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Influence of Training Background on Jumping Height

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Abstract. Ugrinowitsch, C., V. Tricoli, A.L.F. Rodacki, M. Batista, and M.D. Ricard. Influence of training background on jumping height. *J. Strength Cond. Res. 21(3):848–852. 2007.*—The aim of this study was to compare the pattern of force production and center of mass kinematics in maximal vertical jump performance between power athletes, recreational bodybuilders, and physically active subjects. Twenty-seven healthy male subjects (age: 24.5 ± 4.3 years, height: 178.7 ± 15.2 cm, and weight: 81.9 ± 12.7 kg) with distinct training backgrounds were divided into 3 groups: power track athletes (PT, $n = 10$) with international experience, recreational bodybuilders (BB, $n = 7$) with at least 2 years of training experience, and physically active subjects (PA, $n = 10$). Subjects performed a 1 repetition maximum (1RM) leg press test and 5 countermovement jumps with no instructions regarding jumping technique. The power-trained group jumped significantly higher ($p < 0.05$) than the BB and PA groups (0.40 ± 0.05, 0.31 ± 0.04, and 0.30 ± 0.05, respectively). The difference in jumping height was not produced by higher rates of force development (RFD) and shorter center of mass (CM) displacement. Instead, the PT group had greater CM excursion ($p < 0.05$) than the other groups. The PT and BB groups had a high correlation between jumping height and 1RM test ($r = 0.93$ and $r = 0.89$, $p < 0.05$, respectively). In conclusion, maximum strength seems to be important for jumping height, but RFD does not seem relevant to achieve maximum jumping heights. High RFD jumps should be performed during training only when sport skills have a time constraint for force application.

Key Words. rate of force development, strength training, concentric impulse

Introduction

The ability to raise the center of mass in a jump is a fundamental skill required in many sports. Athletes and coaches have spent a lot of time developing training strategies with the purpose of improving vertical jumping performance (24). In addition, several studies have been performed to identify what contributing factors affect skill output the most (2, 12, 24, 31). Many of these studies have analyzed the effect of muscle force on skill output, but the results are inconclusive. Some have shown a significant relationship between strength and performance (10, 28, 30), whereas others have reported moderate, low, or no correlation (2, 12, 31).

Thus, it seems that factors other than muscle force are important in determining vertical jump maximal height. Bobbert and van Soest (24) performed a simulation and concluded that although muscle strength determines maximum jump height achievement, actual performance depends on the control of the muscle force-generating properties (coordination). In that study, neither increasing the muscle strength of the knee extensor muscles nor raising the strength of all lower limb muscles resulted in a jump height improvement, until muscle activation (control) was reorganized (reoptimized). Kollias et al. (19) performed a principal component analysis, and their model revealed that time was an important jumping performance component that explained the same amount of variation as "force." These findings are suggestive that well-trained subjects are likely to achieve high performances during explosive movements (e.g., vertical jumping) due to the coupling of control and muscle force-generating properties. On the other hand, athletes (e.g., bodybuilders) who do not routinely practice the jumping-specific muscular activation sequence will present smaller performances in explosive movements, although their force-generating properties may be similar to that of well-trained athletes. In the same way, the performance of physically active subjects may be smaller in comparison to the other 2 groups due to the reduced muscle force-generating properties and for movement control reasons, because they neither perform such explosive movements in a regular basis nor are involved in systematic training programs designed to improve muscle strength.

In addition, it is logical to assume that power-trained athletes, as a result of the training process, may achieve a well-established coordination pattern in conjunction with a large ability to produce muscle force. The combination of such factors would allow these athletes to have a high rate of force development (RFD). The RFD is defined as the slope of the force-time curve and has been described as an important factor to achieve maximal performance in power events (1). As a corollary, power athletes would optimize force production and control, presenting short-amplitude, high-velocity countermovement to maximize jumping height. On the other hand, bodybuilders and physically active subjects would jump with a longer and slower counter movement due to the lack of specific jump training. Although such arguments are appealing, it is not known whether a large RFD produces maximum jumping heights in power athletes. Kibele (13) suggested otherwise because longer counter movement amplitude produced higher jumping heights than shorter ones. In this perspective, well-trained power athletes should produce an optimal control solution to maximize jumping height due to their ability to produce and control force and the importance of the RFD to achieve maximum jumping heights could be revealed (13). In addition, the importance of maximum strength for the jumping height may be detected in subjects with a distinct training background.

Therefore, the purpose of this study was to compare the pattern of force production (RFD) and center of mass kinematics in maximal vertical jump performance of high-performance power athletes (jumpers and sprinters who are trained to develop high muscle force and have the opportunity to tune their vertical jump control on a daily basis), recreational bodybuilders (who are trained only to produce high forces but do not practice vertical jump coordination), and physically active subjects (who are not trained for force production or vertical jump coordination). A secondary purpose of the study was to determine the association between jumping height and leg press 1 repetition maximum (1RM) in subjects with distinct training backgrounds.

METHODS

Experimental Approach to the Problem

Subjects with distinct training backgrounds should perform a vertical jump with different jumping dynamics. Thus, we compared the ground reaction force curves produced by 3 groups of subjects with distinct training backgrounds. The eccentric and concentric portions of the ground reaction force curves were analyzed separately, and we searched for differences in the kinetics and in the kinematics of the center of mass.

Subjects

Twenty-seven healthy male subjects volunteered to participate in this study. The mean (± *SD*) age (years), height (cm), and mass (kg) were 24.5 (± 4.3), 178.7 (± 15.2), and 81.9 (± 12.7), respectively. Participants were divided into 3 groups according to their training background. The first group was formed by well-trained power athletes (PT, $n = 10$), with national and international experience in jumping and sprint events with daily basic training routines. The second group was formed by recreational bodybuilders (BB, $n = 7$) with more than 2 years of experience of high-volume and high-intensity strength training, with 5 training sessions per week. The third group was formed by physically active subjects (PA, $n = 10$), who did not perform any systematic resistance and power training but exercised at least twice a week for at least 6 months. A preliminary statistical analysis showed no significant differences in anthropometric variables ($p > 0.05$) and revealed a similar physical profile between groups. The university's ethic committee approved the study, and all subjects signed an informed consent form before participation.

Procedures

Subjects reported to the laboratory on 2 separate occasions, 1 week apart. On the first visit, they were allowed to practice some countermovement jumps on a force platform (AMTI DAS-6, Watertown, MA). After the countermovement jumps, participants were allowed to warm up for the 1RM test in an inclined (45°) leg press machine (Nakagym, São Paulo, Brazil) and to perform it, which was conducted according to the procedures described by Brown and Weir (16). On the second visit, participants performed a 5-minute warm-up (jogging at 8.5 $km \cdot h^{-1}$ and leg stretching exercises for 2 minutes) and executed 5 maximal countermovement jumps in intervals of 15 seconds. Subjects chose the amplitude of the countermovement to avoid changes in the coordination pattern. Force-time data were sampled at 1,000 Hz and online low pass filtered at 200 Hz and digitized through a digital converter with a resolution of 16 bits (model PCI 6033; National Instruments, Austin, TX) and stored for further analysis in a custom-made Visual Basic program.

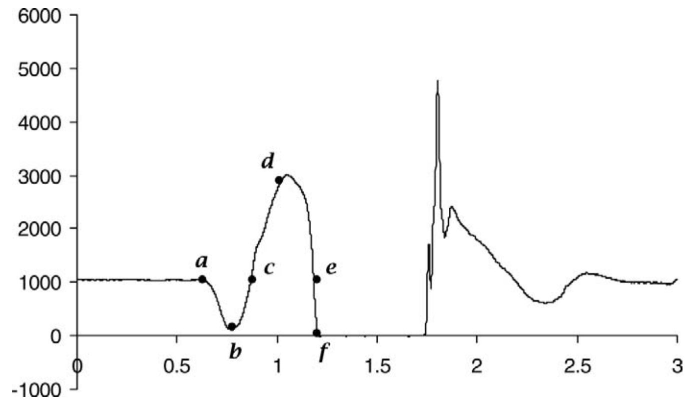

FIGURE 1. Vertical ground reaction force of a countermovement jump.

Data Analysis

Force platform data were used to determine the performance in a number of variables using the best jump (i.e., the jump with the greatest vertical displacement of the center of mass) of the 5 trials. Because concentric impulse determines the jumping height, variables that could alter impulse magnitude were estimated at different instants of the countermovement jump (22). These instants are identified in Figure 1. Point a determined the beginning of the countermovement and was defined as the instant in which the vertical ground reaction force reached body weight minus 5%. Point b was defined as the minimum force obtained during the unweighing phase. Point c was the point in which the vertical force equaled its starting value, described as to point a. The area between points a and c was calculated and defined as the unweighing impulse. Point d was defined as the beginning of the concentric (push-off) phase and was calculated via a computer routine that searched for a time point that produced a positive area, under the ground reaction force curve, of equal magnitude than the unweighing impulse. The accuracy of this point was double checked through double integration of the acceleration trace, and no significant difference was found between methods. Point e was the instant where the vertical force returned to a value corresponding to point a. Finally, point f was the instant where the vertical force reached 0 (take-off). The area under the curve between points d and f represented the concentric impulse, after body weight subtraction. Take-off velocity was calculated from the impulse momentum theorem. Then, jumping height was estimated using a projectile equation. Center of mass (CM) velocity and displacement was obtained by integrating acceleration and velocity data, respectively, between points a and f. In addition, vertical impulse, phase duration, average acceleration, CM velocity, and CM displacement were calculated in the intervals represented by point's a to c, c to d, and d to f. Average RFD (slope of the ground reaction force) was calculated from points b to d. Because no significant differences in the physical characteristics of the participants were found, no normalization procedures were adopted.

Statistical Analyses

A general linear model was used to compare the calculated jumping variables between groups to determine pos-

TABLE 1. Mean (± *SD*) take-off velocity ($m \cdot s^{-1}$), jumping height (m), and leg press 1 repetition maximum (1RM) (kg) of power-trained athletes (PT) and strength-trained (BB) and physically active (PA) subjects.

	Take-off velocity ($m \cdot s^{-1}$)	Jumping height (m)	Leg press 1RM (kg)
PT	2.80 (± 0.18)*	0.40 (± 0.05)*	364.5 (± 115.1)
BB	2.48 (± 0.17)	0.31 (± 0.04)	382.7 (± 85.4)
PA	2.41 (± 0.20)	0.30 (± 0.05)	304.0 (± 47.3)

* Significantly different from the other 2 groups ($p < 0.05$).

TABLE 2. Mean (± *SD*) duration (ms) of the countermovement jump phases of power-trained athletes (PT) and strength-rained (BB) and physically active (PA) subjects.

	Duration A–B (ms)	Duration B–D (ms)	Duration C–D (ms)	Duration D–F (ms)
PT	180.1 (± 33.4)	328.4 (± 78.9)	187.8 (± 40.9)	272.0 (± 34.2)
BB	160.6 (± 27.1)	342.7 (± 90.9)	194.9 (± 68.7)	255.6 (± 32.6)
PA	184.9 (± 43.2)	311.4 (± 69.4)	165.2 (± 24.2)	253.0 (± 33.2)

TABLE 4. Mean (± *SD*) acceleration ($m \cdot s^{-2}$) of the countermovement jump phases of power-trained athletes (PT) and strength-trained (BB) and physically active (PA) subjects.

	Acceleration A–F ($m \cdot s^{-2}$)	Acceleration A–B ($m \cdot s^{-2}$)	Acceleration B–D ($m \cdot s^{-2}$)	Acceleration C–D ($m \cdot s^{-2}$)	Acceleration D–F ($m \cdot s^{-2}$)
PT	3.7 (± 0.5)	−4.3 (± 1.0)	2.6 (± 0.9)	8.3 (± 2.7)	10.4 (± 1.2)
BB	3.3 (± 0.5)	−3.7 (± 0.7)	1.9 (± 0.8)	6.9 (± 2.3)	9.9 (± 1.5)
PA	3.3 (± 0.3)	−3.6 (± 1.2)	2.3 (± 1.0)	7.7 (± 1.9)	9.7 (± 1.2)

TABLE 5. Mean (± *SD*) concentric impulse ($N \cdot s$) of power-trained athletes (PT) and strength-trained (BB) and physically active (PA) subjects.

	Concentric impulse ($N \cdot s$)
PT	235.1 (± 42.9)*
BB	210.2 (± 34.8)
PA	191.6 (± 28.5)

* Significantly different from the other 2 groups ($p < 0.05$).

sible differences. Whenever a significant F-value was obtained, a posthoc test with a Tukey adjustment was performed for multiple comparison purposes. Pearson moment correlation coefficient between the leg press 1RM test and the jumping height was also calculated. Significance level was set at $p \leq 0.05$.

RESULTS

Well-trained PT showed a greater take-off velocity and jumping height than the BB and PA ($p < 0.05$). Table 1 shows the results for take-off velocity and jump height in all experimental groups.

Movement duration was similar between groups, irrespective of the movement phases. Power athletes seemed to have a trend towards longer concentric phase (D–F) duration (effect size = 0.5) than the other 2 groups. Movement durations across different phases of the movement are described in Table 2.

The analysis of the CM displacement indicated that the PT were able to move their bodies over a greater distance than the other 2 groups during the concentric phase ($p < 0.05$). No differences between groups were found during the eccentric phase of the movement ($p > 0.05$), except for the instant between points *c* and *d*, where PT showed larger CM displacement than the PA ($p < 0.05$). Table 3 presents the CM displacement in several instants of the movement.

The mean acceleration of the body's CM was similar between groups in all segments of the force-time curve (Table 4). However, it should be pointed out that the PT tend towards higher accelerations in all phases of the jump. Acceleration data are showed in Table 4.

The average rate of force development was similar ($p > 0.05$) between groups (5,876.07 ± 2,589.81, 5,199.16 ± 2,606.68, 5,299.36 ± 1,522.53, for PT, BB, and PA, respectively). The slightly greater duration and acceleration observed during the concentric phase of the movement may have produced a "washout effect" (i.e., dissipated across the movement) for PT, when the rate of force development was compared between groups. On the other hand, the cumulative effect of the slightly higher acceleration and duration during the concentric phase produced greater concentric impulses for the PT (Table 5). The eccentric impulse was similar between groups ($p > 0.05$).

The PT and BB presented a high correlation between 1RM and jumping height ($r = 0.93$ and $r = 0.89$, $p < 0.05$, respectively), while the PA presented a moderate correlation ($r = 0.52$; $p < 0.05$).

DISCUSSION

Our results showed that PT achieved greater jumping height by generating greater concentric impulses than BB and PA. In addition, leg press 1RM had a high correlation with jumping height for PT and BB. The novel find of this study was that PT did not perform stiff jumps (high RFD) to achieve greater jumping height. Our results are in direct contrast with other studies that have indicated the rate of force development as the most important factor to determine actual performance (18). Several arguments may explain such findings.

One possible explanation refers to the combination of 2 factors. The greater concentric impulse presented by PT may have been achieved by the combination of a slightly greater acceleration and duration of the concentric phase of the movement. The combination of these 2 factors allowed the PT to perform the vertical jumps using a greater center of mass vertical excursion, irrespective of the RFD.

In theory, PT would jump higher due their ability to

TABLE 3. Mean (± *SD*) displacement (m) of the countermovement jump phases of power-trained athletes (PT) and strength-trained (BB) and physically active (PA) subjects.

	Displacement A–B (m)	Displacement B–D (m)	Displacement C–D (m)	Displacement D–F (m)
PT	−0.048 (± 0.019)	−0.337 (± 0.063)	−0.175 (± 0.030)	0.450 (± 0.056)
BB	−0.031 (± 0.010)	−0.297 (± 0.052)	−0.155 (± 0.038)	0.381 (± 0.038)*
PA	−0.042 (± 0.020)	−0.277 (± 0.061)	−0.135 (± 0.027)*	0.386 (± 0.059)*

* Significantly different than PT ($p < 0.05$).

accelerate the CM more than the other 2 groups. This greater capacity would be a reflection of a higher RFD and a smaller CM excursion. Instead, the PT used a greater CM excursion, which supports van Ingen Schenau's suggestion that elongating force application enhances time for the muscles to build force up (8). Another argument to explain why PT achieved a greater performance may be a greater excursion of the CM during the eccentric phase of the movement. If the athletes lower their CM deeper, they would, in theory, have more time to accelerate upward during the concentric phase of the jump. Our results do not support this argument because subjects used a similar excursion of the CM in the eccentric phase (Table 3). On the other hand, a greater movement excursion during the concentric phase (points *d* to *f*) is hard to explain. Two possible explanations could be forwarded. The first could be related to a greater plantar flexion during the final instants of the take-off phase, and the second could be related to the amplitude of the hip extension that could have altered the position of the CM during take-off. Unfortunately, it was not possible to test these hypotheses in the present study.

The high redundancy of the neuromuscular system may allow the increment of the concentric impulse through different strategies that produced greater forces and durations of the movement. This redundancy was showed in stretch shortening cycle studies. As an example, subjects were able to maintain jumping height in a fatigued situation, decreasing the force produced but increasing the time of force application (5). It is possible that an optimal combination of ability to produce force at fast rates and the movement duration would result in maximized performances. For instance, if muscle produces force too fast, they will work in a nonoptimal range of the force-velocity curve. This range will not allow a maximal acceleration of the CM. On the other hand, a long period of force production will lead to a submaximal force production; otherwise, the subject would take-off. Because subjects were free to select their preferred countermovement amplitude, PT used a more compliant movement, which led them to an increased performance. The work of Bobbert and van Zandwijk (15) showed similar results. The maximum height of the CM in the squat jump was not affected by faster muscle activation and consequently by higher RFDs. It is reasonable to think that there is noise in the neural signal to the muscles; otherwise we would not observe the stochastic characteristic of the jump in humans. As a matter of fact, the jumping height had a tendency to increase with slower muscle activation, and the jump movement pattern became more robust. However, the authors reported an optimal value, after which jumping height starts to decrease. In addition, a delay in the activation from proximal to distal muscles also decreased the performance, indicating the importance of coordination in muscle activation.

Many research papers have indicated that the capacity to generate force rapidly is important for sports that are dependent of the jumping ability power production (e.g., volleyball, basketball) (6, 26). Based on that, many training methods have been used to develop the ability to generate force quickly, such as plyometrics. Coaches instruct athletes to perform stiff jumps, making the transition from the eccentric to the concentric phase as short and fast as possible. These training ideas were developed based on the concept of elastic energy restitution and the efficacy of the stretch reflex in stiff jumps described in many stretch shortening cycle papers (3, 20, 21). Our data are very intriguing because it was expected that the PT would have a stiffer jump than the other 2 groups due to the time constraints to apply force in their events. However, this was not the case; the PT chose a more compliant jump than the other 2 groups, and this control strategy produced greater elevations of the CM. These results are opposite to the data presented by Bosco and Komi (21), who stated that small amplitude movements enhanced force and power production in relation to more compliant jumps. However, stiffer jumps may decrease metabolic energy production for the same jumping height and, thus, enhance efficiency (9) but not the elevation of the CM. It must be emphasized that the amplitude of the countermovement was self-selected, indicating that the PT chose greater countermovement amplitude to maximize jumping height.

We may not be certain of such astrategy because of the lack of kinematics data. Trained subjects tend to have a greater hip flexion than untrained subjects (11), which decreases the height of the CM. This control strategy increases the ability of the hip extensors to produce work and therefore the jumping height.

The performance of the was similar to PA, even though they had a tendency towards higher 1RM values. A few papers have indicated that increased maximum strength affects jumping height the most when combined with training that "tunes" the jump (23, 25, 27), increasing the control of muscle activation (24). The high correlation between leg press 1RM and jumping performance obtained in our study points in the same direction. Strength-trained subjects probably did not have optimal control solutions to enhance jumping ability because physically active subjects had the same average jumping height. Bobbert and van Soest (24) data support this hypothesis because increased strength without an improved timing of muscle activation decreased the CM elevation. When there are delays in muscle activation, there is a tendency to take-off at lower CM heights than in "tuned" jumps (15). Because BB and PA had similar negative excursion of the CM but smaller positive excursion than PT, we believe that both groups had problems in activating the muscle in a proximal-distal fashion accordingly.

Thus, it seems that both coordination and muscle strength are the most important aspects in enhancing jumping ability (14, 17, 29) and should be trained concomitantly, at least in a situation in which there is no time constraint. Training studies have also pointed in this direction. Strength exercises, plyometrics, and depth jumps have similar efficacy in improving jumping performance (4, 7), but the combination of strength and jumps is more effective.

Practical Applications

Based on these facts, coaches around the world may have been exposing their athletes to high stress loads unnecessarily in an attempt to increase the RFD with stiff jumps. They should be recommended only when there is a reduced time frame to execute the skill and consequently to generate force. As an example, volleyball middle blockers need to jump as fast as possible to block quick sets and to move and jump across the net to block outside sets. In the same way, basketball centers and power forwards need to jump to get a rebound and jump back immediately to shoot when they are close to the basket. On the other hand, volleyball outside hitters do not need to jump as fast as possible, nor do point guards in basketball. They do not have a time constraint to execute the jump in most of their skills. In this way, regular strength training combined with skill training may be enough to produce positive adaptations in jumping height, increasing muscle strength and "tuning" the muscle activation.

In conclusion, the RFD does not seem to be relevant to achieve maximum jumping heights when there is no time constraint. Well-trained power athletes jump higher due to a combination of slightly greater CM acceleration and duration of the concentric of the jump.

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