THE POWER OUTPUT-DROP HEIGHT RELATIONSHIP TO DETERMINE THE OPTIMAL DROPPING INTENSITY AND TO MONITOR THE TRAINING INTERVENTION

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ABSTRACT

Di Giminiani, R and Petricola, S. The power output-drop height relationship to determine the optimal dropping intensity and to monitor the training intervention. *J Strength Cond Res* 30(1): 117–125, 2016—The literature currently lacks in methodological approaches to quantify the drop jump intensity and to control the training intervention. This study aimed to determine the average power output-drop height relationship and to quantify the reliability of this relationship across 2 different training interventions (each 8 weeks in length). The relationships were determined for 52 volunteer sports science students who took part in this study (25 male/27 female participants). The drop jumps from 20 to 60 cm were performed on a resistive platform. The reliability of the power output-drop height relationships was quantified for 29 subjects who were selected from the sample and were assigned to a drop jump, vibration, or control groups. The average power output during the drop jump statistically depends on the gender ($F_{(1,250)} = 18.844$; $p = 0.0001$) and drop height ($F_{(4,250)} = 7.195$; $p = 0.0001$), whereas the interaction between gender and height did not affect the power output ($F_{(4,250)} = 0.458$; $p = 0.767$). Both the drop jump and the vibration groups showed a significant main effect over time ($F_{(3,200)} = 40.059$, $p = 0.0001$; and $F_{(3,160)} = 11.422$, $p = 0.0001$, respectively). The intrasession and interday reliability ranged from "high" (intraclass correlation coefficient [ICC] > 0.80) to "excellent" (ICC > 0.90) among the various drop heights. This study suggests that an individual drop height that maximizes the power output during a drop jump exists and that the test to select this optimal drop height is repeatable over time. Consequently, the test can monitor the improvement in the power output following different training regimens.

KEY WORDS optimal drop height, individualization plyometric training, drop jump performance, whole-body vibration, reliability

INTRODUCTION

The drop jump is a plyometric exercise widely used in explosive strength training to develop vertical jump performance (11,28,34–36) in musculoskeletal injury (i.e., anterior cruciate ligament injuries) (37) and ankle postsprain rehabilitation protocols (32). During drop jumps, subjects are instructed to jump from a fixed height and immediately jump off the ground as soon as possible with small angular displacement (5,7,8). In the drop jump (stretch-shortening cycle [SSC]), the pre-activated muscle is first stretched (eccentric action-amortization phase) and then followed by shortening (concentric action). In the active braking phase of the SSC, the impact loads and the nature of stretches involved are generally very fast, are of short duration, and are controlled simultaneously by reflex and central neural pathways (31). The pre-activation allows the muscles to accumulate muscle force to control the stiffness regulation and then contribute to the drop jump performance (20).

A major issue in the methodological approach of the drop jump exercise for training and rehabilitation is the quantification of the optimal dropping intensity of the workload. To date, studies have not considered that drop height may determine the best drop jump performance (highest jump power output) to individualize the workload when using drop jumps to train and rehabilitate. In other words, the dropping heights reported in the literature have been preselected without considering their effect on the individual jump performance (maximal height, force, or power output produced) (28,32,37,39). The workload or stretch load (21) imposed on the neuromuscular system at the contact phase is given by the equation of the gravitational potential energy: $Ep = m \times g \times h$ ($N \cdot m$) where Ep is the potential energy, m is the mass, g is the force of gravity ($9.81\ m \cdot s^{-2}$), and h is the drop height. Because the force of gravity and the mass of each subject are constant, we can deduce that changing the drop height will determine the workload during the braking phase.

Dorgo et al. (16) have demonstrated that increasing the drop height (faster prestretch) results in a decrease in the duration of the eccentric phase (up to certain values) and an increase in the relative peak force production during the

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30(1)/117–125

Journal of Strength and Conditioning Research

concentric phase. During the eccentric contraction (active braking phase), the mechanical energy is stored in the tendons of the leg extensor muscles, which in turn improves the mechanical efficiency and power output during concentric movement as the muscle-tendon unit reuses the elastic energy (2,10,30,43). This process of storage and subsequent recoil of the elastic energy of tendinous tissue is positively affected by the dropping height (21). The stretch reflex activation, by modulating the stiffness of the muscle-tendon unit, is considered to be an important factor in the ability to transfer energy from the pre-activated and eccentrically stretched muscle-tendon unit to the concentric positive phase (16,18).

Therefore, the mechanical power output in the positive phase of the drop jump was hypothesized to depend on the drop height and thus also depends on the individual participant's characteristics. This study first aimed to determine the average power output in the positive phase-drop height relationship in physically active male and female subjects. Second, this study quantifies the reliability (intrasession and interday) of the power output-drop height relationships across 2 different training regimens (specific–using drop jump exercises; nonspecific–using exercises different from those used in testing).

METHODS

Experimental Approach to the Problem

A single-group, repeated-measures study design was used to determine the effect of the drop height, sex, and the interaction between drop height and sex on the following dependent variables of the drop jump performance: average power output of the positive work, flight time, and contact time (first aim, number of subjects = 52). A 3-group repeated-measures study design was used to quantify the reliability and training effect (second aim, total number of subjects = 29).

Subjects

The power output-drop height relationships were determined for 52 volunteer sports science students who took part in this study (25 men: age 22.0 years [0.41], height 174.9 cm [1.57], body mass 76.5 kg [2.67], body mass index 24.86 $kg \cdot m^{-2}$ [0.53]; and 27 women: age 22.0 years [0.43], height 163.8 cm [1.07], body mass 56.8 kg [1.00], body mass index 21.14 $kg \cdot m^{-2}$ [0.24]). The age of the subjects ranged from 20 to 27 years. The reliability of the power output-drop height relationships was quantified for 29 subjects who were selected from the sample (voluntarily participated) and then allocated to a vibration group (4 men/5 women: age 22.1 years [0.31], height 169.0 cm [2.15], body mass 64.8 kg [2.92], body mass index 22.62 $kg \cdot m^{-2}$ [0.67]), a drop jump group (7 men/4 women: age 21 years [0.42], height 172.4 cm [2.92], body mass 71.4 kg [4.74], body mass index 23.8 $kg \cdot m^{-2}$ [1.12]), or a control group (5 men/4 women: age 20.9 years [0.31], height 173.7 cm [3.32], body mass 66.6 kg [5.98], body mass index 22.5 $kg \cdot m^{-2}$ [0.90]).

All the subjects were recreationally active and participated in physical activities, such as gymnastics, swimming, and track and field activities, at least twice per week. However, none of the subjects had previous experience with drop jumps training. The participants provided written informed consent before participating, and the study was approved by the Ethics Committee of the University.

Test Procedure

The tests were carried out in the laboratory of biomechanics of the university. During the first laboratory visit, the subjects were familiarized with the testing procedures. During the second laboratory visit, the subjects performed 2 trials (T_0 and T_1 were separated by approximately 30 minutes) to quantify the intrasession reliability. Trial T_2 was performed after 4 weeks of training (72 hours after the end of the last session), and trial T_3 was performed after 8 weeks of training (72 hours after the end of the last session). Finally, trial T_4 was performed 1 week after the end of training. Therefore, the interday reliability was quantified between T_2-T_1, T_3-T_2 (after 4 and 8 weeks of training, respectively), and T_4-T_3 (without training) (Figure 1). The drop heights (independent variable) were randomly assigned during the test procedures. In each laboratory visit, the subjects performed a 15-minute warm-up (10 minutes of running on a treadmill at a speed of 6 $km \cdot h^{-1}$, 5 minutes of dynamic stretching) before performing a series of vertical jumps. The jumps were executed in random order from heights of 20, 30, 40, 50, and 60 cm. Three jumps were collected for each drop height, and a 1-minute pause between jumps was observed. The average value was considered for analysis. All drop jumps were performed with hands on hips, and the subjects were

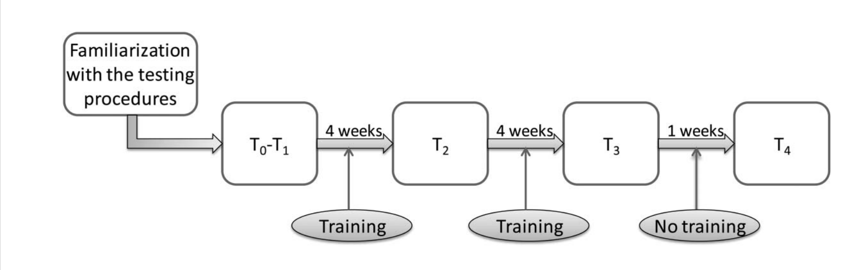

Figure 1. Experimental design used to determine the power output-drop height relationship and to quantify the intrasession and interday reliability over time. T = trial performed; T_0 and T_1 were performed in the same session training.

instructed to jump as high as possible with the shortest ground contact time (9). The maximum knee flexion was inspected using an electrogoniometer connected to a data collection unit (MuscleLab-Ergotest Innovation, Langesund, Norway), which, in turn, was connected to a personal computer using the USB port. The knee flexion across subjects was not fixed; it ranged from approximately 110–120°. However, the jump was repeated when the knee angle variation was higher than 5–7°. Thus, the knee angular displacement (negative and positive work) of the jumps was kept constant within each subject and across the various drop heights. The drop jumps were performed on a resistive platform (MuscleLab-Ergotest Innovation) that measured the flight time (T_f) and contact time (T_c). The average power output during the push-off phase

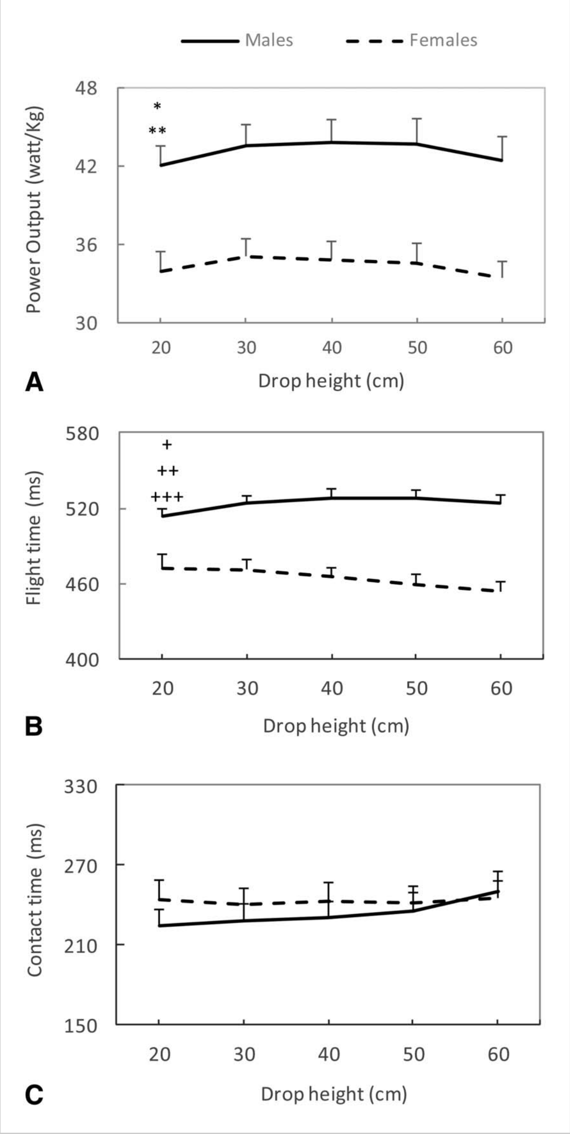

Figure 2. Average values and *SE* are shown. A, The power output estimated during the propulsive phase of the drop jump depended on the sex ($*p = 0.0001$) and the drop height ($**p = 0.0001$). B, The flight time depended on the sex ($+p = 0.0001$) and drop height ($++p = 0.0001$), and the interaction between drop height and sex was also significant ($+++p = 0.0001$).

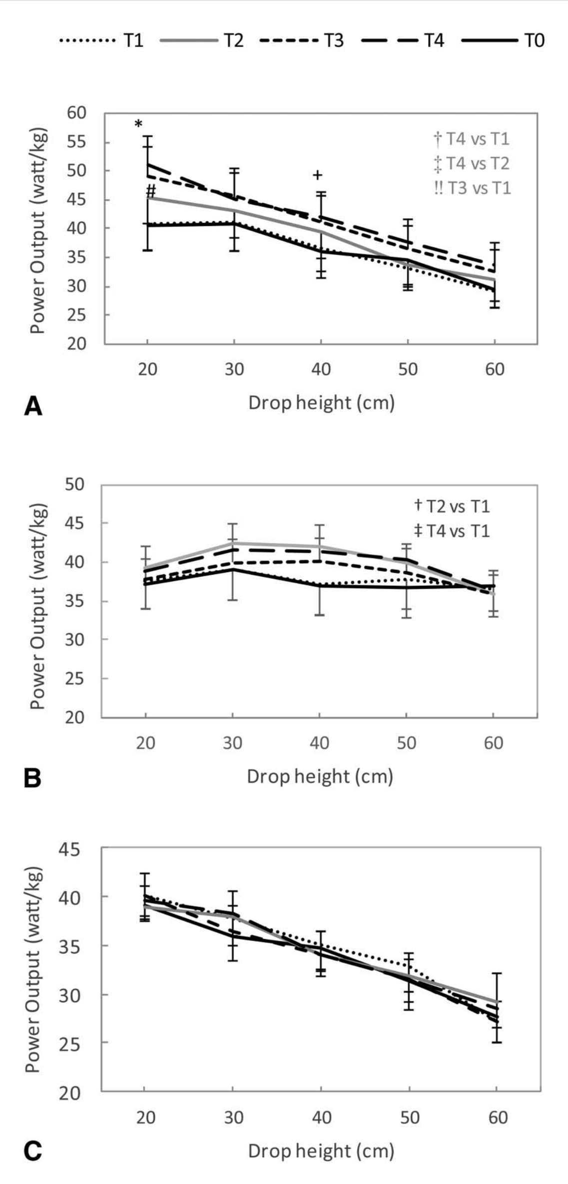

Figure 3. Power output-drop height relationships were determined at T_0 and T_1 (both at first laboratory visit), T_2 (after 4 weeks), T_3 (after 8 weeks), and T_4 (1 week after the end of the interventions). Average values and *SE*s are shown for the drop jump group (A), vibration group (B), and control group (C). A, The symbol "†" indicates an overall significant difference between T_4 and T_1 ($p = 0.0001$), "‡" indicates an overall significant difference between T_4 and T_2 ($p = 0.006$), and "‼" indicates an overall significant difference between T_3 and T_1 ($p = 0.001$); "*" indicates significant difference at drop height of 20 cm between T_4 and T_1 ($p = 0.002$); "#" indicates significant difference at drop height of 20 cm between T_3 and T_1 ($p = 0.012$); "+" indicates significant difference at drop height of 40 cm between T_4 and T_1 ($p = 0.044$). B, The symbol "†" denotes an overall significant difference between T_2 and T_1 ($p = 0.034$) and "‡" denotes an overall significant difference between T_4 and T_1 ($p = 0.025$).

was then calculated using the following formula (11): power output $= (g^2 \cdot T_f \cdot T_t)/(4 \cdot T_c)$ [$W \cdot kg^{-1}$], where g is the acceleration because of gravity (9.81 $m \cdot s^{-2}$), and T_t is the total time.

Training Intervention

The subjects of the vibration group were exposed to vertical sinusoidal whole-body vibration (WBV) 3 times per week (on Mondays, Wednesdays, and Fridays) for 8 weeks. They stood on the vibration platform (Nemes-Lsb, Bosco-System, Rieti, Italy) with their knees flexed to 120° (14,33) and underwent 10 series of 1-minute (10 × 1) WBVs with a 1-minute pause between series and a 4-minute pause after the first 5 series of vibrations (5 × 1) in each training session. The acceleration load was set individually for each participant by recording the electromyographic activity (EMG_{rms}). The vibration frequency was determined for each subject by monitoring the EMG_{rms} activity of the vastus lateralis at different frequencies. The vibration frequency corresponding to the highest EMG_{rms} muscle response was used to identify an individual's frequency of stimulation during the vibration intervention (15). Similarly, the subjects of the drop jump group were trained for 8 weeks using drop jump exercises. The training intervention was organized in 3 weekly sessions (on Mondays, Wednesdays, and Fridays). Each subject trained at their own optimal drop height determined by using the test explained above (the power output-drop height relationship). The power output-drop height relationship was carried out during each testing session (Figure 1). The optimal drop height did not change significantly over the 8-week training intervention. In the first 2 weeks, the subjects performed 3 × 8 drop jumps, in the third and fourth weeks they performed 4 × 8 drop jumps, and in the last 4 weeks they were exposed to 5 × 8 drop jumps (1,39). During each drop jump, subjects took about 20–30 seconds of rest, and 2 minutes of rest between each series. They were instructed to jump as high as possible with as low a contact time as possible. The subjects of the 2 experimental groups were supervised for the entire training period. The subjects of the control group were instructed to avoid vibration and plyometric exercises, whereas all the subjects participated in systematic physical activities (gymnastics, swimming, and track and field) at least twice per week.

Statistical Analyses

The analysis was performed using the statistical software XLSTAT 2013.2.07 (Addinsoft; SARL, New York, NY, USA). For descriptive purposes only, untransformed data are reported in the figures and expressed as mean values and standard errors. The values of the mechanical variables were positively skewed, and we applied a logarithmic transformation to obtain normally distributed responses. The power output-drop height relationship was analyzed by using a mixed-model repeated-measures analysis of variance (ANOVA) with a compound symmetry working covariance matrix. The effect of training on the power output-drop height relationship was assessed over time and in each group by using 1-way repeated-measures ANOVA. The Bonferroni correction was used to adjust the *p*-values according to the

TABLE 1. Reliability of the average power output estimated during the positive phase of the drop jumps in the drop jump group.

	T_1-T_0		T_2-T_1		T_3-T_2	
Variables	ICC	CV	ICC	CV	ICC	CV
DJ20 (95% CL)	0.99 (0.98–1.00)	3.1 (2.1–6.0)	0.98 (0.92–1.00)	5.8 (3.9–11.4)	0.97 (0.89–0.99)	7.2 (4.8–14.2)
DJ30 (95% CL)	0.99 (0.97–1.00)	4.3 (2.9–8.3)	0.98 (0.89–0.99)	8.1 (5.4–16.1)	0.99 (0.98–1.00)	3.7 (2.5–7.20)
DJ40 (95% CL)	0.99 (0.95–1.00)	6.0 (4.0–11.8)	0.97 (0.89–0.99)	8.5 (5.6–16.9)	0.97 (0.86–0.99)	9.6 (6.4–19.3)
DJ50 (95% CL)	0.99 (0.96–1.00)	4.6 (3.1–9.1)	0.98 (0.90–0.99)	7.1 (4.7–14.1)	0.96 (0.85–0.99)	9.5 (6.3–18.9)
DJ60 (95% CL)	0.99 (0.95–1.00)	5.0 (3.3–9.8)	0.98 (0.91–1.00)	7.0 (4.7–13.8)	0.98 (0.93–1.00)	6.8 (4.6–13.5)

	T_4-T_3		Mean	
Variables	ICC	CV	ICC	CV
DJ20 (95% CL)	0.99 (0.95–1.0)	4.8 (3.2–9.3)	0.98 (0.96–1.00)	5.4 (4.3–7.8)
DJ30 (95% CL)	0.99 (0.96–1.0)	4.7 (3.1–9.1)	0.99 (0.97–1.00)	5.4 (4.3–7.8)
DJ40 (95% CL)	0.99 (0.97–1.0)	3.8 (2.5–7.3)	0.98 (0.95–0.99)	7.3 (5.8–10.5)
DJ50 (95% CL)	0.99 (0.95–1.00)	5.3 (3.6–10.4)	0.98 (0.95–0.99)	6.9 (5.4–9.9)
DJ60 (95% CL)	0.99 (0.97–1.00)	4.5 (3.0–8.7)	0.99 (0.96–1.0)	5.9 (4.7–8.5)

T_1-T_0 = trials performed on the first laboratory visit; T_2 = trial performed after 4 week of training; T_3 = trial performed after 8 week of training; T_4 = trial performed 1 week after the end of training intervention; mean = average values for the several pairs of trials; ICC = intraclass correlation coefficient; CV = coefficient of variation (%); DJ = drop jump performed at different drop heights (20-30-40-50 e 60 cm); CL = confidence limit.

number of comparisons that were performed. The intrasession and interday reliability of the power output-drop height relationship was quantified using the intraclass correlation coefficient (ICC of single measures) and the coefficient of variation (CV) of the log transformed values (19). In agreement with previous studies (38), values of ICC less than 0.50 are defined as "poor," those from 0.50 to 0.69 are defined as "moderate," those from 0.70 to 0.89 are defined as "high," and those greater than 0.90 are defined as "excellent." The significance level was set at $\alpha = 0.05$.

RESULTS

The baseline measurements relative to the descriptive characteristics and experimental data were not significant among the groups ($p > 0.05$). Because the shape of the power output-drop height relationship did not differ between male and female subjects, the training effect and the reliability of the 3 groups was quantified by pooling the data of both.

The Power Output-Drop Height Relationship

The data analyses demonstrated that the average power output of the positive work during the drop jump statistically depended on the sex ($F_{(1,250)} = 18.844$; $p = 0.0001$) and drop height ($F_{(4,250)} = 7.195$; $p = 0.0001$), whereas the interaction between sex and height did not affect the power output ($F_{(4,250)} = 0.458$; $p = 0.767$) (Figure 2A). Similar to the power output, the flight time depended on the sex ($F_{(1,250)} = 39.508$; $p = 0.0001$), drop height ($F_{(4,250)} = 9.208$; $p = 0.0001$), and the interaction between sex and drop height ($F_{(4,250)} = 9.208$; $p = 0.001$) (Figure 2B). Finally, the contact time did not depend on the sex ($F_{(1,250)} = 0.270$; $p = 0.604$), drop height ($F_{(4,250)} = 1.098$, $p = 0.358$), or the interaction between sex and drop height ($F_{(4,250)} = 0.880$; $p = 0.477$) (Figure 2C).

Training Effect

Drop jump training determined a significant main effect over time ($F_{(3,200)} = 40.059$; $p = 0.0001$). The interaction between drop jump effect and drop jump height over time also showed a significant main effect ($F_{(16,200)} = 47.611$; $p = 0.0001$). Contrast analysis indicated an overall significant difference 1 week after the end of the 8 weeks of training (T_4 vs. T_1; $p = 0.0001$). In addition, an overall significant difference was observed after 8 weeks of training in comparison with the values recorded after the first 4 weeks of training (T_4 vs. T_2; $p = 0.006$) and after 8 weeks of training in comparison with the pretraining values (T_3 vs. T_1; $p = 0.001$). Significant differences were observed at the drop height of 20 cm (T_4 vs. T_1; 26.84%; $p = 0.002$) (T_3 vs. T_1; 21.89%; $p = 0.012$) and at the drop height of 40 cm (T_4 vs. T_1; 16.53%; $p = 0.044$) (Figure 3A).

Vibration training induced a significant main effect over time ($F_{(3,160)} = 11.422$; $p = 0.0001$). The interaction between vibration training and drop jump height over time did not show a significant main effect ($F_{(16,160)} = 1.424$; $p = 0.137$). Contrast analysis showed an overall significant difference

TABLE 2. Reliability of the average power output estimated during the positive phase of the drop jumps in the vibration group.

	T_1-T_0		T_2-T_1		T_3-T_2		T_4-T_3		Mean	
Variables	ICC	CV	ICC	CV	ICC	CV	ICC	CV	ICC	CV
DJ20 (95% CL)	0.99 (0.96–1.00)	3.5 (2.3–6.8)	0.85 (0.48–0.96)	12.3 (8.1–24.8)	0.88 (0.54–0.97)	8.0 (5.7–17.0)	0.80 (0.34–0.95)	10.1 (6.7–20.1)	0.90 (0.77–0.97)	9.1 (7.2–13.2)
DJ30 (95% CL)	0.99 (0.95–1.00)	4.4 (3.0–8.7)	0.80 (0.34–0.95)	14.1 (9.2–28.7)	0.72 (0.16–0.93)	11.8 (7.8–23.7)	0.82 (0.39–0.96)	10.1 (6.7–20.3)	0.88 (0.72–0.97)	10.6 (8.4–15.4)
DJ40 (95% CL)	0.98 (0.91–1.00)	5.6 (3.8–11.00)	0.87 (0.52–0.97)	11.6 (7.7–23.3)	0.93 (0.71–0.98)	6.9 (4.6–13.7)	0.93 (0.91–0.98)	6.9 (4.6–13.6)	0.94 (0.83–0.98)	8.0 (6.3–11.6)
DJ50 (95% CL)	0.99 (0.95–1.00)	4.0 (2.7–7.7)	0.84 (0.44–0.96)	11.8 (7.8–23.8)	0.91 (0.65–0.98)	7.8 (5.2–15.4)	0.94 (0.75–0.99)	6.6 (4.4–13.1)	0.93 (0.83–0.98)	8.0 (6.3–11.5)
DJ60 (95% CL)	0.98 (0.93–1.00)	4.1 (2.8–8.0)	0.89 (0.58–0.97)	9.9 (6.6–19.8)	0.86 (0.50–0.97)	9.2 (6.1–18.3)	0.87 (0.53–0.97)	9.3 (6.2–18.5)	0.91 (0.78–0.98)	8.4 (6.6.-12.1)

T_1-T_0 = trials performed on the first laboratory visit; T_2 = trial performed after 4 week of training; T_3 = trial performed after 8 week of training; T_4 = trial performed 1 week after the end of training intervention; mean = average values for the several pairs of trials; ICC = intraclass correlation coefficient; CV = coefficient of variation (%); DJ = drop jump performed at different drop heights (20-30-40-50 e 60 cm); CL = confidence limit.

TABLE 3. Reliability of the average power output estimated during the positive phase of the drop jumps in the control group.

	T_1-T_0		T_2-T_1		T_3-T_2	
Variables	ICC	CV	ICC	CV	ICC	CV
DJ20 (95% CL)	0.85 (0.48–0.97)	6.7 (4.5–13.3)	0.93 (0.73–0.98)	5.3 (3.5–10.4)	0.83 (0.41–0.96)	8.2 (5.5–16.3)
DJ30 (95% CL)	0.99 (0.94–1.00)	3.7 (2.5–7.2)	0.95 (0.80–0.99)	6.4 (4.3–12.6)	0.88 (0.57–0.97)	8.8 (5.9–17.5)
DJ40 (95% CL)	0.96 (0.82–0.99)	5.5 (3.7–10.9)	0.98 (0.92–1.00)	3.7 (2.5–7.3)	0.91 (0.65–0.98)	7.7 (5.2–15.3)
DJ50 (95% CL)	0.95 (0.80–0.99)	8.0 (5.3–15.9)	0.92 (0.69–0.98)	8.4 (5.6–16.7)	0.91 (0.66–0.98)	7.9 (5.3–15.7)
DJ60 (95% CL)	0.94 (0.76–0.99)	7.6 (5.1–15.1)	0.87 (0.52–0.97)	12.6 (8.3–25.5)	0.86 (0.50–0.97)	12.9 (8.6–26.3)

	T_4-T_3		Mean	
Variables	ICC	CV	ICC	CV
DJ20 (95% CL)	0.95 (0.80–0.99)	4.3 (2.9–8.5)	0.89 (0.73–0.97)	6.3 (5.0–9.0)
DJ30 (95% CL)	0.96 (0.82–0.99)	5.0 (3.4–9.8)	0.95 (0.86–0.99)	6.2 (4.9–9.0)
DJ40 (95% CL)	0.97 (0.86–0.99)	4.4 (2.9–8.6)	0.95 (0.88–0.99)	5.5 (4.4–8.0)
DJ50 (95% CL)	0.92 (0.69–0.98)	7.3 (4.9–14.5)	0.93 (0.83–0.98)	7.9 (6.3–11.4)
DJ60 (95% CL)	0.99 (0.95–1.00)	2.9 (1.9–5.6)	0.90 (0.76–0.97)	9.8 (7.7–14.2)

T_1-T_0 = trials performed on the first laboratory visit; T_2 = trial performed after 4 week of training; T_3 = trial performed after 8 week of training; T_4 = trial performed 1 week after the end of training intervention; mean = average values for the several pairs of trials; ICC = intraclass correlation coefficient; CV = coefficient of variation (%); DJ = drop jump performed at different drop heights (20-30-40-50 e 60 cm); CL = confidence limit.

after 4 weeks of training (T_2 vs. T_1; $p = 0.034$) and 1 week after the end of the 8 weeks of training (T_4 vs. T_1; $p = 0.025$). No significant differences were localized at specific drop heights ($p > 0.05$) (Figure 3B). The subjects of the control group did not show any significant main effect over time ($F_{(3,160)} = 0.409$; $p = 0.747$) (Figure 3C).

Reliability of the Power Output-Drop Height Relationship

In the drop jump group, the intrasession and interday reliability were "excellent" (ICC > 0.90) for all the drop height measurements, and the CV ranged from 3.1 to 9.6% (Table 1). The vibration group showed "excellent" intrasession reliability (ICC > 0.90) with a CV that ranged from 3.5 to 5.6%. The interday reliability ranged from "high" to "excellent" ($0.72 \leq$ ICC > 0.90) and the CV from 6.6 to 14.1% (Table 2). The control group showed "excellent" intrasession reliability (ICC ≥ 0.90) with the exception of the measurement performed at the drop jump of 20 cm (ICC $= 0.85$). The intrasession CV ranged from 3.7 to 8.0%. The interday reliability ranged from "high" to "excellent" ($0.83 \leq$ ICC > 0.90) and the CV from 2.9 to 12.9% (Table 3).

DISCUSSION

The results of the present study confirm our hypothesis that the mechanical power output in the positive phase of the drop jump depends on the dropping heights in a parabolic fashion in both male and female subjects. In addition, the power output-drop height relationship yielded intrasession and interday reliability values that ranged from "high" (ICC = 0.80–90) to "excellent" (ICC > 0.90), even when a training stimulus was applied to the subjects between trials.

Even though male subjects produced a higher power output than female subjects at each drop height, the power output-drop height relationship was similar in shape between both genders. Interestingly, female and male subjects demonstrated a different dropping jump technique when they dropped from a higher position (from 30 to 60 cm) (Figure 2A). Male subjects tended to jump more slowly than female subjects to develop power output during drop jumps from 30 to 60 cm. In contrast, female subjects, who maintained a constant contact time among the several drop heights, could not develop the same impulse when dropping from higher positions; consequently, their flight times decreased. However, because we did not differentiate the braking and the propulsive phases during the drop jump in the present study, we cannot conclude that female or male subjects changed the mechanical structure (impulse time/eccentric time) of the jump as a function of the dropping height (16,25). Indeed, an inverse relationship exists between the duration of the eccentric phase and the relative peak concentric force production, which could depend on the drop height. This, in turn, should optimize the energy available for the elastic components (up to a certain height) (16).

Previous studies reported a similar parabolic shape for the ground reaction force and jump height/drop height (6,42) as well as for the relationship of the electromyography (EMG) activity of the leg muscles with the drop height (14).

The involvement of the neural factors, which have been recently examined in studies of the modulation of soleus H reflexes (which coincided with the short latency response [SLR] of the stretch reflex) at different drop heights (23,26), could explain the power output-drop height relationship that was observed in the present study. In fact, the power output produced as a function of the drop height (i.e., stretch load) suggest that increases in the stretch load initially increase the excitatory inflow mediated by the reflex muscular contractions (23,26), which increase the EMG amplitude and power output performance. However, the inhibitory inflow becomes predominant as the stretch load increases (27), which could reduce the neuromuscular response at higher drop heights to prevent injuries of the muscle-tendon unit caused by excessive gravitational load (23). Leukel et al. (27) have argued that of the mechanisms that modulate Ia afferent input, the presynaptic inhibition of Ia afferents is most likely responsible for the adjustment of spinal gating according to the drop height. Furthermore, the authors suggested that changes in the presynaptic inhibition at SLR are controlled by supraspinal mechanisms.

In synthesis, the highest power output that we recorded as a function of the drop height (i.e., the vertex) may define a balance point between the excitatory stimuli (muscle spindles, Ia afferents) and the inhibitory stimuli (presynaptic inhibition, Golgi tendon organ), which is most likely to retain equilibrium between a stiff muscle-tendon unit (16,20) and possible overload injuries (18,23,27). In addition, this balance point could also be optimal in maximizing the efficiency of positive work because the stretch load considerably influences the process of storage and subsequent recoil of the elastic energy during plyometric exercise (3,10,16,21). However, the optimal drop height may be reached differently across subjects. Furthermore, considering the "high" and "excellent" intrasession and interday reliability of the power output-drop height relationship (Tables 1–3), the intensity (i.e., drop height) should be individually prescribed similarly to exercise prescription for power output training, in which the training parameters (e.g., movement speed and relative strength to maximal isometric) are extrapolated from the force-velocity curve.

In the present study, significant changes were revealed based on the power output-drop height relationship following 8 weeks of training by using 2 different training regimens (specific drop jumps; nonspecific WBV) (Figures 3A, B). However, the best training strategy seems to be the use of the drop jump for training and testing (specific) and to individually determine the optimal drop heights over time. In fact, the power output-drop height relationship of the drop jump group is largely modified to subjects' optimal drop heights that were used during the training (21.89% at 20 cm and 16.53% at 40 cm) (Figure 3A). The optimal drop heights of the group, which ranged from 20 cm (for 6 subjects) to 40 cm (for 2 subjects) with a mean value of 26.4 cm, did not change significantly over the 8-week training intervention.

In contrast, the power output-drop height relationship of the vibration group (nonspecific) tends to assume a parabolic shape with a vertex (Figure 3B) corresponding to a drop height of 30–40 cm. Similarly to the drop jump group, the optimal dropping heights did not change significantly over the 8-week vibration intervention; however, the optimal drop heights ranged from 20 to 60 cm with a mean value of 40 cm.

Therefore, the shape of the power output-drop height relationship seems to be unaffected by the 2 different training regimens applied in this study. The drop height will probably require a longer adaptation time because it is affected by the maximal strength (cross-sectional area), that is, subjects with high values of maximal strength tend to have the highest dropping heights (4). Interestingly, WBV intervention induced significant changes faster (after 4 weeks of training) than those of the drop jump training (after 8 weeks). A possible explanation could be that the training stimulus when applying WBV was more effective at first (4 weeks) but not sufficiently adequate (strong) to induce further improvements after the first 4 weeks of training because the vibration load (acceleration and number of repetitions) was held constant over the entire intervention period (8 weeks). Vice versa, the load in the drop jump group was progressively increased.

These results demonstrate that the power output-drop height relationship represents a reliable test to determine the optimal drop height or stretch load and that is sensitive to drop jump performance changes linked to specific (drop jump exercises)-nonspecific (vibration intervention) training processes and is, consequently, an appropriate tool for testing.

Recently, Jarvis et al. (22) have proposed a number of neuromuscular variables (surface EMG of vastus lateralis and rectus femoris during concentric and eccentric phases) and mechanical variables (peak force, impulse, and eccentric power output by using a force platform) to describe the global intensity of several plyometric exercises (counter movement jump, rebound jump, drop jump, hop, etc.). However, the authors have not specified how their system would discriminate the magnitude of a difference in intensity relative to a subjects' responsiveness during a training intervention.

Similar to other parametric relationships (force-velocity, power output-velocity, force-time), a major advantage of using a relationship as a test rather than a single measurement test is its capability to capture different adaptations that could be related to the multiple specific requirements of the sports discipline within the training periodization or to large variations in the outcome of SSC training protocols (because of differences in the jumping technique, drop height applied during training, extent of countermovement, time of ground contact, foot placement, and activation pattern) (24,41). A recent study by Taube et al. (39) confirmed that training from different drop heights induces specific neuromuscular adaptations, which in turn influences the drop jump technique. Specifically, the subjects, who performed drop jumps from 30, 50, and 75 cm drop heights for 4 weeks of training, increased their rebound jump height and ground contact time, which was accompanied by an increased activity of the soleus toward takeoff (between 120 and 170 milliseconds after touchdown). When the subjects performed the same amount of jumps exclusively from 30 cm, the rebound height did not increase, but the ground contact time decreased and the soleus activity enhanced shortly after ground contact (20–70 milliseconds after touchdown), whereas the performance index (rebound height/ground contact time) improved similarly after both training intensities. However, the stretch loads or intensities were preselected without taking the individual characteristics (mechanical and neural) of the athletes into account. Therefore, we suggest that the drop height should be determined in an individualized fashion similar to exercise prescription for progressive resistance exercise in terms of load.

Overall, this study suggests that an individual drop height (the vertex of the power output-drop height relationship) can maximize the power output during a drop jump and that the test to select this optimal drop height is repeatable over time. Consequently, an individual drop height optimizes the improvement in the power output performance during plyometric training.

A possible point of concern in this study is the use of a referenced method (11) to estimate the power output as performance variables rather than direct measurements that could provide crucial data (i.e., EMG activity, negative and positive work, peak eccentric and concentric forces, rate of force development characteristics, etc.). Although direct measurements have been extensively used to study the neuronal and mechanical mechanisms involved in SSC exercises (30,31,40,43), they have been rarely used in methodological approaches to quantify the drop jump intensity (21) because they require time, expertise, and high equipment costs. As a result, the drop height has been fixed and preselected during training and rehabilitation protocols.

However, the power output or performance index during drop jump is a good indicator of sprint running and jump performance and for plyometric training in the short-term protocol. It is also related to adaptive changes in neuromuscular function, such as increased neural drive to the agonist muscles activation strategies–improved intermuscular coordination and changes in the mechanical characteristics of the muscle-tendon unit of plantar flexors (1,13,29,40).

Considering that our study subjects were healthy males and females who were recreationally active, the power output-drop height relationship could be different for other groups (age, training status, or plyometric skill) or patients. In any case, the power output-drop height relationship could be adjusted by varying the drop heights to fit the training or plyometric skill levels. For example, trained subjects, who develop higher eccentric, concentric force, and mechanical efficiency than untrained subjects, could produce the highest power output at high drop heights (30). Young subjects (age 9–12 years) do not have the capacity to tolerate high stretch loads because the central nervous system is developing and the threshold for Golgi tendon organ activation is low and the bones are also growing during puberty. Therefore, they show the highest power output at low drop heights (10).

In short, age and/or plyometric skill of the subjects must be considered when selecting the drop heights to construct the power output-drop height relationship. This ensures that the highest power output is detected using this method.

PRACTICAL APPLICATIONS

The results of this investigation provide a simple and reliable test for coaches and therapists. It can be performed in the laboratory and on the field to determine the individual drop height by means of a resistive platform. The test can monitor a training process that involves plyometric exercises or vibration intervention.

ACKNOWLEDGMENTS

We disclose to have received funding for this work from any of the following organizations: National Institutes of Health, Wellcome Trust, Howard Hughes Medical Institute, and other(s).

REFERENCES

1. Alkjaer, T, Meyland, J, Raffalt, PC, Lundbye-Jensen, J, and Simonsen, EB. Neuromuscular adaptations to 4 weeks of intensive drop jump training in well-trained athletes. *Physiol Rep* 1: e00099, 2013.
2. Arteaga, R, Dorado, C, Chavarren, J, and Calbet, JA. Reliability of jumping performance in active men and women under different stretch loading conditions. *J Sports Med Phys Fitness* 40: 26–34, 2000.
3. Aura, O and Komi, PV. Effects of pre-stretch intensity on mechanical efficiency of positive work and on elastic behavior of skeletal muscle in stretch-shortening cycle exercise. *Int J Sports Med* 7: 137–143, 1986.
4. Barr, MJ and Nolte, VW. The importance of maximal leg strength for female athletes when performing drop jumps. *J Strength Cond Res* 28: 373–380, 2014.
5. Bobbert, MF. Drop jumping as a training method for jumping ability. *Sports Med* 9: 7–22, 1990.
6. Bobbert, MF, Huijing, PA, and van Ingen Schenau, GJ. Drop jumping I. The influence of jumping technique on the biomechanics of jumping. *Med Sci Sports Exerc* 19: 332–338, 1987.
7. Bobbert, MF, Huijing, PA, and van Ingen Schenau, GJ. Drop jumping. II. The influence of dropping height on the biomechanics of drop jumping. *Med Sci Sports Exerc* 19: 339–346, 1987.
8. Bobbert, MF, Mackay, M, Schinkelshoek, D, Huijing, PA, and van Ingen Schenau, GJ. Biomechanical analysis of drop and countermovement jumps. *Eur J Appl Physiol Occup Physiol* 54: 566–573, 1986.
9. Böhm, H, Kole, GK, Brüggemann, GP, and Ruder, H. Contribution of muscle series elasticity to maximum performance in drop jumping. *J Appl Biomech* 22: 3–13, 2006.
10. Bosco, C and Komi, PV. Influence of aging on the mechanical behavior of leg extensor muscles. *Eur J Appl Physiol Occup Physiol* 45: 209–219, 1980.

11. Bosco, C, Luhtanen, P, and Komi, PV. A simple method for measurement of mechanical power in jumping. *Eur J Appl Physiol* 50: 273–282, 1983.
12. Bosco, C, Viitasalo, JT, Komi, PV, and Luhtanen, P. Combined effect of elastic energy and myoelectrical potentiation during stretch-shortening cycle exercise. *Acta Physiol Scand* 114: 557–565, 1982.
13. de Villarreal, ES, Kellis, E, Kraemer, WJ, and Izquierdo, M. Determining variables of plyometric training for improving vertical jump height performance: A meta-analysis. *J Strength Cond Res* 23: 495–506, 2009.
14. Di Giminiani, R, Masedu, F, Tihanyi, J, Scrimaglio, R, and Valenti, M. The interaction between body position and vibration frequency on acute response to whole body vibration. *J Electromyogr Kinesiol* 23: 245–251, 2013.
15. Di Giminiani, R, Tihanyi, J, Safar, S, and Scrimaglio, R. The effects of vibration on explosive and reactive strength when applying individualized vibration frequencies. *J Sports Sci* 27: 169–177, 2009.
16. Dorgo, S, Smith, D, Ortiz, M, and King, G. The effects of eccentric phase duration on concentric phase force production during depth Jumps. In: Proceedings of the 24th International Symposium on Biomechanics in Sport, Salzburg, Austria, July 14–18, 2006. pp: 667–670.
17. Dyhre-Poulsen, P, Simonsen, EB, and Voigt, M. Dynamic control of muscle stiffness and H reflex modulation during hopping and jumping in man. *J Physiol* 437: 287–304, 1991.
18. Gollhofer, A, Strojnik, V, Rapp, W, and Schweizer, L. Behaviour of triceps surae muscle-tendon complex in different jump conditions. *Eur J Appl Physiol* 64: 283–291, 1992.
19. Hopkins, WJ. Measures of reliability in sports medicine and science. *Sports Med* 30: 1–15, 2000.
20. Horita, T, Komi, PV, Nicol, C, and Kyröläinen, H. Interaction between pre-landing activities and stiffness regulation of the knee joint musculoskeletal system in the drop jump: Implications to performance. *Eur J Appl Physiol* 88: 76–84, 2002.
21. Ishikawa, M and Komi, PV. Effects of different dropping intensities on fascicle and tendinous tissue behavior during stretch-shortening cycle exercise. *J Appl Physiol* 96: 848–852, 2004.
22. Jarvis, MM, Graham-Smith, P, and Comfort, P. A methodological approach to quantifying plyometric intensity. *J Strength Cond Res* 2014 May 1. Epub ahead of print.
23. Komi, PV and Gollhofer, A. Stretch reflexes can have an important role in force enhancement during SSC exercise? *J Appl Biomech* 13: 451–460, 1997.
24. Kovács, I, Tihanyi, J, Devita, P, Rácz, L, Barrier, J, and Hortobágyi, T. Foot placement modifies kinematics and kinetics during drop jumping. *Med Sci Sports Exerc* 31: 708–716, 1999.
25. Laffaye, G and Choukou, MA. Gender bias in the effect of dropping height on jumping performance in volleyball players. *J Strength Cond Res* 24: 2143–2148, 2010.
26. Leukel, C, Gollhofer, A, Keller, M, and Taube, W. Phase- and task-specific modulation of soleus H-reflexes during drop-jumps and landings. *Exp Brain Res* 190: 71–79, 2008.
27. Leukel, C, Taube, W, Gruber, M, Hodapp, M, and Gollhofer, A. Influence of falling height on the excitability of the soleus H-reflex during drop-jumps. *Acta Physiol (Oxf)* 192: 569–576, 2008.
28. Markovic, G. Does plyometric training improve vertical jump height? A meta-analytical review. *Br J Sports Med* 41: 349–355, 2007.
29. Markovic, G and Mikulic, P. Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Med* 40: 859–895, 2010.
30. McBride, JM and Snyder, JG. Mechanical efficiency and force–time curve variation during repetitive jumping in trained and untrained jumpers. *Eur J Appl Physiol* 112: 3469–3477, 2012.
31. Nicol, C, Avela, J, and Komi, PV. The stretch-shortening cycle: A model to study naturally occurring neuromuscular fatigue. *Sports Med* 36: 977–999, 2006.
32. O'Driscoll, J, Kerin, F, and Delahunt, E. Effect of a 6-week dynamic neuromuscular training programme on ankle joint function: A case report. *Sports Med Arthrosc Rehabil Ther Technol* 9: 3–13, 2011.
33. Padulo, J, Di Giminiani, R, Ibba, G, Zarrouk, N, Moalla, W, Attene, G, Migliaccio, GM, Pizzolato, F, Bishop, D, and Chamari, K. The acute effect of whole body vibration on repeated shuttle-running in young soccer players. *Int J Sports Med* 35: 49–54, 2014.
34. Ramírez-Campillo, R, Alvarez, C, Henríquez-Olguín, C, Baez, EB, Martínez, C, Andrade, DC, and Izquierdo, M. Effects of plyometric training on endurance and explosive strength performance in competitive middle- and long-distance runners. *J Strength Cond Res* 28: 97–104, 2014.
35. Ramírez-Campillo, R, Meylan, C, Alvarez, C, Henríquez-Olguín, C, Martínez, C, Cañas-Jamett, R, Andrade, DC, and Izquierdo, M. Effects of in-season low-volume high-intensity plyometric training on explosive actions and endurance of young soccer players. *J Strength Cond Res* 28: 1335–1342, 2014.
36. Ramírez-Campillo, R, Meylan, CM, Alvarez-Lepín, C, Henriquez-Olguín, C, Martinez, C, Andrade, DC, Castro-Sepúlveda, M, Burgos, C, Baez, EI, and Izquierdo, M. The effects of inter-day rest on adaptation to 6-weeks of plyometric training in young soccer players. *J Strength Cond Res* 29: 972–979, 2015.
37. Risberg, MA, Mork, M, Jenssen, HK, and Holm, I. Design and implementation of a neuromuscular training program following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther* 31: 620–631, 2001.
38. Sole, G, Hamren, J, Milosavljevic, S, Nicholson, H, and Sullivan, SJ. Test–retest reliability of isokinetic knee extension and flexion. *Arch Phys Med Rehabil* 88: 626–631, 2007.
39. Taube, W, Leukel, C, Lauber, B, and Gollhofer, A. The drop height determines neuromuscular adaptations and changes in jump performance in stretch-shortening cycle training. *Scand J Med Sci Sports* 22: 671–683, 2012.
40. Taube, W, Leukel, C, Schubert, M, Gruber, M, Rantalainen, T, and Gollhofer, A. Differential modulation of spinal and corticospinal excitability during drop jumps. *J Neurophysiol* 99: 1243–1252, 2008.
41. Váczi, M, Rácz, L, Hortobágyi, T, and Tihanyi, J. Dynamic contractility and efficiency impairments in stretch-shortening cycle are stretch-load-dependent after training-induced muscle damage. *J Strength Cond Res* 27: 2171–2179, 2013.
42. Viitasalo, JT and Bosco, C. Electromechanical behaviour of human muscles in vertical jumps. *Eur J Appl Physiol Occup Physiol* 48: 253–261, 1982.
43. Voigt, M, Simonsen, EB, Dyhre-Poulsen, P, and Klausen, K. Mechanical and muscular factors influencing the performance in maximal vertical jumping after different prestretch loads. *J Biomech* 28: 293–307, 1995.