Optimal Load Magnitude and Placement for Peak Power Production in a Vertical Jump: A Segmental Contribution Analysis

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Abstract

Bordelon, NM, Jones, DH, Sweeney, KM, Davis, DJ, Critchley, ML, Rochelle, LE, George, AC, and Dai, B. Optimal load magnitude and placement for peak power production in a vertical jump: a segmental contribution analysis. *J Strength Cond Res* XX(X): 000–000, 2020—Weighted jumps are widely used in power training, however, there are discrepancies regarding which loading optimizes peak jump power. The purpose was to quantify the effects of load magnitudes and placements on the force, velocity, and power production in a countermovement vertical jump. Sixteen male and 15 female subjects performed vertical jumps in 7 conditions: no external load, 10 and 20% dumbbell loads, 10 and 20% vest loads, and 10 and 20% barbell loads with load percentages relative to body weight. Arm swing was encouraged for all, but the barbell load conditions. Kinematics were collected to quantify the whole-body (the person and external loads) forces, velocities, and power as well as segments' contributions to the whole-body forces and velocities. Repeated-measure analyses of variance were performed followed by paired comparisons. Jump heights were the greatest for the no external load and 10% dumbbell conditions. The 10 and 20% dumbbell conditions demonstrated the greatest peak whole-body power, while the 2 barbell conditions showed the lowest peak whole-body power. At the time of peak whole-body power, the 2 dumbbell and 2 vest conditions resulted in greater whole-body forces. Whole-body velocities were the greatest for the no external load and 10% dumbbell conditions. Holding the dumbbells in the hands magnified the effects of external loads in producing forces and velocities. The constraint of arm movements in the barbell conditions limited power production. These findings highlight the importance of load placement and arm swing in identifying the optimal configuration for power production in weighted jumps.

Key Words: external load, power training, kinetics, biomechanics, forces

Introduction

Linear power is defined as the product of force and velocity, representing the ability to rapidly produce force during dynamic tasks such as jumping, throwing, and changing directions (17). Although strength training alone can improve peak power (1,13,18), greater increases have been observed in combination with power training using light to moderate loads (1). Previous research has suggested effective power training should consist of loading variations that maximize peak power (6,15,17,21). A weighted jump is a potential approach, however, factors such as load magnitudes and placements should be considered since they may affect power production.

Previous researchers have quantified power production in squat jumps, reporting optimal loads to be between 0 and 60% of a subject's one repetition maximum (1-RM) of a barbell back squat, with the unloaded conditions frequently demonstrating greater power compared to loaded conditions (3,4,9,11,17,24–26). The discrepancy in optimal loading percentages may be the result of different populations, jump types, and load placements. While some studies have assessed weighted jumps without a countermovement (11), external loading was commonly imposed through barbells, likely constraining arm movement for bar stabilization (3,9,24–26). Some researchers have used a vest as an external load (11), but it is unknown how a vest may affect jump performance compared to other load placements. Swinton et al. (25) demonstrated that a hexagonal bar held in the hands resulted in greater jump height and power compared to a straight bar held on the shoulders, highlighting the potential effects of load placements. Both load placements, however, constrained arm movement by requiring subjects to hold the bar.

Arm swing has been shown to result in greater jump heights along with increased vertical ground reaction forces (VGRF) and power during unloaded jumps (12,14). Hara et al. (14) showed that arm swing increased jump height mainly by increasing hip and ankle joint work. Feltner et al. (12) analyzed segmental contributions to the whole-body acceleration in unloaded jumps and found increased jump velocities associated with arm swing explained by increased duration of the propulsive phase with similar average forces. In addition, arm swing decreased the negative contributions of the trunk, head, and thigh to the whole-body acceleration while increasing lower extremity extensor torques later in the propulsive phase. Considering the significant contribution of the arms to vertical jump performance, holding external loads such as dumbbells in the hands may promote force and power production and therefore be considered a viable option for power training. However, there are limited studies quantifying the effects of load placements on power production during weighted jumps. Understanding the factors that optimize

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Journal of Strength and Conditioning Research 00(00)/1–9

power production will help improve power training guidelines for weighted jumps. The findings could provide information for strength and conditioning practitioners to choose better strategies for power training and avoid sub-optimal movements. The results could also help practitioners understand how the manipulation of different factors such as weight magnitudes, placements, and arm swing may affect the development of whole-body power.

Therefore, the purpose of the current study was to quantify the effects of load magnitudes and placements on the force, velocity, and power production during a countermovement vertical jump (CMVJ). Seven conditions (no external load, 10 and 20% dumbbell, 10 and 20% vest, and 10 and 20% barbell) were performed with external loads relative to body weight. Based on previous research analyzing the effects of arm swing on jump performance (12,14,22), it was hypothesized that the dumbbell conditions would produce greater jump heights, whole-body (the person and external loads) forces, velocities, and power compared to the other loaded conditions. It was also hypothesized the external load would make greater contribution to the whole-body forces and velocities at the time of peak power for the dumbbell conditions compared to the other loaded conditions.

Methods

Experimental Approach to the Problem

A cross-sectional randomized repeated-measure design was used with each subject performing 7 CMVJ conditions: no external load, 10 and 20% dumbbell loads, 10 and 20% vest loads, and 10 and 20% barbell loads with external load percentages relative to the body weight. Subjects included 16 male and 15 female recreational athletes who had experience in jump-landing activities. Subjects performed all the jump conditions in a single visit without a familiarization session. Arm swing was encouraged for all but the barbell load conditions. Kinematics were collected to quantify vertical whole-body forces, velocities, and powers as well as trunk-head, arm, leg, and external-load components' contributions to these whole-body forces and velocities. These variables were extracted at peak whole-body power to compare among the 7 CMVJ conditions using repeated-measure analysis of variables (ANOVAs) followed by paired comparisons.

Subjects

Based on a previous study comparing the effects of arm swing on peak jump velocities (12), a large effect size was expected for dependent variables between the dumbbell condition and other weighted-jump conditions. Based on an effect size of 0.6 for a paired comparison, a sample size of 24 was needed for a type I error at the level of 0.05 to achieve a power of 0.8. Subjects included 16 men and 15 women older than 18 years of age (age range: 18-30 years). Subjects were required to have experience in sports or exercises involving jump-landing activities and participate in sports or exercises at least 2 times per week for a minimum of 2 hours per week. Individuals were excluded if they (a) lacked jump-landing experience or were not physically active, (b) sustained any major lower extremity or spinal injuries that involved surgical treatments (c), had an injury that kept them from participation in physical activities for a period greater than 2 weeks within the preceding 6 months, (d) possessed any condition preventing participation in physical activities with maximal efforts, (e) were allergic to adhesive tapes, or (f) were pregnant. This study was approved by the University of Wyoming Institutional Review Board. All subjects signed an informed consent form prior to participation.

Procedures

Subjects wore Ghost 5 athletic shoes (Brooks Sports, Inc., Seattle, WA), a spandex top, a spandex pant, and a baseball cap for the placement of a vertex marker. Subjects performed a warm-up protocol consisting of a 5-minute jog at a self-selected speed followed by 30 yards each of walking toe touches, walking quadriceps stretch, walking lunges, and 2 sets of lateral shuffles (20). Retroreflective markers were placed on subjects' bony landmarks on the head, arms, trunk, pelvis, and legs (8,16). The kinematic model of the human body was based on a previous model established by de Leva (10). For external loads, makers were placed on the 2 ends of the bar, 2 ends of each dumbbell, and the center of each pocket row for load placements of the vest. Eight Vicon Bonita-10 infrared cameras (Oxford Metrics Ltd, Oxford, United Kingdom) were used to capture kinematic data at a sampling frequency of 160 Hz. Two force platforms (FP4060-10; Bertec Corporation, Columbus) were utilized to measure VGRF at a sampling frequency of 1,600 Hz. Force platforms were connected through a Vicon 64-channel analog/digital system for synchronization of analog devices with the cameras. Kinematic and force data were collected simultaneously by the Vicon Nexus 1.8.2 software.

Subjects first performed one static trial in a T-pose. For the CMVJ trials, subjects started with feet hip-width apart and hands by the side on 2 force platforms. Subjects then lowered the body to a self-selected depth and immediately jumped vertically as high as possible. Arm swing was encouraged for all but the barbell load condition, in which subjects held the bar with both hands. A previous study showed that an external load of 7% of body weight placed in a vest resulted in greater power compared to 0 and 14% of body weight in a squat jump in strength and power athletes (11). In addition, a pilot study was performed with 2 male subjects. Jump heights and peak whole-body forces, power, and velocities were calculated from VGRF. Both subjects demonstrated the greatest peak whole-body power for the 10% dumbbell condition and consistent variables of interests among the 3 official trials after 1–2 practice trials. Based on this previous study and the pilot study, 10 and 20% of body weight have been chosen as external loads for the current study, as it was expected that further increases in external loads were not likely to increase peak whole-body power. For the no load condition, no external load was applied to the subject (Figure 1). For the dumbbell load conditions, an external load of 10 or 20% of body weight was equally distributed to 2 dumbbells held at the hands (Figure 2). For the vest load conditions, an external load of 10 or 20% of body weight was added by a weighted vest (ZFO Sports, San Jose, CA; Figure 3). Weights were placed in the pockets with an order of the first row on the front (a maximum of 5.44 kg, 0.17 m inferior to the shoulder), the first row on the back (a maximum of 6.8 kg, 0.17 m inferior to the shoulder), and the second row on the front (a maximum of 6.8 kg, 0.3 m inferior to the shoulder). For the barbell load conditions, an external load of 10 or 20% of body weight was imposed by a bar and equally distributed plates (Figure 4). External loads were added with a minimal increment of 0.45 kg and were taped to the dumbbells and bar when necessary. Subjects performed a minimum of 1 successful practice trial for each condition. Subjects then completed 3 successful recorded trials for each condition with a randomized order of the 7 CMVJ conditions. At least one minute of rest was provided between consecutive trials.

Figure 1. Jump without external load.

Data Reduction. Markers were tracked using the Vicon Nexus software. When a small gap was observed for a marker, the "Pattern Fill" function was used to fill the gap using the nearest markers on the same segment. A limited number of large gaps were filled using the singular decomposition method (23) using other makers on the same segment in data process. Marker positions and VGRF were filtered using a fourth-order Butterworth filter at a low-pass cut-off frequency of 15 Hz (19). The whole-body included 15 body segments (8,16) and the external load component. A trunk-head component was defined with the head, upper trunk, and pelvis, and an arm component was defined with the 2 upper arms, forearms, and hands, and a leg component was defined with the 2 thighs, shanks, and feet. Center of mass (COM) positions of the whole-body and each component were calculated using the segmental method (27). Velocities and acceleration were calculated using the first central difference method (27). Whole-body power in the vertical direction was calculated as the VGRF multiplied by the vertical velocity (equation 1). Whole-body VGRF was modeled as the product of the mass of the whole body and the sum of its vertical acceleration and gravity. Previous studies have typically measured VGRF from force platforms to calculate whole-body power (9,11,25), while the current study computed VGRF from segment mass and acceleration (12). The validity of the current method was assessed by comparing the computed VGRF with directly measured VGRF. At the time of peak whole-body power, the differences between the computed VGRF and measured VGRF ranged 1–4% among the 7 conditions, supporting the validity of the current method. The whole-body VGRF and vertical velocities were further broken into the contributions from the trunk-head, arm, leg, and external-load components (equation 1, Figures 5 and 6). The force and velocity contribution from each component were calculated based on equations 2 and 3.

$$\begin{aligned} \mathrm{Pwb} &= \mathrm{VGRFwb} \times \mathrm{Vwb} = (M\mathrm{wb} \times [\mathrm{Awb} + 9.8]) \times \mathrm{Vwb} \\ &= (\mathrm{FCth} + \mathrm{FCl} + \mathrm{FCa} + \mathrm{FCel}) \\ &\quad \times (\mathrm{VCth} + \mathrm{VCl} + \mathrm{VCa} + \mathrm{VCel}) \end{aligned} \tag{1}$$

Pwb: whole-body power; VGRFwb: whole-body vertical ground reaction force; Vwb: whole-body vertical velocity; Mwb: whole-body mass; Awb: whole-body acceleration; FCth: force contribution from the trunk-head component; FCl: force contribution from the leg component; FCa: force contribution from the arm component; FCel: force contribution from the external load

Figure 2. Jump with 10% dumbbells.

Figure 3. Jump with a 10% vest.

component; VCth: velocity contribution from the trunk-head component; VCl: velocity contribution from the leg component; VCa: velocity contribution from the arm component; VCel: velocity contribution from the external load component;

$$\mathrm{FCcomp} = (\mathrm{Acomp} + 9.8) \times \mathrm{Mcomp} \quad (2)$$

FCcomp: whole-body force contribution from a given component; Acomp: acceleration of the component; Mcomp: mass of the component;

$$\mathrm{VCcomp} = \mathrm{Vcomp} \times \mathrm{Mcomp}/\mathrm{Mwb} \quad (3)$$

VCcomp: whole-body velocity contribution from a given component; Vcomp: velocity of the component; Mcomp: mass of the component; Mwb: whole-body mass.

Jump height was determined using 2 methods, calculating the vertical displacement between the static trial (Jump Height 1) or the COM position at takeoff (Jump Height 2) and the peak COM position during the jump trial. The first method allowed comparisons of the jump height of the current population to the literature using similar methods. The second method was more accurate as the static trial was performed without external loads. For the CMVJ trials, whole-body powers, forces, and velocities, along with force and velocity contributions from the trunk-head, arm, leg, and external-load components were calculated at the time of peak whole-body power. Power and forces were normalized to body weight. In addition, the duration of the concentric phase was calculated as the time between the lowest COM position and takeoff. The timing of peak power as a percentage of the concentric phase was also quantified. Data calculation was performed in MATLAB R2017b (MathWorks, Natrick, MA).

Statistical Analyses

The intraclass correlation (ICC [3, k]) values among the 3 official trials were calculated for each dependent variable in each jump condition. Outliers were identified as numbers with absolute z-scores greater than 2. Normal distribution of variables was checked using the Kolmogorov-Smirnov test. A repeated-measure ANOVA with the 7 jump conditions as a within-subject variable was performed for each dependent variable. Paired t-tests were performed when significant jump-condition effects were observed. To assess the effect of outlier and violation of normal distribution on the results of paired t-tests, the *p* values of paired t-tests were compared to those calculated from Wilcoxon signed-rank tests. The Benjamini–Hochberg

Figure 4. Jump with a 10% barbell.

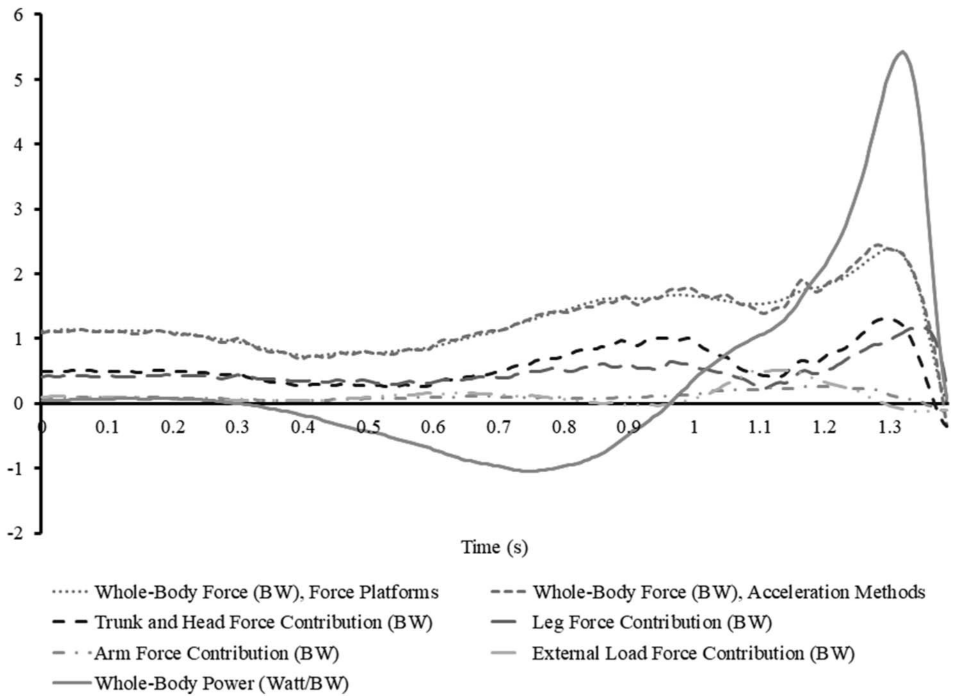

Figure 5. Segmental contributions to the whole-body forces for a jump trial with 10% dumbbells. Initiation of the countermovement: 0.36 seconds; initiation of the upward jump: 0.97 seconds; timing of peak power: 1.33 seconds.

procedure was applied to all paired t-tests or Wilcoxon signed-rank tests to control the study-wide false discovery rate to be 0.05. Cohen's dz was calculated between the no load condition and loaded conditions with Cohen's dz >0.8 considered "large," 0.5 <Cohen's dz <0.8 considered "medium," and Cohen's dz <0.5 considered "small" (5). Statistical analyses were performed using the SPSS Statistics 22 software (IBM Corporation, Armonk, NY).

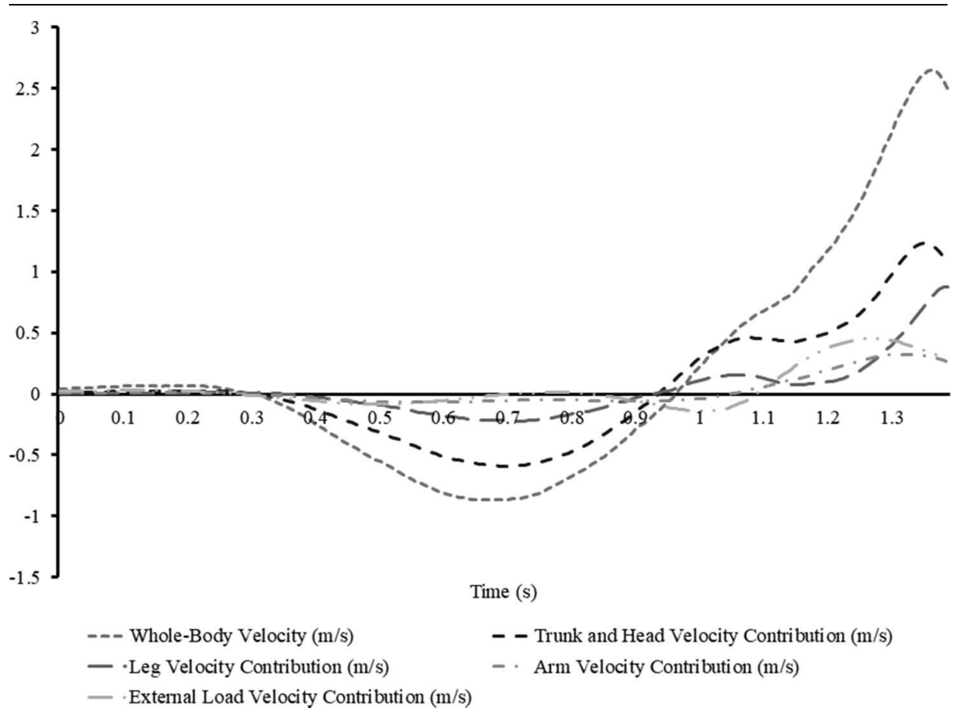

Figure 6. Segmental contributions to the whole-body velocities for a jump trial with 10% dumbbells. Initiation of the countermovement: 0.36 seconds; initiation of the upward jump: 0.97 seconds; timing of peak power: 1.33 seconds.

Results

Subjects' age, height, and mass were 21.9 ± 2.3 (mean ± *SD*) years, 1.75 ± 0.94 m, and 69.4 ± 11.5 kg, respectively. Most variables demonstrated ICCs greater than 0.9, while the no load condition showed similar ICCs as the loaded condition (Table 1). Although outliers and violation of normal distribution were found for several variables, statistical significance was consistent between paired *t*-tests and Wilcoxon signed-rank tests except for concentric contraction duration. To keep consistency among variables, all *p* values were based on paired *t*-tests except for concentric contraction duration which was based on Wilcoxon signed-rank tests.

Significant jump-condition effects were observed for all variables (Table 2). Both Jump Height 1 and Jump Height 2 were the greatest for the no external load and 10% dumbbell conditions and the lowest for the 2 barbell conditions. The 2 dumbbell conditions demonstrated the greatest peak whole-body power, while the 2 barbell conditions showed the lowest peak whole-body power. The effect size of the increase in peak power was large for the 10% dumbbell condition but small for the 20% dumbbell condition compared to the no load condition (Table 3). At the time of peak whole-body power, the 20% dumbbell conditions resulted in the greatest whole-body forces with a large effect size of increases compared to the no load condition. Different jump conditions demonstrated different force contribution patterns from each component. The 10% dumbbell, no external load, 20% dumbbell, and 20% vest conditions demonstrated the greatest force contributions from the trunk and head, legs, arms, and external load, respectively. Whole-body velocities were the greatest for the no external load and 10% dumbbell conditions and the lowest for the 20% barbell condition. The no load condition demonstrated the greatest velocity contribution from the trunk and head, arms, and legs. The velocity contribution from the external load was the greatest for the 20% dumbbell condition and the second greatest for the 10% dumbbell and 20% vest conditions. The concentric phase duration and timing of peak power during the concentric phase were generally greater for the 2 dumbbell conditions and less for the no load condition.

Discussion

The purpose of this study was to quantify the effects of load magnitudes and placements on the force, velocity, and power production during a CMVJ. The results support the hypothesis that the 2 dumbbell conditions would produce greater jump heights, forces, velocities, and power compared to the other loaded conditions. The 10% dumbbell condition also demonstrated greater jump forces and power and similar jump heights and velocities compared to the no load condition. However, the findings do not support the hypothesis that the external load would make greater contribution to the whole-body forces at the time of peak power for the dumbbell conditions compared to the other loaded conditions. For the no load condition, the arm component made a negative contribution to the whole-body force at the time of peak power, indicating the arms were decelerating towards the end of the jump. These findings were consistent with the study by Feltner et al. (12), showing arm swing made the greatest contribution during the middle phase of the jump. Although the arms demonstrated negative acceleration near the time of peak velocity, arm swing increased lower extremity joint torques in the later phase of the jump, resulting in increased peak velocities. However, the current observation was not aligned with a previous study, showing the arms could make a greater than 30% contribution to the peak forces during unloaded CMVJ (22). This discrepancy could be due to different arm swing techniques, as the previous study required arm swing with a large range of motion, ending with the arms above the head at the end of the jump, while the current study allowed self-selected arm swing. Additionally, arms and external loads both made positive contributions to the whole-body forces at the time of peak power for the 10% dumbbell condition, suggesting subjects were less likely to actively decelerate the arms when the dumbbells were held in hands. Instead, a follow-through motion was more likely utilized with the dumbbells naturally slowed down by the gravity. The dumbbell conditions also demonstrated the longest concentric phase duration and the latest timing of peak power, which could be associated with the increased time to swing the arms. Regarding jump velocities, the findings support the hypothesis that the external load would make greater contribution to the whole-body velocities at the time of peak power for the dumbbell conditions compared to the other loaded conditions. Although the 10% dumbbell condition had decreased velocity contributions from the trunk and head, legs, and arms compared to the no load condition, the velocity of the external load compensated for these decreases to achieve similar whole-body velocities. As such, the increased force contribution from the arms and external loads

Table 1
Intra-class coefficients (ICC (3, k)) among the 3 official trials for each variable.

	No load	10% dumbbell	20% dumbbell	10% vest	20% vest	10% barbell	20% barbell
Jump height 1	1.0	0.99	0.99	0.99	0.99	0.99	0.99
Jump height 2	0.99	0.99	0.98	0.99	0.99	0.99	0.99
Peak whole-body power	0.99	0.99	1.0	0.99	0.99	0.99	0.99
Whole-body force	0.97	0.99	0.99	0.98	0.97	0.98	0.98
Trunk and head force contribution	0.92	0.95	0.97	0.96	0.93	0.97	0.97
Leg force contribution	0.97	0.98	0.98	0.99	0.97	0.98	0.98
Arm force contribution	0.92	0.96	0.94	0.86	0.83	0.75	0.79
External load force contribution	—	0.88	0.92	0.85	0.88	0.81	0.91
Whole-body velocity	0.95	0.98	0.97	0.96	0.97	0.98	0.97
Trunk and head velocity contribution	0.95	0.99	0.98	0.97	0.97	0.95	0.95
Leg velocity contribution	0.77	0.89	0.89	0.81	0.77	0.87	0.83
Arm velocity contribution	0.97	0.98	0.99	0.96	0.93	0.98	0.99
External load velocity contribution	—	0.98	0.99	0.94	0.95	0.95	0.98
Concentric contraction duration	0.42	0.98	0.98	0.97	0.73	0.95	0.95
Timing of peak power during concentric contraction	0.64	0.94	0.88	0.83	0.81	0.90	0.88

Table 2

Means (*SDs*) of dependent variables for different jumping conditions and *p* values of analyses of variance.*

	No load	10% dumbbell	20% dumbbell	10% vest	20% vest	10% barbell	20% barbell	*p*
Jump height 1 (m)	0.44 (0.11) A	0.45 (0.11) A	0.40 (0.11) BCD	0.42 (0.09) B	0.41 (0.09) C	0.37 (0.07) E	0.38 (0.06) DE	<0.001
Jump height 2 (m)	0.31 (0.08) A	0.30 (0.08) A	0.27 (0.07) B	0.27 (0.07) B	0.24 (0.07) C	0.23 (0.06) D	0.20 (0.06) E	<0.001
Peak whole-body power ($W \cdot BW^{-1}$)	5.53 (1.16) B	5.87 (1.11) A	5.78 (1.12) A	5.52 (1.12) B	5.36 (1.06) C	4.77 (0.76) D	4.71 (0.78) D	<0.001
Whole-body force (BW)	2.21 (0.31) CD	2.36 (0.23) B	2.47 (0.23) A	2.33 (0.27) B	2.36 (0.25) B	2.13 (0.18) D	2.21 (0.17) C	<0.001
Trunk and head force contribution (BW)	1.17 (0.25) BC	1.16 (0.17) AB	1.11 (0.16) C	1.13 (0.20) BC	1.05 (0.19) D	0.89 (0.09) E	0.87 (0.08) F	<0.001
Leg force contribution (BW)	1.12 (0.10) A	1.06 (0.09) B	1.01 (0.09) C	1.04 (0.10) BC	0.99 (0.09) D	0.98 (0.09) D	0.93 (0.08) E	<0.001
Arm force contribution (BW)	−0.07 (0.10) D	0.12 (0.05) C	0.14 (0.04) AB	−0.10 (0.08) D	−0.08 (0.08) D	0.13 (0.03) C	0.13 (0.02) BC	<0.001
External load force contribution (BW)	0.00 (0.00) E	0.03 (0.08) E	0.20 (0.11) C	0.25 (0.05) C	0.40 (0.07) A	0.14 (0.02) D	0.28 (0.04) B	<0.001
Whole-body velocity ($m \cdot s^{-1}$)	2.49 (0.32) A	2.48 (0.33) A	2.33 (0.32) B	2.36 (0.29) B	2.26 (0.29) C	2.23 (0.25) C	2.12 (0.24) D	<0.001
Trunk and head velocity contribution ($m \cdot s^{-1}$)	1.40 (0.18) A	1.17 (0.16) B	0.99 (0.13) D	1.17 (0.15) B	1.03 (0.14) C	1.17 (0.15) B	1.00 (0.13) D	<0.001
Leg velocity contribution ($m \cdot s^{-1}$)	0.66 (0.09) A	0.56 (0.07) C	0.49 (0.05) E	0.56 (0.06) C	0.50 (0.06) DE	0.58 (0.05) B	0.51 (0.05) D	<0.001
Arm velocity contribution ($m \cdot s^{-1}$)	0.43 (0.12) A	0.32 (0.06) C	0.24 (0.05) E	0.36 (0.09) B	0.30 (0.08) D	0.23 (0.03) E	0.20 (0.03) F	<0.001
External load velocity contribution ($m \cdot s^{-1}$)	0.00 (0.00) E	0.44 (0.10) B	0.62 (0.15) A	0.27 (0.03) C	0.44 (0.06) B	0.25 (0.03) D	0.43 (0.05) B	<0.001
Concentric contraction duration (s)	0.35 (0.07) E	0.44 (0.16) BC	0.45 (0.18) AB	0.39 (0.10) D	0.40 (0.09) C	0.36 (0.05) CD	0.39 (0.06) BC	0.009
Timing of peak power during concentric contraction (%)	0.77 (0.05) C	0.81 (0.05) A	0.80 (0.06) AB	0.78 (0.05) BC	0.79 (0.04) BC	0.79 (0.04) AB	0.80 (0.04) AB	0.018

*The forces and velocities of the whole body and different components were calculated at the time of peak whole-body power. The effect of jumping conditions on each dependent variable was grouped, where A>B>C>D>E>F. Jumping conditions with the same letters indicate non-significant differences among them. Significance level set at 0.05 after the adjustment for the false discovery rate.

with similar jump velocities resulted in increased power for the 10% dumbbell condition compared to the no load condition. The 20% dumbbell condition showed the greatest jump forces, but it also significantly decreased jump velocities, resulting in less effect sizes of increases in jump power compared to the 10% dumbbell condition. Therefore, the 10% dumbbell conditions appeared to be the optimal load magnitude and placement in the current study.

A weighted vest has been previously used to quantify the effect of 5 and 10 kg external loads corresponding to approximately 7 and 14% of body weight on peak power in a squat jump without countermovement or arm swing (11). While the 5 kg external load condition demonstrated the greatest power for strength and power athletes, the no load condition was optimal for sedentary individuals. In the current study, the 10% vest condition showed similar jump power compared to the no external load, while the 20% vest condition decreased jump power. It was unknown whether a smaller percentage of external load would increase jump power for the vest conditions. The major difference between the 10% dumbbell and 10% vest conditions was the velocity contribution from the external loads, which were greater for the 10% dumbbell condition. These findings support the importance of load placement in producing power, as both conditions allowed arm swing. A 10% external load in the vest condition increased jump forces but decreased jump velocities, resulting in similar jump power compared to the no load condition. However, the augmented effects of arm swing on the external loads to increase jump velocities and concentric phase duration could not be achieved for the vest conditions.

Table 3

Cohen's dz between each loaded condition and the no load condition for each variable.

	10% dumbbell vs. no load	20% dumbbell vs. no load	10% vest vs. no load	20% vest vs. no load	10% barbell vs. no load	20% barbell vs. no load
Jump height 1	0.16	−0.75	−0.74	−0.98	−1.23	−1.15
Jump height 2	−0.17	−1.45	−1.69	−2.70	−2.31	−3.39
Peak whole-body power	0.81	0.48	−0.01	−0.43	−1.35	−1.57
Whole-body force	0.98	1.37	0.65	1.09	−0.39	0.01
Trunk and head force contribution	−0.07	−0.27	−0.20	−0.86	−1.42	−1.56
Leg force contribution	−0.70	−1.19	−1.08	−2.00	−1.89	−2.12
Arm force contribution	1.91	2.18	−0.35	−0.05	2.08	2.01
External load force contribution	0.35	1.81	5.10	5.71	5.78	7.67
Whole-body velocity	−0.10	−1.07	−0.97	−1.69	−2.05	−2.78
Trunk and head velocity contribution	−3.48	−4.82	−2.57	−4.55	−2.89	−4.35
Leg velocity contribution	−1.70	−2.61	−1.30	−2.40	−1.19	−2.42
Arm velocity contribution	−1.47	−2.16	−1.21	−2.28	−2.10	−2.46
External load velocity contribution	4.37	4.25	8.02	7.49	8.63	7.92
Concentric contraction duration	0.53	0.52	0.36	0.50	0.11	0.45
Timing of peak power during concentric contraction	0.53	0.45	0.20	0.30	0.41	0.59

The optimal load to produce jump power has been mostly studied with barbells (3,4,9,24–26). The current findings, however, do not support barbells as the most effective way to promote jump power. The barbell conditions demonstrated the least jump forces, velocities, and power, and the decreased forces and velocities were seen in multiple components of the body. Previous studies have shown that arm swing imposed additional loading to the lower extremities, which then generated greater joint torques and work during the later phase of the jump (12,14). The constraint of the arms influenced not only the arms but also the whole-body force and power production. Previously, Swinton et al. (25) found that weighted jumps with a straight bar on the shoulders resulted in decreased jump power compared to unloaded jumps and jumps with a hexagonal bar. An external load of 20% of 1 RM imposed by the hexagonal bar demonstrated 6.5% greater peak power than the unloaded condition. However, subjects kept their arms placed vertically on the side of the body for the unloaded jumps, thus the 6.5% increase in peak power could be similar to an unloaded jump with arm swing. Because of the disadvantages of the barbell conditions in producing jump power, it is reasonable that the no load condition has been commonly shown to produce the greatest power (4,9,25). On the other hand, some studies have reported optimal loading between 10 and 60% for peak power production in squat jumps with barbells (3,24,26), and an external load of 0–60% of 1-RM has also been recommended for lower body power training (2). But it should be noted that these studies (3,24,26) did not compare peak power in the weighted jumps with unloaded jumps with arm swing. In summary, the current findings do not support using barbells as an optimal strategy to increase jump power due to the constraint of arm movements. From a practical perspective, while arm swing is commonly used in most jump activities, it should be noted that the use of arm swing may depend on difference scenarios. Athletes who commonly perform jump activities with limited arm swing may warrant different approaches. For these athletes, using barbells with constrained arm movements may allow greater emphasis of the lower extremities.

Several limitations existed in the current study. First, the load magnitudes were limited to 10 and 20% of body weight. Analyzing additional increments of loading percentages and expressing the loads as a function of 1 RM may provide a more comprehensive insight into the optimal load for each load placement. Second, subjects were instructed to jump as high as possible with their self-selected jump and arm swing techniques. Instruction related to the jump and arm swing techniques may affect power production and warrant future investigation. In addition, subjects had experience in jump-landing activities, but they were not required to have experience in weighted jumps. A familiarization session was not performed, as the pilot study showed that subjects could consistently perform the weighted jumps after 1–2 practice trials. The ICCs supported that subjects were able to produce reliable movement patterns compared to the no load condition in the current study. However, a greater extent of familiarization would likely improve their performance in weighted jumps. Third, the current findings were mostly limited to recreational athletes who had jump-landing experience at the varsity level in high school. When the Jump Height 2 was compared to the normative data of jump height in Division I athletes (7), male and female subjects were at approximately 10 and 25% percentiles, respectively. Therefore, future studies are encouraged to include elite athletes with greater jump performance. Fourth, the safety of weighted jumps, specifically in the landing phase, was not assessed. Subjects were required to hold on the external loads throughout the jump and landing, and the increased weight during the landing phase might increase injury risk. Further studies should quantify the impact load during the landing phase and evaluate how different landing techniques or dropping the weight in the air might affect impact loads. Fifth, the biomechanical analyses were limited to whole-body kinetics. Future analyses should include joint kinematics and kinetics to provide additional insight into joint power production. Additionally, the statistical analyses were limited to discrete data. Future studies should consider the inclusion of statistical parametrical mapping of time-series data. Finally, the current findings were limited to the analyses of immediate changes associated with different load conditions. Further studies should examine the effect of long-term training of different load magnitudes and placements on power production during jump activities.

In conclusion, the 10 and 20% dumbbell condition resulted in the greatest jump power while the 2 barbell conditions resulted in the least jump forces, velocities, and power. The 10% vest condition showed similar power as the no load condition. Holding the dumbbells in the hands magnified the contribution of external loads in producing forces and velocities. The constraint of arm movements in the barbell conditions limited the power production of the whole body. The findings highlight the importance of load placement and arm swing in identifying the optimal load for power production in weighted jumps.

Practical Applications

The findings provide information for trainers and professionals to design power training programs to include weighted jumps that may optimize peak jump power. In addition to load magnitudes, the load placement is another factor that can affect the development of forces and velocities of body segments and external loads. For example, the dumbbells conditions are likely to increase the velocity contribution of external loads to the whole-body velocities. When the goal is to maximize jump power, it may be beneficial to use a countermovement jump with arm swing and 10% of body weight held in dumbbells at the hands. Holding 20% of body weight of dumbbells might further increase jump forces but may result in slightly less jump power compared to the 10% of body weight of dumbbells. Weighted jump with a 10% external load in a vest may be considered to maintain jump power compared to the no load condition but increase jump forces without greater involvements of the arms. Although weighted jumps with barbells placed on the shoulders are frequently performed, they may be considered as sub-optimal strategies for power production due to the constraint of the arms. Future studies are needed to identify effective strategies to decrease potential high impact load during the landing phase associated with weighted jumps. Guidelines related to power training may need to include the potential effects of load placements and arm swing on the identification of optimal loads.

Acknowledgments

The authors claim no conflict of interest; the results of the current study do not constitute as an endorsement of the equipment used in the current study by the authors nor the National Strength and Conditioning Association.

D.H. Jones received a fellowship from the Wyoming INBRE, which was supported by a grant from the National Institute of General Medical Sciences (P20GM103432) from the National Institutes of Health.

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