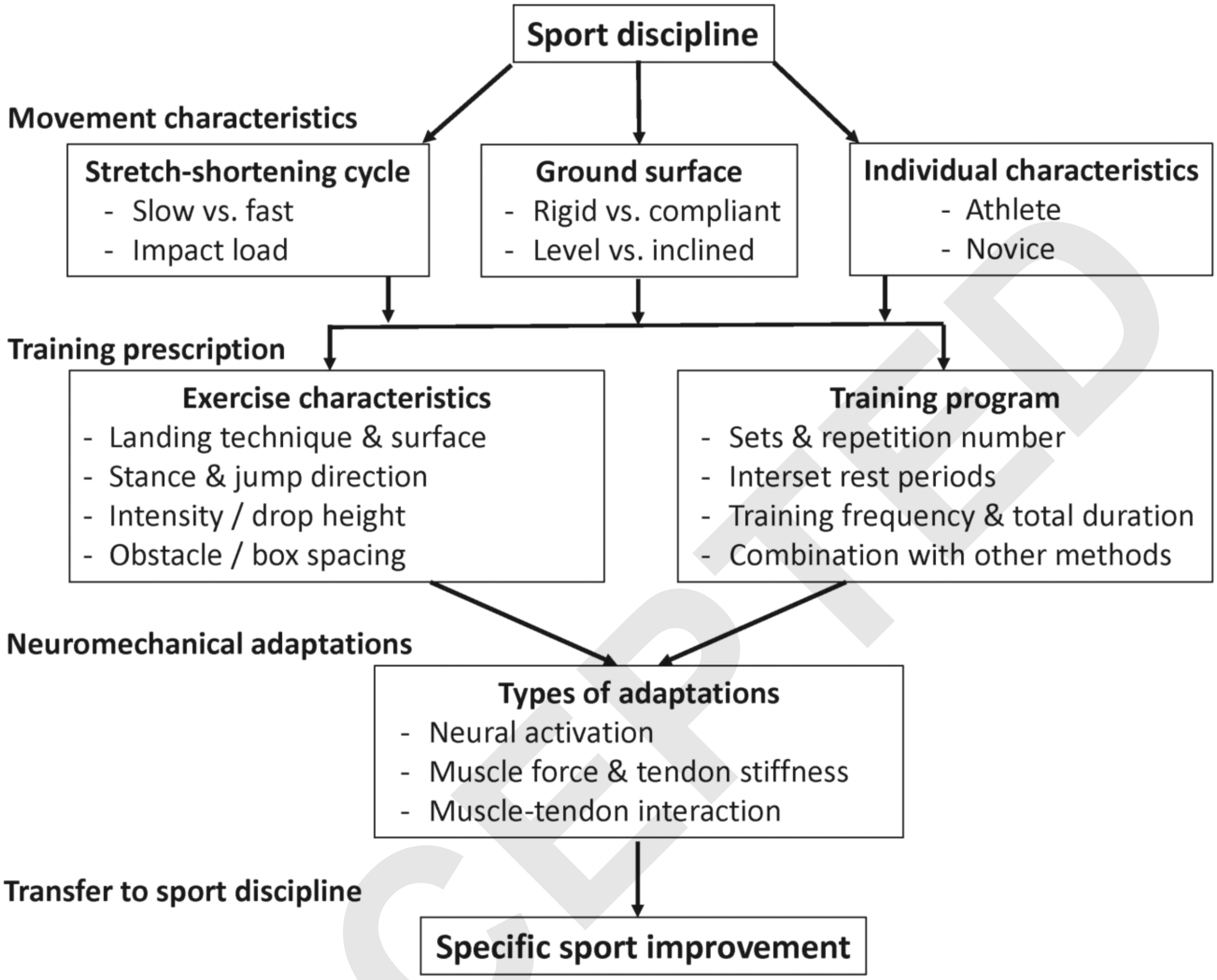

Sport discipline
Movement characteristics
Stretch-shortening cycle
- Slow vs. fast
- Impact load
Ground surface
- Rigid vs. compliant
- Level vs. inclined
Individual characteristics
- Athlete
- Novice
Training prescription
Exercise characteristics
- Landing technique & surface
- Stance & jump direction
- Intensity / drop height
- Obstacle / box spacing
Training program
- Sets & repetition number
- Interset rest periods
- Training frequency & total duration
- Combination with other methods
Neuromechanical adaptations
Types of adaptations
- Neural activation
- Muscle force & tendon stiffness
- Muscle-tendon interaction
Transfer to sport discipline
Specific sport improvement

Figure 2

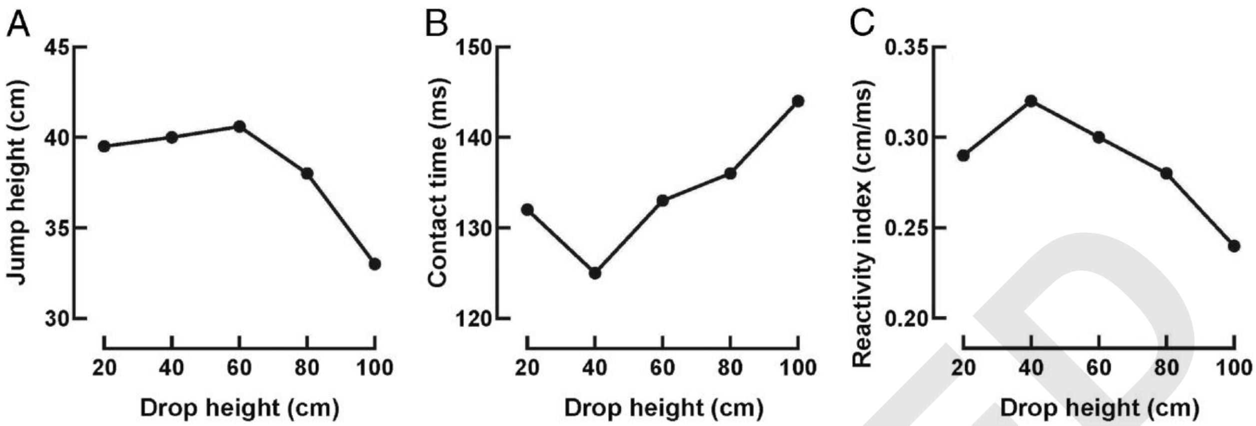
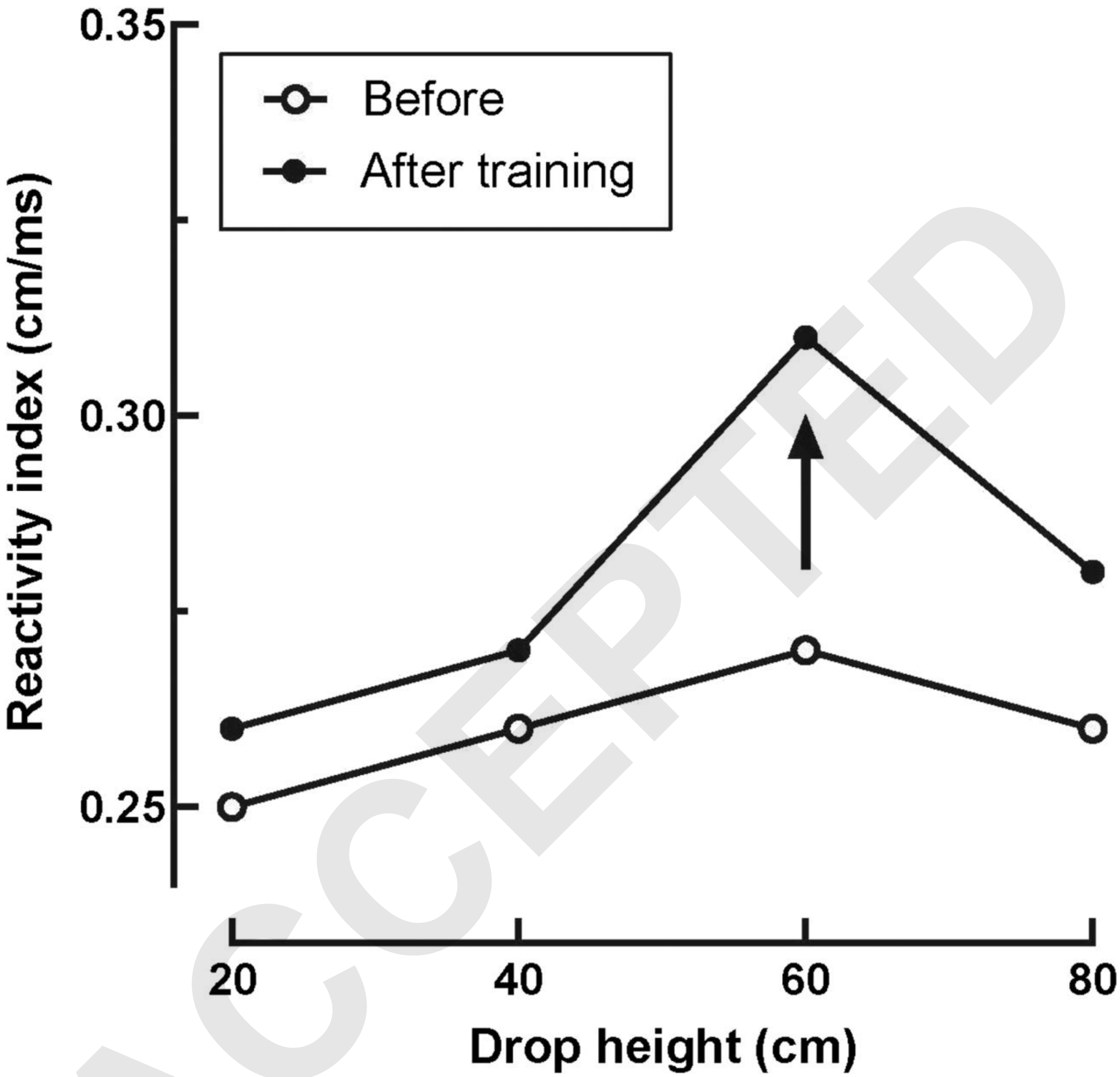

A
45
40
35
30
Jump height (cm)
20
40
60
80
100
Drop height (cm)
B
150
140
130
120
Contact time (ms)
20
40
60
80
100
Drop height (cm)
C
0.35
0.30
0.25
0.20
Reactivity index (cm/ms)
20
40
60
80
100
Drop height (cm)

Figure 3



Before
After training
Reactivity index (cm/ms)
0.35
0.30
0.25
20
40
60
80
Drop height (cm)