Power-Time, Force-Time, and Velocity-Time Curve Analysis During the Jump Squat: Impact of Load

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The purpose of this investigation was to examine the impact of load on the power-, force- and velocity-time curves during the jump squat. The analysis of these curves for the entire movement at a sampling frequency of 200–500 Hz averaged across 18 untrained male subjects is the most novel aspect of this study. Jump squat performance was assessed in a randomized fashion across five different external loads: 0, 20, 40, 60, and 80 kg (equivalent to 0 ± 0, 18 ± 4, 37 ± 8, 55 ± 12, 74 ± 15% of 1RM, respectively). The 0-kg loading condition (i.e., body mass only) was the load that maximized peak power output, displaying a significantly (p ≤ .05) greater value than the 40, 60, and 80 kg loads. The shape of the force-, power-, and velocity-time curves changed significantly as the load applied to the jump squat increased. There was a significantly greater rate of power development in the 0 kg load in comparison with all other loads examined. As the first comprehensive illustration of how the entire power-, force-, and velocity-time curves change across various loading conditions, this study provides extensive evidence that a load equaling an individuals body mass (i.e., external load = 0 kg) maximizes power output in untrained individuals during the jump squat.

Keywords: optimal load, power training, counter-movement jump

Power has been identified as a vital component in jumping based on the fact that superior ability to execute the movement explosively typically results in a more desirable performance (Carlock et al., 2004; Driss et al., 1998; Stockbrugger & Haenmel, 2003; Stone et al., 2000; Vandewalle et al., 1987). As a result, emphasis has been placed on determining the best manner to improve power output during jumping activities (Kraemer & Newton, 2000; Kyrolainen et al., 2004, 2005; McBride et al., 2002). Investigations have indicated that training with a load that maximizes power output is the best stimulus for further improvements in power (Hoffman et al., 2005; McBride et al., 2002; Newton et al., 1999; Toji & Kaneko, 2004; Wilson et al., 1993). Numerous investigators have studied the impact of loading on peak and average power, force, and velocity during jump squats in an attempt to determine the optimal load to use during power training (Baker et al., 2001; Cormie et al., 2007b; Driss et al., 2001; Dugan et al., 2004; Izquierdo et al., 2002; Siegel et al., 2002; Stone et al., 2000; Toji & Kaneko, 2004). However, no previous investigation has examined how loading influences power, force, and velocity throughout the entire movement. Thus it is unclear whether the shape of the power-time, force-time, and velocity-time curves differ as the load applied to a jump squat changes.

The gradient of the power-time, force-time, and velocity-time curves during the concentric phase of an unloaded jump squat is hypothesized to be higher in comparison with loaded jump squats as a result of increased acceleration throughout the movement. It is evident that acceleration of the system mass during a jump squat decreases as the external load is increased (McBride et al., 2002). Consequently, the shape of the power-time, force-time, and velocity-time curves may be “flattened out” (i.e., marked decreases in the gradient of the curves) causing a decrease in the peak power,
force, and velocity of the jump. Thus, the stimulus to the neuromuscular system when training with unloaded jump squats may result in selective motor unit recruitment, increased firing frequency, and synchronization of active motor units to a greater degree in comparison with loaded jump squats (Fitts et al., 1991; Kyrolainen et al., 2005; Moritani, 1993; Van Cutsem et al., 1998). These hypotheses regarding the effect of load on power-time, force-time, and velocity-time curves during the jump squat have yet to be tested as no previous publications have conducted a comprehensive temporal phase analysis of any ballistic movement.

A temporal phase analysis of the jump squat across a variety of loading conditions may provide novel insights into the nature of adaptations to power training and the biomechanical mechanisms involved in improving power output. Thus, the purpose of this investigation was to examine the impact of load on the power-time, force-time, and velocity-time curves of the jump squat. The use of average power-time, force-time, and velocity-time data at a sampling frequency of 200–500 Hz from 18 subjects highlights the uniqueness of this examination.

Methods

Subjects

Eighteen male subjects not currently involved in any formal sports or resistance training participated in this investigation (age: 21.4 ± 2.6 years; height: 175.9 ± 8.3 cm; weight: 80.8 ± 16.9 kg; percentage body fat: 16.0 ± 6.3%; squat one repetition maximum (1RM): 112.8 ± 23.3 kg; squat 1RM to body weight ratio: 1.4 ± 0.3). The participants were notified about the potential risks involved and gave their written informed consent, approved by the Institutional Review Board at Appalachian State University.

Experimental Design

This investigation used an acute, randomized design to examine the impact of load on the power-, force-, velocity-, and displacement-time curves of the jump squat. Subjects completed a single testing session involving assessment of maximal dynamic strength of the lower body through a squat 1RM test. Following adequate recovery (20 min), performance in the jump squat was examined across five different intensities in a randomized order: 0 kg (i.e., body mass only), 20 kg, 40 kg, 60 kg, and 80 kg. These absolute external loads were equivalent to 0 ± 0, 18 ± 4, 37 ± 8, 55 ± 12, and 74 ± 15% of 1RM, respectively.

Testing Procedures

Maximal dynamic strength of the lower body was assessed through a squat 1RM test. A 1RM was estimated for each subject based on body weight and training experience, with the subject then performing a series of warm-up sets and several maximal lift attempts until a 1RM was obtained (Winchester et al., 2005). During a 20 min recovery period, anthropometric measures (height, weight, and body composition—three-site skin fold: chest, abdomen, thigh) were assessed. Following the recovery period, subjects completed jump squats (i.e., countermovement jumps performed with a barbell placed across the shoulders) with external loads of 0, 20, 40, 60, and 80 kg in a randomized order. Participants set up for the jump squat in a standing position while holding a plastic barbell (0 kg) or a standard barbell with the appropriate load (20, 40, 60, or 80 kg) across their shoulders. Subjects initiated the jump squat via a downward countermovement to a visually monitored knee angle of approximately 90° and then immediately propelled the system (i.e., their body and the bar) explosively off the ground. Participants were instructed to keep constant downward pressure on the barbell throughout the jump and encouraged to reach a maximum jump height with every trial in an attempt to maximize power output (Behm & Sale, 1993). The subjects were instructed to keep the bar on their shoulders. If these requirements were not met the trial was repeated. Subjects completed a minimum of two trials, with subsequent trials required if performance was not consistent (peak power within 5% of a previous trial qualified as consistent). Adequate rest was given between all trials (3 min).

Data Collection Procedures

All testing was performed with the subjects standing on a force plate (AMTI, BP6001200, Watertown, Massachusetts, USA) while holding a standard barbell or an unweighted (plastic) barbell across their shoulders. The right side of the barbell was attached to two linear position transducers (LPTs; Celesco Transducer Products, PT5A-150, Chatsworth, California, USA). The LPTs, located above-anterior and above-posterior to the subject, when attached to the bar resulted in the formation of a triangle, which allowed for the calculation of vertical and horizontal displacements (through trigonometry involving the measurement of displacement and known constants). The combined retraction tension of the LPTs was 16.4 N; this was accounted for in all calculations. Analog signals from the force plate and LPTs were collected for every trial at 1,000 Hz using a BNC-2010 interface box with an analog-to-digital card (National Instruments, NI PCI-6014, Texas, Austin, USA). LabVIEW (National Instruments, Version 7.1, Austin, Texas, USA) was used for recording and analyzing the data. This data collection methodology has been validated previously (Cormie et al., 2007a) and test–retest reliability for maximal peak power output in the jump squat was consistently $r \geq 0.95$ in our laboratory.

Data Analysis Procedures

Signals from the two LPTs and the force plate underwent rectangular smoothing with a moving average half-width
of 12. From laboratory calibrations, the LPTs and force plate voltage outputs were converted into displacement and vertical ground reaction force, respectively. Vertical velocity was derived from the displacement and time data, and vertical ground reaction force was measured directly by the force plate. Power was calculated as the product of the velocity and force data. Variables were assessed in both the eccentric and concentric phases, which were defined as a) eccentric phase—the portion of the jump squat preceding takeoff in which the change in displacement is negative and b) concentric phase—the portion of the jump squat prior to takeoff in which the change in displacement is positive. Peak power (PP), peak force (PF), peak velocity (PV), and peak displacement (PD) were determined as the maximal value achieved during the concentric phase of the jump. Peak force during the eccentric phase was also assessed. Rate of force development (RFD) was assessed in both the eccentric and concentric phases as follows: Eccentric RFD—from the first point in which the change in displacement is negative to the last point where the change in displacement is negative (i.e., initiation of the countermovement to the end of the downward phase); concentric RFD—from the point at which the change in displacement becomes positive (i.e., end of the countermovement) to the point at which peak concentric force occurred before takeoff. The rate of power development was also assessed from the initiation of the concentric phase to peak concentric power. Acceleration of the system during the concentric phase of the movement was calculated using a second-order derivative of the displacement data. A series of coupling variables were assessed by overlaying the power-, force-, velocity-, and displacement-time curves and examining the time between peaks (Figure 1). Additionally, the force and velocity output at the time in which peak power occurred was also examined (i.e., force at PP, velocity at PP). Total work was calculated through integrating the power-time curve from the beginning of the countermovement, through the concentric phase until the power output reached zero. Similarly, the area under the force-velocity curve was determined by integrating the area under the curve from the beginning of the countermovement, through the concentric phase until the force output reached zero.

Temporal phase analyses of the jumps were conducted through the following process. The power-, force-, and velocity-time curves from all subjects were selected from the beginning of the eccentric phase, through the concentric phase, to the point at which each variable reached zero. The displacement-time curve was selected from the beginning of the eccentric phase through to peak displacement. Using a specialized LabVIEW program, the number of samples in each individual curve was then modified to equal 500 samples by changing the time delta ($dt$) between samples and resampling the signal ($dt =$ number of samples in the original signal/500). Consequentially, the sampling frequency of the modified signals was then equivalent to $502 \pm 99$, $502 \pm 99$, $388 \pm 61$, and $394 \pm 64$ Hz at 0 kg and $318 \pm 73$, $318 \pm 73$, $209 \pm 61$, and $293 \pm 62$ at 80 kg for the power-, force-

![Figure 1](image_url) — The force-, velocity-, power-, and displacement-time curves during a representative trial of a jump squat with no external load (i.e., 0 kg). Coupling variables indicated by the numbered arrows; 1—time between peak power and peak velocity; 2—time between peak power and peak force; 3—time between peak power and peak displacement; 4—time between peak force and peak velocity; and 5—time from beginning of movement to takeoff.
velocity-, and displacement-time curves, respectively. This resampling allowed for all power, force, velocity, or displacement curves to be expressed over equal periods of time (i.e., the 300 samples represented relative time from 0 to 100%). In other words, the various data sets are normalized to time so that data could be pooled. Each sample of the normalized power-, force-, velocity-, and displacement-time curves was then averaged across all subjects, resulting in averaged curves with very high resolution (sampling frequency ranged from 200 to 500 Hz across the curves).

**Statistical Analyses**

The Shapiro–Wilks test was used to test for normality, and all variables of importance were found to be normally distributed. General linear model with repeated measures and Bonferroni post hoc tests were used to determine the impact of load on a variety of performance variables during the jump squat (SPSS, Version 13.0). Statistical significance for all analyses was defined by \( p \leq .05 \).

**Results**

Changes occurred throughout the power-, force-, velocity-, and displacement-time curves as the external load was increased (Figure 2–4, Table 1). Whereas increases in the force output throughout the jump squat mirrored the external load applied to the movement, the shape of the power-, velocity-, and displacement-time curves was altered as the load increased (i.e., the gradient of the curves underwent various changes; Figure 2). The following comparisons refer to differences in variables at specific relative time points during the movement (i.e., from 0 to 100% of normalized time). Significant differences (\( F = 2.96; p \leq .05 \)) in power existed between (1) 0 and 20 kg at 16.8–29.4%, 54.8–68.6%, and 81.2–88.4% of normalized time (Figure 3); (2) 0 and 40 kg at 4.0–33.0%, 47.8–69.8%, and 79.8–98.4% of normalized time; (3) 0 and 60 kg at 2.2–33.0%, 46.0–69.6%, and 78.0–98.6% of normalized time; and (4) 0 and 80 kg at 3.0–33.0%, 43.6–69.0%, and 77.0–99.6% of normalized time. Significant differences (\( F = 3.01; p \leq .05 \)) in force existed between (1) 0 and 20 kg at 0.0–5.2%, 9.4–67.2%, and 87.2–95.0% of normalized time; (2) 0 and 40 kg at 0.0–73.2% and 78.2–96.8% of normalized time; (3) 0 and 60 kg at 0.0–97.8% of normalized time; and (4) 0 and 80 kg at 0.0–97.0% of normalized time. Significant differences (\( F = 3.25; p \leq .05 \)) in velocity existed between (1) 0 and 20 kg at 26.0–43.8%, 55.4–77.4%, 84.0–88.4%, and 94.4–100% of normalized time; (2) 0 and 40 kg at 6.2–9.2%, 23.0–47.4%, 56.2–81.0%, 86.0–91.3%, and 95.4–99.8% of normalized time; (3) 0 and 60 kg at 20.8–48.2%, 55.2–83.2%, 87.0–93.8%, and 98.2–99.6% of normalized time; and (4) 0 and 80 kg at 20.2–49.0%, 55.6–84.8%, and 88.4–94.4% of normalized time. Significant differences (\( F = 5.14; p \leq .05 \)) in displacement existed between (1) 0 and 20 kg at 60.2–100% of normalized time; (2) 0 and 40 kg at 6.2–25.6% and 63.4–100% of normalized time; (3) 0 and 60 kg at 4.8–24.4%, 48.6–55.2%, and 64.4–100% of normalized time; and (4) 0 and 80 kg at 7.6–23.0% and 68.2–100% of normalized time (Figure 2).

Examination of the performance and coupling variables revealed concentric peak power output was maximized under the 0 kg loading condition, which elicited significantly (\( F = 7.21; p \leq .01 \)) greater peak power than the 40, 60, and 80 kg loads. Similarly, concentric peak velocity, peak displacement, velocity at peak power, as well as time between peak power and peak displacement at 0 kg, were significantly greater (\( F \geq 4.43; p = .00 \)) than all other loads examined (Table 1). Changes in the shape of the power-time and velocity-time curve were reflected by significant (\( F \geq 29.31; p \leq .05 \)) differences between 0 kg and all other loads in both the rate of power development and acceleration during the concentric phase of the jump squat (Table 1). The area under the power-time curve was maximized at 0 kg, which was significantly (\( F \geq 4.43; p \leq .03 \)) greater than the 60 and 80 kg curves (Table 1). Furthermore, a similar relationship was observed in the force-velocity curve with the area under the 0 kg force-velocity curve significantly (\( F = 8.63; p = .00 \)) greater than the 40, 60, and 80 kg curves (Figure 4, Table 1).

**Discussion**

The most significant findings of the current investigation were that the 0 kg loading (i.e., body mass only) resulted in the greatest concentric peak power output, significantly greater rate of power development (watts per second), area under the force-velocity curve (watts), and work (i.e., area under the power-time curve [joules]). It should be noted that even though concentric peak power output was not significantly higher at 0 kg in comparison with 20 kg, power was higher under the 0 kg load during many portions of the movement. Specifically, power output was significantly higher in 0 kg compared with 20 kg throughout the following phases of the jump: 16.8–29.4%, 54.8–68.6%, and 81.2–88.4% (Figure 3). Therefore, the 0 kg jump squat elicited higher power output than the 20 kg jump squat during 33.6% of the movement. These variables indicate that there are significant differences in the kinetics and kinematics of jump squatting with a 0 kg load beyond simply peak power. No previous investigation has quantified these characteristics of the power-, force-, and velocity-time curves associated with jump squats using various loads.

Rate of power development (watts per second) has not been previously analyzed as a function of load in the jump squat. The rate of power development, which is independent of peak force, was significantly higher during the 0 kg load jump squat compared with all other loads examined. Therefore, the stimulus of 0 kg load jump squat is unique and thus may coincide with specific patterns of motor unit recruitment (Van Cutsem et al., 1998). It
Table 1  The Impact of Load on Jump Squat Performance and Coupling Variables. The asterisk indicates significantly \((F \geq 4.43; p \leq 0.05)\) different from 0 kg.

<table>
<thead>
<tr>
<th>Performance and Coupling Variables</th>
<th>External Load</th>
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<tbody>
<tr>
<td></td>
<td>0kg</td>
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<tr>
<td>Peak Power (W)</td>
<td>4616.44 ± 1040.80</td>
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<tr>
<td>Peak Concentric Force (N)</td>
<td>1688.45 ± 286.35</td>
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<tr>
<td>Peak Eccentric Force (N)</td>
<td>1525.58 ± 304.13</td>
</tr>
<tr>
<td>Peak Velocity (m/s)</td>
<td>3.09 ± 0.31</td>
</tr>
<tr>
<td>Peak Displacement (m)</td>
<td>0.45 ± 0.06</td>
</tr>
<tr>
<td>Concentric Rate of Force Development (N/s)</td>
<td>2012.70 ± 880.50</td>
</tr>
<tr>
<td>Eccentric Rate of Force Development (N/s)</td>
<td>2519.52 ± 111.11</td>
</tr>
<tr>
<td>Concentric Rate of Power Development (W/s)</td>
<td>21446.47 ± 6750.26</td>
</tr>
<tr>
<td>Acceleration (m/s²)</td>
<td>11.02 ± 2.17</td>
</tr>
<tr>
<td>Force at Peak Power (N)</td>
<td>1807.92 ± 296.45</td>
</tr>
<tr>
<td>Velocity at Peak Power (m/s)</td>
<td>2.86 ± 0.31</td>
</tr>
<tr>
<td>Work (J)</td>
<td>383.07 ± 97.80</td>
</tr>
<tr>
<td>Area under the Force-Velocity Curve (W)</td>
<td>5774.56 ± 1344.01</td>
</tr>
<tr>
<td>Time from Beginning of Movement to Takeoff (s)</td>
<td>1.04 ± 0.28</td>
</tr>
<tr>
<td>Time between Peak Power &amp; Peak Velocity (s)</td>
<td>0.05 ± 0.02</td>
</tr>
<tr>
<td>Time between Peak Power &amp; Peak Force (s)</td>
<td>-0.10 ± 0.13</td>
</tr>
<tr>
<td>Time between Peak Power &amp; Peak Displacement (s)</td>
<td>0.34 ± 0.02</td>
</tr>
<tr>
<td>Time between Peak Force &amp; Peak Velocity (s)</td>
<td>0.15 ± 0.13</td>
</tr>
</tbody>
</table>
Figure 2 — Comparison of the average (209–504 Hz; n = 18) power-time (A), force-time (B), velocity-time (C), and displacement-time (D) curves during jump squats with external loads of 0, 20, 40, 60, and 80 kg. The significant differences between loads are provided in Results section.
has been theorized that submaximal loading potentiates neuromuscular activity and thus velocity of movement (Duchateau & Hainaut, 1985). In addition to greater peak power output, work (i.e., the area under the power-time curve) was maximized during the 0 kg loading condition. This variable supplements the description of the unique characteristics of submaximal loading. Possibly more important is the observation of a significantly greater
value for area under the force-velocity curve during the 0 kg loading condition. This variable represents the total amount of power (force × velocity) achieved during the entire concentric phase and again highlights the unique characteristics of 0 kg loading.

As mentioned previously, several investigations have examined the effect of loading on peak power output during the jump squat (Baker et al., 2001; Cormie et al., 2007b; Driss et al., 2001; Dugan et al., 2004; Fitts et al., 1991; Siegel et al., 2002; Stone et al., 2000; Toji & Kaneko, 2004). Loads ranging of 0–60% of 1RM have been identified as the load that maximizes peak power output (Baker et al., 2001; Cormie et al., 2007b; Stone et al., 2000). The current investigation has identified that peak power and area under the force-velocity curve (total power) is the largest during the 0 kg loading condition. This finding is supported by previous research involving well-trained athletes (Bourque, 2003; Cormie et al., 2007b; McBride et al., 1999; Stone et al. 2000). This load can also be expressed in combination with body mass and is referred to as maximal dynamic strength (MDS), which is calculated by adding an individual’s 1RM and body mass minus shank mass (12% of body mass). This method has been recommended by a previous investigation owing to the limited motion of shank mass during the force development phase of the jump squat (Dugan et al. 2004). The 0 kg loading condition expressed in terms of 1RM would be 0%. However, the 0 kg load expressed relative to MDS is equivalent to approximately 30% (specifically 32.12 ± 5.38% of MDS for the current data set). This value coincides with the load shown to result in maximal peak power output from single muscle fiber investigations and the bench press throw (McDonald et al., 1994; Newton et al., 1997). It should be noted that in the bench press throw the internal mass of the system is quite small (i.e., arms). Thus, expressing the load as a percentage of 1RM in the bench press throw is more appropriate in comparison with the jump squat in which an individual must move both the external load and their body mass minus shank mass. However, the substantial amount of internal mass (body mass − shank mass) must be considered and added to 1RM (external mass) when analyzing the jump squat. Therefore, the load that maximizes peak power output in a jump squat is approximately 0% of 1RM and 30% of MDS for untrained individuals. This coincides exactly with the bench press throw in which peak power output is maximized with 30% of 1RM as a result of the insignificant impact of arm mass on the total system mass (Newton et al., 1997).

In conclusion, this investigation has demonstrated that variables relating to power output other than just peak power during a 0 kg load jump squat are significantly different from higher loading conditions (20 kg, 40 kg, 60 kg, and 80 kg) in untrained individuals. This data highlights the significance of 0 kg loading in maximizing power output and identifies this load as being unique in terms of its stimulus to the neuromuscular system. Future research should move beyond simply examining peak power to investigating variables related to the whole power-, force-, and velocity-time curves during ballistic movements. Longitudinal examinations involving these variables may help elucidate the precise nature of adaptations to power training (i.e., physiological verses biomechanical).

References


