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Brief Review

Determining the Optimal Load for Jump Squats: A Review of Methods and Calculations

Eric L. Dugan,[1] Tim L.A. Doyle,[2] Brendan Humphries,[1] Christopher J. Hasson,[1] and Robert U. Newton[2]

[1]Biomechanics Department, Ball State University, Muncie, Indiana 47306; [2]School of Biomedical and Sports Sciences, Edith Cowan University, Perth, Australia.

Abstract. Dugan, E.L., T.L.A. Doyle, B. Humphries, C.J. Hasson, and R.U. Newton. Determining the optimal load for jump squats: A review of methods and calculations. *J. Strength Cond. Res. 18(3):668–674. 2004.*—There has been an increasing volume of research focused on the load that elicits maximum power output during jump squats. Because of a lack of standardization for data collection and analysis protocols, results of much of this research are contradictory. The purpose of this paper is to examine why differing methods of data collection and analysis can lead to conflicting results for maximum power and associated optimal load. Six topics relevant to measurement and reporting of maximum power and optimal load are addressed: (a) data collection equipment, (b) inclusion or exclusion of body weight force in calculations of power, (c) free weight versus Smith machine jump squats, (d) reporting of average versus peak power, (e) reporting of load intensity, and (f) instructions given to athletes/participants. Based on this information, a standardized protocol for data collection and reporting of jump squat power and optimal load is presented.

Key Words. validity, strength, performance, intensity, instruction, measurement

Introduction

In an effort to maximize training efficiency for athletes in sports that require high levels of lower-body power, there has been increasing research activity concerning optimal loads for maximal power output during the jump squat. As early as Hill's work (8), it has been known that when muscle is maximally activated against a given load, there is an "optimum" that elicits the highest mechanical power output, which is a direct result of the force-velocity relationship of muscle contractile mechanics (6). While this research has shown promise for training applications, the various methods used for measurement and calculation of power and the resulting optimal load have been under scrutiny of late because of various methodological differences. At present, a wide range of values, based on 1 repetition maximum (1RM) squat strength, are cited in the literature for optimal load during the jump squat. Research by Wilson et al. (15) suggested that optimal load for maximal power during jump squats is approximately 30% of 1RM squat. This differs greatly from the optimal load reported by Baker et al. (3) of 48–63% of squat 1RM. Sleivert et al. (13) reported an even higher range, 50–80% 1RM for maximal power. More recently, Stone et al. (14) reported the load that elicited the highest power during squat jumps was 10% of 1RM squat. However, differences in optimal load were found when the 5 strongest and 5 weakest lifters of their participant group were compared. The optimal load for the 5 strongest lifters was 40% of 1RM squat, while the optimal load for the weakest 5 lifters was 10% of their 1RM squat. The discrepancies reported in the literature for optimal loads and peak power outputs can, in part, be attributed to the methods of power calculation, experimental protocol, and equipment used for data collection. Because of this large range in values reported in the literature, it has become difficult to implement specific training recommendations based on the current research.

The purpose of this paper is to examine how differing methods of data collection and analysis can lead to very different results for maximum power measurement and the associated optimal load for jump squats. This discussion will be divided into 6 sections: (a) data collection equipment, (b) inclusion or exclusion of body weight force in the calculation of power, (c) free weight versus Smith machine jump squats, (d) reporting of average versus peak power, (e) reporting of load intensity, and (f) instructions given to athletes/participants. As an aid to this discussion, data collected over a wide range of conditions will be used to illustrate the affects of differing assumptions and methods. Finally, based on this analysis, a standardized method for calculation and reporting of optimal load will be presented.

Methods

Data Collection Equipment

There are 4 commonly used experimental setups for the collection of data during the jump squat and the calculations of power and optimal load; each of these will be discussed. The first method of calculating power utilizes only displacement data. The second method involves using only vertical ground reaction force (VGRF) data obtained from a force platform. The third method involves using a combination of VGRF and displacement data. Finally, the fourth method involves using an accelerometer system. For the purposes of this review, it will be assumed that the equipment necessary for each type measurement is properly calibrated. As with any type of measurement, the proper calibration of the measurement devices is necessary for the accurate collection and reporting of data. In most instances, for these types of data collection procedures, calibration of equipment prior to each testing session is standard practice.

Displacement Only. In the case where only position data are available, the force must be derived from knowledge of bar kinematics and the mass of the system in question. Bar displacement can be accurately measured using a variety of technologies, such as linear position transducer, rotary encoder, or V-scope (Lipman Electronic Engineering Ltd, Ramat Hahayal, Israel). The linear position transducer involves a high-precision potentiometer that produces a voltage signal that varies in proportion to the displacement. This must then be collected using some form of analog-to-digital conversion to derive displacement-time data (10). The rotary encoder generates pulses in proportion to displacement, and a computer card called a quadrature decoder combined with software can be used to collect displacement-time data with high resolution (3). The V-scope uses infrared and ultrasound technology to track bar displacement. An ultrasound-emitting transponder is attached to the end of a barbell and is triggered by infrared signals regularly emitted from 3 devices or towers. The barbell is tracked by measuring the time taken for each ultrasound signal to travel from the transponder to the towers. The transponder-to-tower distance is calculated by multiplying the elapsed time by the known velocity of the ultrasound signal. The use of 3 towers enables spatial positions of the transponder to be determined by triangulation, generating 3-dimensional Cartesian coordinates (14).

Regardless of the technology used, with knowledge of displacement and time between samples, the instantaneous velocities of the bar can be calculated for its entire path by differentiating the displacement data. A second-order derivative of displacement data provides instantaneous accelerations of the system. At this point, the total force acting on the system can be calculated by adding acceleration due to gravity to the calculated instantaneous acceleration of the bar/body system, then multiplying by the mass of the system. Instantaneous power is calculated by multiplying the force and velocity obtained from the previous calculations. The peak instantaneous power produced during the propulsive phase of the jump squat can be determined as the highest power output or averaged over the concentric phase to derive average power output.

For each i, or time point based on sampling (equation set for position data only),

$$v_{(i)} = dx/dt$$

$$a_{(i)} = d^2x/dt^2$$

$$F_{(i)} = (m_{body} + m_{load})(a_{(i)} + a_g)$$

$$P_{(i)} = F_{(i)} * v_{(i)}$$

where v = velocity, x = displacement, t = 1/sampling frequency, a = acceleration, F = force, m_{body} = mass of body, m_{load} = mass of loaded barbell, a_g = acceleration due to gravity, and P = power. Only the vertical displacement and vertical forces are considered in these equations; therefore, the power calculated is along the vertical axis only.

VGRF Only. When only a force platform is available, the impulse-momentum approach can be utilized to calculate power and the resulting optimal load. To implement this calculation method, knowledge of the sampling rate and VGRF is needed as well as an initial velocity of zero for the system. Impulse is equal to a change in momentum, or force multiplied by time. Since the force, mass, and initial velocity conditions are known, the instantaneous velocity can be calculated using this approach. As before, instantaneous power can then be calculated as force multiplied by velocity, and the peak of these values can be determined for the propulsive phase of the jump squat.

For each i, or time point based on sampling frequency (equation set for the force data only),

$$v_{(0)} = 0$$

$$F_{(i)}t = m(v_{(i+1)} - v_{(i)})$$

$$\Delta v = (F_{(i)}t)/m$$

$$P_{(i)} = F_{(i)} * v_{(i)}$$

where F = force, t = 1/sampling frequency, m = mass of body + load, v = velocity, and P = power. This approach is valid only if data are collected with the subject's initial velocity being zero. Again, power is calculated along the vertical axis only.

VGRF and Displacement. McBride et al. (10) and Newton et al. (12) recorded both VGRF and bar displacement; typically, these data are recorded at the same sampling rate by means of a computer and customized software. Once data are collected, the next step is to determine the first-order derivative of the displacement data with respect to time to obtain the instantaneous velocities throughout the jump squat. It is assumed that the bar and the subject move as 1 and therefore the velocity of the bar is assumed to be equal to that of the entire system. The instantaneous power is calculated as the product of VGRF and the instantaneous velocity throughout the jump. The last step is to determine peak instantaneous power during the propulsive phase of the jump squat.

For each i, or time point based on sampling frequency (equation set for calculation of power using VGRF and displacement data),

$$v_{(i)} = dx/dt$$

$$P_{(i)} = F_{(i)} * v_{(i)}$$

where v = velocity, x = displacement, t = 1/sampling frequency, F = force, and P = power. Only vertical displacement and vertical forces are considered in these equations; therefore, the power calculated is along the vertical axis only.

Accelerometer System. This method involves measuring the acceleration of the load (e.g., barbell) using a transducer that outputs a voltage proportional to the gravitational acceleration (a_g) plus any linear acceleration the body is experiencing. This signal is recorded by an analog-to-digital system and computer software. Force can be calculated simply by multiplying the acceleration at any given time point by the mass of the body. Velocity data are derived by single integration of the acceleration data with respect to time.

For each i, or time point based on sampling frequency (Equation set for calculation of power using accelerometer data),

$$F_{(i)} = ma_{(i)} - ma_g$$

$$v_{(i)} = \int a(t)dt$$

$$P_{(i)} = F_{(t)} * v_{(i)}$$

where F = force, m = mass of system, a = acceleration, a_g = acceleration due to gravity, v = velocity, t = 1/sampling frequency, and P = power.

Comparison of Techniques. Each of these techniques is based on valid but different mathematical premises. However, the displacement-only, VGRF-only, and accelerometer techniques are at a disadvantage because of the limited amount of data collected in each, only displacement or VGRF data. In each case, the data are manipulated, differentiated, or integrated, and this process amplifies any noise in the raw signal (for detailed discussion, see Wood [17] and Winter [16]). The increased data manipulation leads to a greater risk of accumulating error in the results and reduces the validity and reliability of the calculated power output. In addition to the disadvantage of excessive data manipulation, the VGRF-only technique requires at least 1 point within the data where velocity is zero. This is necessary to use the impulse-momentum approach, which is very sensitive to this condition. The use of accelerometry also has the disadvantage that the signal must be integrated to derive velocity data, and this can be error prone, but the greatest problems relate to orientation of the transducer and their susceptibility to damage. First, the axis of the accelerometer must remain aligned with the plane of movement, or the acceleration will not be accurately measured. Second, because of their construction and the fact that in measuring accelerations during jump squat, the magnitudes are relatively low (i.e., <5 g), the appropriate accelerometers are rather delicate and easily damaged by any shock such as would occur if they were dropped or impacted in any way. In light of these facts, the most appropriate method of data collection is to utilize a force platform to collect VGRF and a linear transducer to accurately measure displacement (or other position-measuring device) when measuring power to determine the optimal load.

To illustrate the differences in power-load spectrum measured by the first 3 techniques, both force and displacement data were collected on subjects performing jump squats over a range of loads. At each load, peak power output was calculated by each of the 3 methods, and the results are displayed in Figure 1. Clearly, quite different results are produced depending on the data set used. Note that the optimal load ranges from 20 to 50% of squat 1RM.

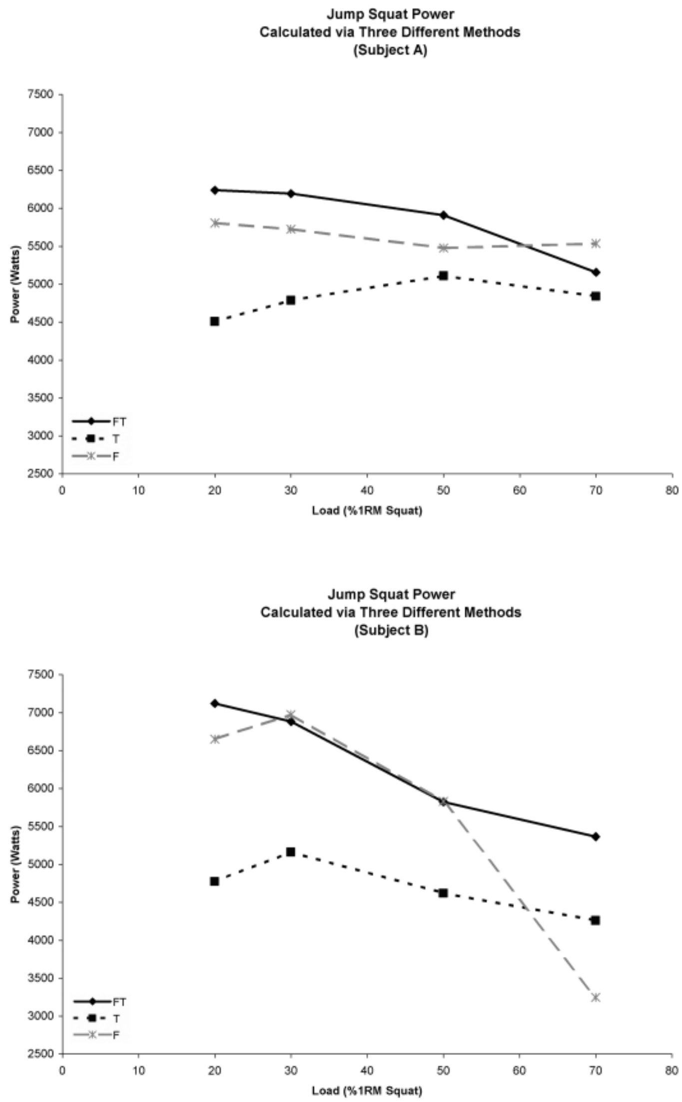

FIGURE 1. Power-load curves derived from different data collection equipment and the associated calculations for 2 representative subjects. All calculations include body weight. FT = force platform and linear position transducer; T = transducer only; F = force platform only.

Inclusion or Exclusion of Body Weight

The inclusion or exclusion of body weight from the power calculations is another important factor to consider when examining the various reported values for the optimal load of a jump squat. Throughout the literature, both the inclusion and the exclusion of body weight have been utilized when calculating power and the resulting optimal load. Figure 2 illustrates the problems of comparing results from each type of calculation.

These representative data illustrate how the optimal load may shift (from 20 to 70% of 1RM) based on whether body weight is included in the calculations. The slope of the resulting load-power curve will be heavily influenced by the inclusion or exclusion of body mass in the calculation of power. In Figure 2, the optimal load shifts from 20% of the subject A's 1RM to 50% of 1RM. Likewise, the optimal load shifts from 30 to 70% of 1RM for subject B. When recommending training protocols these differences are obviously important and will result in very different training loads.

Arguments about whether to include or exclude body weight still persist. It is the authors' opinion that body weight must be included in the calculation of power. This viewpoint is based on the fact that the inherent contraction properties of the leg extensors and the resulting force and velocity of the system are determined by the total load, body mass, and bar to be accelerated. As demonstrated previously, the exclusion of body weight from power calculations causes substantial shifts toward the higher 1RM percentage for the optimal load. By excluding body mass, a proportionately larger error is inherent at lighter loads (e.g., 20–40%) compared to heavier loads (e.g., 70–80%). This error reverses the load-power relationship. In other words, when the body mass is excluded from light loads, a greater proportion of the load is now neglected, and the decreased load will result in a lower power value. On the other hand, at relatively high loads, the exclusion of body mass is a smaller relative reduction in the load; therefore, power at the higher loads is less affected by the exclusion of body weight in the calculations.

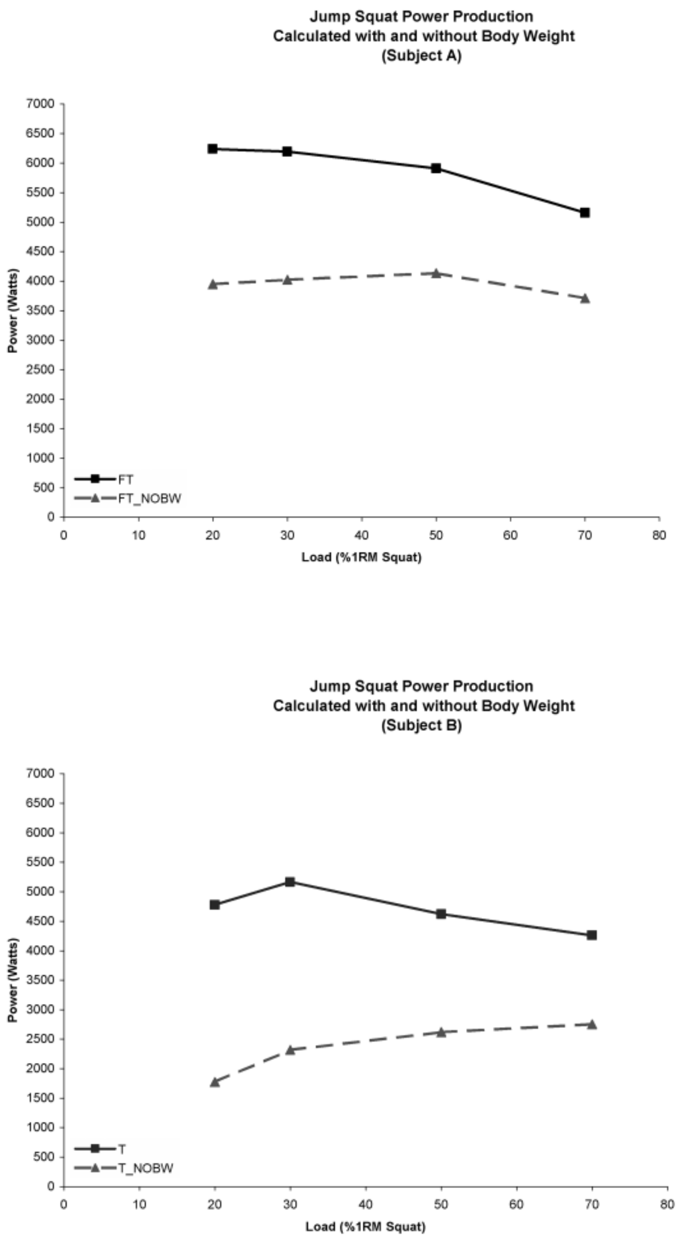

FIGURE 2. Representative power-load curves for jump squats when body weight of the subject is included or excluded for the same trials. FT = force platform and linear position transducer with body weight; FT_NOBW = force platform and linear position transducer without body weight; T = transducer only with body weight; T_NOBW = transducer only without body weight.

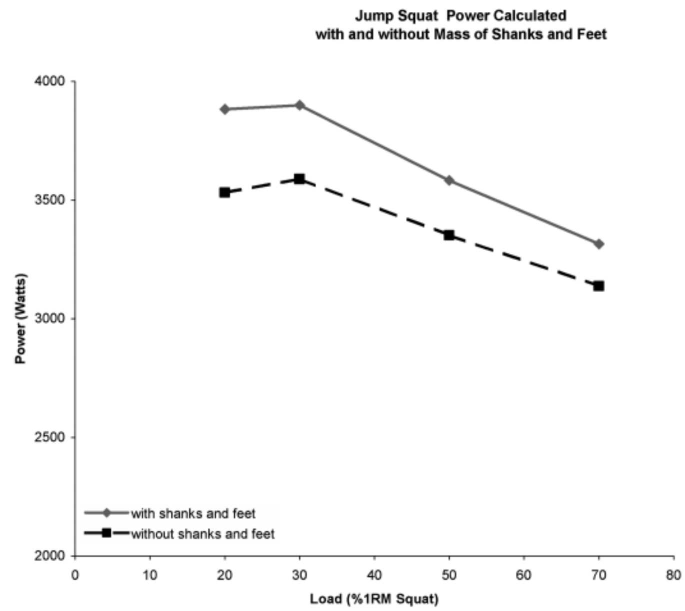

FIGURE 3. Power-load curve calculated with and without the mass of the shanks and feet for a representative subject.

Further justification for the inclusion of body weight is based on the incongruity between research reporting optimal load to be 50–80% of maximal strength (3, 13) and the considerable body of knowledge of the relationship between force, velocity, and power output in bundles of muscle fibers (6, 8) and single joint movements (9, 11). The majority of this research concurs that the force capability of muscle in concentric actions decreases with increasing velocity of shortening and that maximal power output is produced at approximately 30% of maximum isometric force and approximately 30% of maximum shortening velocity (5, 6, 8, 9, 11).

A further consideration is whether the whole body mass should be used in power calculations or body mass less mass of the shanks (lower leg) and feet. This will depend on the precision deemed necessary by the researcher. Technically, the shanks and feet should be excluded from the power calculations because of their relatively static positioning during the concentric phase of the jump squat prior to takeoff, during which peak power is produced. However, the inclusion or exclusion of the mass of the shanks and feet will not have a large impact on the shape of the load-power curve (Figure 3).

Free Weight Versus Smith Machine Jump Squats

Another difference in the determination of jump squat power and the resulting optimal load is whether the jump squats were performed with free weights or in a Smith machine. All 4 methods of measurement—displacement only, VGRF only, VGRF and displacement, and accelerometry—can be employed with free weights or the Smith machine. The question is whether it is reasonable to compare the 2 modes of jump squat to each other. To this end, representative data illustrating the differences in jump squat power production across these 2 modes of performance are presented in Figure 4.

The type of jump squat for these representative subjects did not affect the load at which maximum power was generated. One could speculate that skill level or training status may influence whether an athlete performs better with a free weight jump squat or the more constrained Smith machine jump squat, although further study would be required to substantiate this hypothesis. This point leads to the issue of specificity and how each type of jump squat training may or may not influence sport performance. It seems just as valid to use either type of jump squat, free weight or Smith machine, with the qualification of choosing the appropriate mode based on the population of interest and their proficiency with free weight and/or Smith machine squats along with their intended training goals.

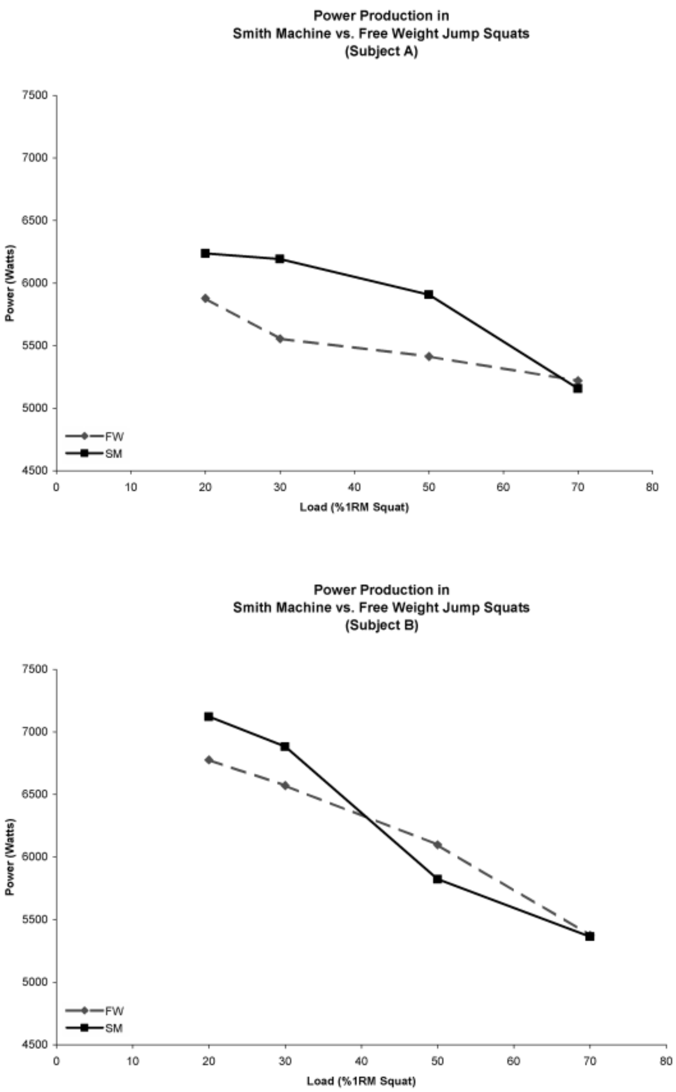

FIGURE 4. Representative power-load curves from 2 subjects performing jump squats with the same loads in a Smith machine apparatus and with a free weight barbell. FW = jump squats performed with free weight barbell; SM = jump squats performed in Smith machine apparatus.

Reporting Average Versus Peak Power

The use of average power or peak power, when reporting jump squat performance, is another contentious point in the literature. Wilson et al. (15) and McBride et al. (10) used peak power produced during the propulsive phase of the jump squat to determine the load-power relationship. Baker et al. (2) used average power during the propulsive phase when determining optimal loads of the jump squat. This makes it difficult to compare results obtained from these 2 different approaches to reporting data. It is technically correct to report either of these values, yet 1 may be more favorable than the other in terms of application. In a study by Aragon-Vargas and Gross (1), whole body peak power was found to be the single best predictor of vertical jump performance. Harman et al. (7) reported that peak power was very highly correlated with vertical jump performance, $r = 0.88$, while average power had a much lower correlation, $r = 0.54$, with vertical jump performance. In another study, Dowling

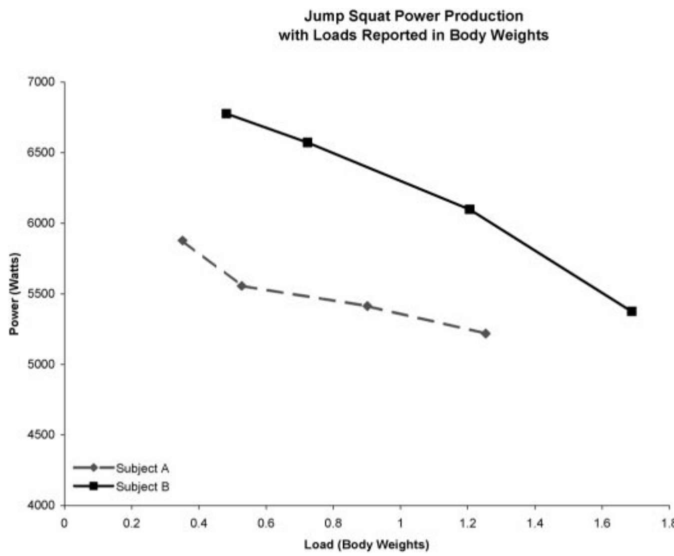

FIGURE 5. Power-load curves from free weight jump squats for 2 representative subjects with loads reported in terms of body weight.

and Vamos (4) report similar findings and further report that the next 3 best predictors combined could not explain more of the variance than that accounted for by peak power. If the ultimate goal of jump squat research/training is to maximize vertical jump performance, it is logical to measure and report the parameter most associated with vertical jump performance (i.e., peak power).

Reporting of Load Intensity

It is common to see the optimal load for jump squats represented as a percentage of a squat 1RM. This leads to large ambiguities in reporting results because it is difficult to standardize how 1RM squat values are obtained. The first problem is that reported 1RMs could be for full squats, half squats, quarter squats, or any other variation of the squat. There is also the question of whether the 1RM squat was performed in a Smith machine or with a standard free weight barbell. The constrained movement of the bar during the Smith machine squat will result in different squat kinematics when compared to that of the free weight squat. Differing kinematics along with the familiarization of the athletes/participants with the 2 types of squat may greatly affect their performance during the determination of their 1RM. These complications are further exacerbated by factors such as the use of lifting belts, knee wraps, and other assistive devices. Therefore, it is suggested that reporting optimal loads in terms of 1RM squat strength is problematic. An alternative is to report optimal load values in terms of body weights (Figure 5).

Reporting load intensities in terms of body weights eliminates the ambiguities associated with using squat 1RM and allows for a simple prescription of loads for power training without the need for maximal strength testing.

Instructions Given to Athletes/Participants

Because of the somewhat ambiguous terminology "jump squat," it is possible that researchers, coaches, and athletes have different actions, movements, and motivations in mind when referring to a jump squat. For this reason it is important to address the affect of instructions on the jump squat technique, performance, power, and resulting optimal load. For some individuals, the term "jump squat" refers to the motion of jumping preceded by a squat, parallel or otherwise. For others, it simply refers to a loaded countermovement jump, where the load is applied via a barbell, either free weight or in a Smith machine. For example, Stone et al. (14) reported peak powers and optimal loads based on dynamic and static squat jumps from a parallel squat position. However, McBride et al. (10) reported peak power and the resulting optimal load based on jump squats performed with a self-selected depth. While the effect of instructions on jump squat performance has not been researched, a similar study by Young et al. (18) reported changes in drop jump performance based on instructions given. Considering this information, the instructions given to the athlete or participant may have a tremendous effect on the resulting optimal load and the resulting training recommendations. Therefore, it is imperative that researchers report the instructions given to the participants performing jump squats so that future researchers can replicate and compare the results obtained.

DISCUSSION

Future Research

There is much still to learn from the study of power production and optimal loading conditions of the jump squat. This area of research has the potential to provide valuable information to coaches and athletes, enabling them to develop more efficient and productive training programs. For this line of research to continue effectively, an understanding of the advantages and disadvantages of differing data collection and reporting protocols is necessary. Standardization of jump squat research is critical in order for the replication of experiments, which will lead to a greater understanding of load-power relationship for jump squats. As it stands now, it is difficult to make any broad assumptions as to the nature of the load-power relationship for jump squats because of the lack of standardization of research protocols. Once these issues of data collection and reporting are put to rest, important questions can be answered; What is the optimal load for a given athlete or type of athlete? Is there a better carryover from free weight jump squat training than training with a Smith machine? Does it depend on the skill level or experience of the athlete? These questions and many others can and should be addressed in an effort to provide athletes with the most efficient and effective training programs.

Summary

This discussion is intended to illuminate some of the major issues that must be accounted for when performing research on optimal loads for the jump squat. However, there are still many intricacies that have not been discussed that warrant future research, such as the affects of familiarization protocols, nutritional status, and gender of subjects. This field of research does show promise in regard to understanding, designing, and implementing training protocols for power athletes. However, with the recent surge of interest and published literature on the topic, there has been a lack of standardization of collecting and reporting data. This has led to further confusion and ambiguity in terms of implementing training protocols and understanding the load-power relationship. In order for coaches and athletes to utilize this information effectively and for researchers to replicate these studies and verify the relationships, these issues must be addressed. Further, a standardized protocol for the data collection and the reporting of jump squat power and optimal load must be developed. Based on the current state of information and the discussion presented in this paper, the authors propose the following method for collecting, analyzing, and reporting such data.

PRACTICAL APPLICATIONS

Data collection should involve both a force platform and a linear transducer when possible. By using both measurement tools, fewer data manipulation is required, leading to more accurate results. It is also necessary to include body mass in the calculations of power output. The mass of the body must be moved during a jump squat; therefore, there is no logical reason to ignore it in the calculations of power. The very nature of this research is an attempt to determine how differing loads affect power production; by excluding body mass, a substantial portion of that load is ignored, and the resulting power is underestimated. In regard to reporting power-load relationships, the peak power should be reported rather than maximum average power. In addition, the load intensities, or the external load applied to the participant, should be reported in terms of body weights. This recommendation will allow loading conditions to be compared across all studies without concern of how 1RM is calculated. This basic set of protocols, while not exhaustive, is a step toward standardizing the collection, analysis, and reporting of data so that more scrutiny may be directed toward defining the optimal load for different populations instead of attempting to ascertain how data were collected.

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Address correspondence to Eric Dugan, eldugan@bsu.edu