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BRIEF RUNNING HEAD: Power, force & velocity during jump squats

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ABSTRACT

Training at the optimal load for peak power output (PPO) has been proposed as a method for enhancing power output, although others argue that the force, velocity and PPO are of interest across the full range of loads. The aim of the present study was to examine the influence of load on PPO, peak barbell velocity and peak vertical ground reaction force during the jump squat (JS) in a group of professional rugby players. Eleven male professional rugby players (age, 26 ± 3 years; height, 1.83 ± 6.12 m; mass, 97.3 ± 11.6 kg) performed loaded JS at loads from 20 – 100% of 1-RM JS. A force plate and linear position transducer, with a mechanical braking unit, were used to measure PPO, vertical ground reaction force (VGRF) and barbell velocity (BV). Load had very large significant effects on PPO ($P < 0.001$; partial $\eta^2 = 0.915$), peak VGRF ($P < 0.001$; partial $\eta^2 = 0.854$) and peak BV ($P < 0.001$ partial $\eta^2 = 0.973$). PPO and peak BV were highest at 20% 1-RM, though PPO was not significantly greater than at 30% 1-RM. Peak VGRF was significantly greater at 1-RM than all other loads, with no significant difference between 20 and 60% 1-RM. In resistance trained professional rugby players the optimal load for eliciting PPO during the loaded JS in the range measured occurs at 20% 1-RM JS, with decreases in PPO and BV, and increases in VGRF, as load is increased, although greater PPO likely occurs without any additional load.

Key Words: optimal load; ballistic exercise; assessment

INTRODUCTION

In many sports athletes are required to generate forces across a range of velocities, with a resulting power-load spectrum (26), similar to originally characterised by force-velocity characteristics of isolated muscle by AV Hill in the 1930's. It is a common view in the strength & conditioning literature that peak power output (PPO) is an important determinant of performance as this represents the balance between force and velocity above/below which power output declines. However, the evidence regarding the strength of the relationship between PPO and performance is equivocal (12,42) and furthermore, recommendations regarding how best to train PPO are far from conclusive (10,12,17,26,29). Most recommended interventions include explosive lower-body exercises involving the triple-extension of the knee, ankle and hip that avoid a deceleration phase as they are considered closest to the actions of sprinting and jumping seen in many sports (26). Consequently, there has emerged an interest in characterising the power-load relationship in athletes for a range of ballistic (1,2,3,4,9,11,25,30,31,35,37,39,40,43) or Olympic-style lifts (27,28,31) that elicit high PPO, either for the purposes of training prescription or monitoring responses to training. However, there is considerable disagreement in the literature regarding the relative loads that elicit PPO.

The inverted U-shape of the power-load relationship demonstrates that an optimal load exists for eliciting PPO and there is some argument for training at such a load to increase PPO (2,3,17,18,25,26,32,33,43), although others argue of the importance of specificity, i.e. training at a range of loads and velocities encountered during sports performance (9,41,42). For jump squats, an explosive triple-extension exercise that elicits high power outputs, loads ranging from body mass (BM) to as high as 80% of

1-RM (2,4,9,17,25,30,31,37,39,40,43) have been identified as optimal for PPO, with an even greater range when Olympic lifts (15,27,28,31) and upper-body ballistic exercises are included (3,4). Such discrepancies appear to exist primarily due to differences in methodology (6,13). Contributing factors include: the lift being tested (e.g. upper vs lower body, technique, inclusion of a countermovement, single- vs multi-joint exercises); individual differences; calculation of average vs. peak power; inclusion of BM in calculations; data collection methods (e.g. linear position transducer (LPT) vs. force plate); reporting of load intensity (e.g. relative to 1-RM of traditional compared to ballistic lifts). The resistance training history and strength level of participants has varied greatly in the existing research, and yet for the well-trained athlete for whom accuracy in training load is arguably most important, there is not agreement regarding the optimal load for PPO. Some authors have suggested that strength trained athletes require higher relative loads than less-trained individuals (32), yet other data suggests the opposite (22) or little difference (31,34).

Therefore, the aim of the present study was to examine the influence of load on PPO, peak barbell velocity (BV) and peak vertical ground reaction force (VGRF) during the JS in a group of professional rugby players completing a single maximal testing session. Given the available evidence it was hypothesised that there will be a significant effect of load on peak force, velocity and hence PPO. It was further hypothesised that the optimal load for PPO and BV will be the lowest load measured, and peak VGRF at the highest load.

METHODS

Experimental Approach to the Problem

To evaluate the impact of load on PPO during the JS in professional rugby players, a repeated measures design was used with multiple jumps performed at loads ranging from 20 kg – 100% 1-RM JS in a single session following familiarisation. The full-time professional rugby union players were mid-phase of the competitive season (multiple UK and European league and cup competitions), so it was imperative that the study design maximised efficiency of testing, such that training disruption was minimised, yet the protocols could be replicated easily in the gym for monitoring purposes, whilst ensuring accuracy and player safety. The coaches were interested in exploring the use of a range of loads for subsequent training, as well as the potential for using incremental JS for monitoring training in the future. Therefore, data collection was performed using a force plate with linear position transducer to measure vertical ground reaction force, barbell velocity and power output. Peak power output (PPO) was the key dependent variable, with VGRF and peak BV also investigated as the key parameters that underpin PPO. Load above BM was the independent variable, selected as % of an initially estimated 1-RM JS based on a previously determined 5-RM squat, although actual 1-RM JS was deliberately assessed as part of the protocol.

The incremental protocol used does mean that there is a potential for an order effect (either a positive potentiation and/or learning effect, or negative fatiguing effect) on the dependent variables, although this protocol was deliberately used in line with recommendations for 1-RM testing of traditional lifts (25). Sheppard et al. (35) have shown such an approach to be reliable, valid and sensitive to training improvements in athletes although they did not progress to as high relative loads.

Subjects

The study involved 11 professional male rugby players (BM 97.3 ± 11.6 kg; Height 1.83 ± 0.12 m; Age 25.6 ± 3.3 yrs; 1-RM jump squat 183.6 ± 19.6 kg) from the same club who played a range of positions (5 front-row; 1 back-row; 3 half-backs; 2 wingers) as reflected in the considerable variation in size and 1-RM values. Testing was integrated into their regular conditioning program and the testing session took place in the middle of the competitive season during a strength & power maintenance phase characterised by low volume and high intensity relative to pre-season. All subjects provided written informed consent and the study was approved by the ethics committee of the university. Inclusion criteria were that players demonstrated sound technique during the JS, as assessed by an accredited strength & conditioning coach, and were engaged full-time in a supervised strength & conditioning program for at least 2 years.

Experimental Procedures

Following familiarisation with full testing procedures on a different day, participants reported to testing hydrated and having refrained from strenuous exercise and alcohol consumption for at least 24h, as well as caffeine for at least 3h hours, before testing. Each participant completed a 10 minute standardised and supervised warm-up which included dynamic stretching as well as movements specific to the JS. The protocol required participants to perform maximum effort JS at 20 kg – 100% of their estimated 1-RM JS. For those participants that were still successfully completing a JS at 100% of the estimated 1-RM JS the load was further increased until the participant did not complete the JS, as detailed below. During all jumps athletes were instructed to jump as high as possible and verbal encouragement was given.

JS Testing. The JS testing protocol was adapted from the 1-RM testing method outlined by Stone and O'Bryant (38) and was modified to allow a complete load spectrum to be tested. The loading protocol used repetition values (3 reps ≤ 40% estimated 1-RM, 2 reps ≤ 80% estimated 1-RM, 1 rep > 80% estimated 1-RM) at given loads modified to strike a balance between ensuring the detection of PPO (2-5 reps (1)) and reducing the total volume to minimise fatigue. Each attempt was followed by a 3 minute rest period in order to allow adequate recovery. If a participant did not reach their 1-RM at the provided estimate, a load increase of 5-10 kg was added after each further attempt and 3 minutes rest. An individual was deemed to have reached their 1-RM when their feet did not leave the ground, which was monitored and judged using the real-time force plate data. Each participant was allowed one further attempt at improving their 1-RM following a 3 minute rest period.

When performing the jumps, participants were instructed to apply constant downward pressure on the barbell so it remained on their shoulders at all times (6). During pilot testing and familiarisation it was noted that when jumping with anything less than an Olympic barbell (20 kg), e.g. a wooden broom handle for an essentially unloaded JS, the tension from the linear position transducer (LPT) and magnetic braking unit (MBU) (both located above the bar) made it very difficult to maintain contact with the shoulders. Therefore, loads below 20 kg (including unloaded jumps) could not be explored accurately and so this was not included in the protocol. The depth of the initial eccentric portion of the JS was not regulated, as in other studies (9,21). This was based on evidence which suggests that trained humans automatically adjust their squat depth to allow for maximal performance in movements that involve jumping (5).

Power measurement. The FT 700 Power System (Fittech, Australia) was used as a performance platform and data collection tool. The system was connected to a laptop installed with the Ballistic Measurement System software (BMS, Innervations, Australia) and included a linear position transducer (LPT), a magnetic braking unit (MBU) and a force plate (400Series, Fittech, Australia). The combined use of a force plate and an LPT is considered a valid method to assess BV (using LPT), VGRF (using force plate) and power output (LPT + force plate) in human participants (6,8,20). Using the same equipment and analysis Sheppard et al. (35) previously demonstrated reliability of this approach in trained athletes (ICCs ranging 0.8-0.9 for peak power, 0.95-0.97 for peak force and 0.75-0.83 for peak velocity). The MBU was used as an injury-prevention mechanism (21) to unload the landing phase of each JS, adjusted for each load so that a participant never landed with more than 50 kg bar load.

Prior to testing, the force plate and LPT were calibrated using loads and displacements spanning the range of values experienced during the JS. The sampling frequency was set at 500 Hz with sample periods being 20 seconds in length. The total system mass (bodyweight + bar load) was used in all data collection (7,31).

Analysis. As participants were tested at different absolute and relative loads (based on initial estimates), the data were normalised so that all participants could be compared. The loads were expressed as % of the measured 1-RM and then the dependent variables (PPO, VGRF, and BV) were interpolated to 'standard' percentage intervals of each individual's 1-RM JS (20, 30, 40, 50, 60, 70, 80, 90, 100% JS 1-RM). Jump squats were not performed below 20 kg (see above) and as this load represented various percentages of 1-RM for each subject, the lowest percentage that all subjects lifted was 20% 1-RM.

Method of Interpolation. To interpolate the datasets, a cubic polynomial curve was fitted using Microsoft Excel to each of the three dependent variables plotted against the actual percentages of maximum load. This method was similar to that of Jandacka and Vaverka (23). These equations were then used to generate interpolated dependent variables corresponding to the 'standard' independent variables (20-100% 1-RM JS at 10% intervals).

The fit of the equations were assessed in two ways. Firstly the common variance of the equation (R^2) was calculated. Mean (± s) R^2 values for PPO, VGRF and BV were 0.956 (± 0.032), 0.927 (±0.092) and 0.990 (±0.012) respectively. Secondly, the Standard Error of the Estimate (SE_E) was calculated and the 95% Confidence Interval for the regression was then computed (14). The 95% Confidence Intervals were 313.5 (± 180.8) W, 144.6 (±85.1) N and 0.087 (±0.050) $m \cdot s^{-1}$ for PPO, VGRF and BV respectively. These values combined with the high R^2 coefficients indicated good curve fits.

Statistical Analysis

The standard level of significance was set at 0.05. The effects of load on PPO, VGRF and BV were analysed using One-Way Repeated Measures Analyses of Variance (ANOVA) after checking for normality using Shapiro-Wilk tests (14). The Greenhouse-Geisser adjustment of the degrees of freedom was applied if the Mauchly Test of Sphericity was compromised (14). Post-hoc pairwise Bonferroni tests were then performed on significant results (14). Effect sizes were assessed using partial eta squared (partial η^2) values which were square-rooted to give correlation coefficients (14) that were compared with the effect sizes given by Hopkins (19); 0.1-0.3 as small, 0.3-0.5 as moderate, 0.5-0.7 as large and 0.7-0.9 as very large.

Friedman's Non-Parametric test was run for the BV data, instead of the ANOVA, as the data at two loads (90 and 100%) were not normally distributed. Post-hoc Wilcoxon Matched Pair Signed Rank pairwise comparisons were made for each load against the subsequent load (e.g. 10% vs 20%, 20% vs 30% etc.), with the α-level adjusted by dividing by the total number of post-hoc tests (8).

Post-hoc statistical power was calculated using G-Power software (Universitåt Kiel, Germany). The statistical power was 100% at α-levels of 0.05, 0.01 and 0.001, computed with the effect sizes (partial-eta squared) achieved in the ANOVA tests and the inter-trial correlations. Finally a 'pseudo' a-priori 95% power calculation was calculated to show that sample sizes of 2, 3 and 2 for the ANOVAs would have been sufficient to be 95% certain of finding the effect sizes actually seen.

RESULTS

Peak Power Output

For PPO, the result from the ANOVA showed a significant Load effect on PPO (Greenhouse-Geisser Epsilon = 0.318; $F_{2.5, 25.5}$ = 107.1; P < 0.001; partial η^2 = 0.915; Very Large Effect), with PPO highest at 20% 1-RM JS (4509 ± 701 W; 46.9 ± 8.4 $W.kg^{-1}$ BM) and decreasing as the additional load was increased. Pairwise comparisons showed significant differences between power outputs at all percentages of maximum except between 20% and 30%. Figure 1 shows the interpolated PPO, peak VGRF and peak BV plotted against load.

Insert Figure 1 about here

Peak Force

For peak VGRF, the ANOVA showed a significant Load effect on peak force output (Greenhouse-Geisser Epsilon = 0.164; $F_{1.3, 13.1}$ = 58.5; P < 0.001; partial η^2 = 0.854; Very Large Effect), with VGRF increasing as the additional load was increased to a highest value at maximum load (2126 ± 285 N). The pairwise comparisons gave significant differences between forces at all percentages of maximum except 20% v 30%, 40%, 50% & 60%, and 30% v 40% & 50%.

Peak Velocity

Peak BV occurred at 20% 1-RM (2.1 ± 0.1 $m.s^{-1}$) and BV decreased as additional load was increased. The Friedman's Test resulted in a Chi-Square value of 87.8 and a significance of P < 0.001. Pairwise Wilcoxon tests gave significance values of P = 0.003 for all comparisons, except for 90% v 100%, which was P = 0.004, all below the Bonferroni adjusted α-level of 0.006.

DISCUSSION

The purpose of this study was to evaluate the influence of load on peak power ouput, peak vertical ground reaction force and peak barbell velocity during loaded jump squats in a group of professional rugby players. In support of our initial hypothesis, the incremental additional load had significant effects on all dependent variables. Peak power output was elicited at the lowest load tested (20% 1-RM JS), with lower values as load was increased although this was not significant between 20 and 30% 1-RM JS. Also in support of our hypotheses, the peak VGRF was elicited at the highest load (100% 1-RM JS), with lower values at each lower load, although these differences were not significant between 20 and 60% 1-RM JS. Additionally, in support of our hypotheses, the peak BV was elicited at the lightest load (20% 1-RM JS significantly greater than all other loads) with anticipated decreases in peak BV as load was increased. To our knowledge, these are the first force, velocity and power data in the maximum loaded JS across a range of loads up to 1-RM in resistance-trained professional rugby union players.

As well as identifying the optimal load for PPO, the current study measured PPO, BV and VGRF at incremental loads with good data resolution, in comparison to many existing protocols which use only a few arbitrary loads, and in a single in-season testing session without injury by using eccentric braking. Therefore, the data can be used to design training programmes for these athletes based on optimal load (2,3,17,18,25,26,32,33,43), as well as knowing how PPO, VGRF and BV will be affected when training across a range of loads, as has been recommended by others (9,41,42). The analysis also demonstrated the value in using data interpolation techniques across this range to complete the profiles (16,23). Such data enables the force and velocity at each load to be explored to explain the individual power relationship in greater detail. Many authors propose that the optimal load, for example, should be assessed on an individual basis rather than using average fixed relative loads (2,3,28). Such information could be used to inform training prescription based on the sporting demands specific to that individual (i.e. emphasis on forces and velocities encountered) as well as identify specific weaknesses in the force-velocity relationship that could be targeted to provide the most effective training stimulus for that athlete (35). Another rationale behind individually assessing the wider range of loads stems from research findings where large bandwidths of optimal loads (without significant effect on PPO) have been reported (e.g. 9,28), reflecting that the optimal load for PPO (even in relative terms) demonstrates considerable variability between individuals, with maximal strength possibly a key factor (39). For example, in the current investigation, individual power curves show a range of gradients at the lowest loads such that some athletes were beginning to plateau (reach the peak of the power load curve and hence their own optimal load) whereas others would clearly have had higher PPO at lower loads. This may explain the lack of a significant difference in PPO between 20 and 30% 1-RM in the current investigation, although this was close to significance. It is unlikely that this represents a Type II statistical error, given the very large effect sizes and reported statistical power.

This observation highlights the limitation of the current investigation in not assessing PPO in the JS with BM only. However, this was a factor of the study design due to technical factors discussed in the methods section. Interestingly, in some studies it is unclear if the lowest loads also included barbell mass and therefore are truly unloaded jumps. In any case, a very recent study (34) has further extended this range of loads in JS by using unloading apparatus, as well as loading, during the JS in resistance trained athletes. Nuzzo et al. (34) presented data in support of the Maximum Dynamic Output Hypothesis (24), which postulated that in untrained healthy individuals the optimal load for jumping should be BM as this is the load that the leg extensors are habitually contracting against. Nuzzo et al. (34) showed that JS with BM-only elicited significantly higher PPO than lower and greater loads, even in this resistance trained (RT) population. This finding is in contrast to the commonly cited paper of Stone et al. (39) which proposed that stronger athletes required higher relative loads to elicit PPO. A possible explanation for this finding, highlighted by Nuzzo et al. (34), was that the participants in their study were simply not as strong, with factors such as strength, BM and type of resistance training having been shown to have a significant effect on the power-load spectrum (2,7,39). In this regard, it is worth noting that the participants of the current study were heavier and able to JS with loads typically greater than the 1-RM squat in the study by Nuzzo et al. (mean JS 1-RM 184 kg or 1.89*BM vs mean squat 1-RM 168 ± 28 kg or 1.96*BM), but lower than the 1-RM squat in the strong group of Stone et al. (mean JS 1-RM 212 kg or 2.0*BM). Therefore, it remains to be confirmed if the optimal load for PPO is still BM-only in the strongest of athletes, e.g. power-lifters. Furthermore, this relationship importantly remains to be explored more accurately in other populations, e.g. female and older/younger participants. Further explanation may reside in the depth of squat used during the JS protocols, which has variably been controlled.

As mentioned above, the finding that PPO occurs at lower loads during the JS is in contrast to some existing studies (2,36,37), although most of the studies cannot be compared due to the many methodological differences (6,13). The current data do support the findings of some of the well controlled investigations using lower-body ballistic exercises in trained populations (31,39,40,43). For example, the findings and values are similar to Cormie et al. (9) and Sheppard et al. (35), who used similar technology and also used trained athletes. Both of these studies demonstrated that PPO was recorded at the lightest loads used (BM only). However, the power outputs recorded in the current investigation (4509 ± 701 W) are noticeably lower than recorded by Cormie et al. (6437 ± 1046 W (9)) and Sheppard et al. (7386 ± 324 W (35)), but similar to McBride et al. (3775 ± 951 W (31)). The main underpinning factor in these differences appears to be the peak velocities achieved at the lightest loads (2.11 ± 0.10 $m \cdot s^{-1}$ in the current study vs. 3.66 ± 0.26 (9) and 3.47 ± 0.23 $m \cdot s^{-1}$ (35)). Peak forces in the current study at the lowest load (2126 ± 285 N) were closer to Cormie et al. (1990.5 ± 339 N, (9)) and Sheppard et al. (2330 ± 196 N (35)). One possible explanation for these findings is that the values in those studies were recorded during the JS with BM only, compared to BM + 20% 1-RM in the current investigation. Based on the shape of the velocity-load relationship shown in Figure 1 and existing data (e.g. 34), it is highly likely that higher velocities and power outputs would be recorded in our athletes jumping against BM only. Indeed the values reported by McBride et al (31) support this, although their participants had lower 1-RM squat values than 1-RM JS values in the current investigation, illustrating differences in strength levels.

Interestingly, the other available data for professional rugby players (4) reported similar values for PPO in the JS (4256 ± 489 W) at a load similar to 20% 1-RM JS (20% 1-RM squat). However, the velocity data were not reported and VGRF was not recorded (LPT only) meaning that PPO was estimated. As mentioned previously, Duggan et al. (13) and Cormie et al. (6) have demonstrated that for accurate measurement of force, velocity and power output during the JS a combination of force plate and LPT is required. Although all of the data are not available for direct comparison, as the PPO values are so similar in the current study and Bevan et al. (4), this may imply that the LPT alone may be of some practical use for indirect estimation of PPO during the JS in professional rugby players. This would be considerably more feasible in many strength & conditioning settings where force plate equipment and analysis software may not be accessible, accepting the limitations regarding accuracy.

It is also worth noting that as the load was increased in the current investigation, peak velocity was the most sensitive variable measured, with significant differences between all loads. Peak VGRF changes were more variable, as shown by the error bars in Figure 1 and the lack of significant differences in peak VGRF between 20 and 60% 1-RM JS. Combined with the comparison with existing data (9,35) above, this information highlights the importance of peak velocity for PPO during the JS and other ballistic exercises (16). Consequently, the monitoring of BV during training is recommended to ensure that athletes are achieving PPO in sessions, perhaps using a minimum threshold % of peak BV at that load.

Conclusions

Peak power output, peak VGRF and BV are significantly affected by the amount of additional load during the loaded jump squat in professional rugby players. The PPO is elicited using the lightest load used (20% 1-RM JS) with decreases in PPO at greater loads. As anticipated with incremental increases in load, peak VGRF increased and peak BV decreased. The power, force and velocity relationship can be accurately measured in professional rugby players across a full range of loads (up to 1-RM) for the JS in a single session in a competitive phase without injury when eccentric braking is used in combination with a force plate and linear position transducer. Characterisation across this full spectrum of loads on an individual basis will enable greater precision for monitoring training-induced improvements, assessing individual weaknesses and for prescription of training.

PRACTICAL APPLICATIONS

This study presents relevant data for professional rugby union players that can be compared with athletes trained for other sports. The findings add to the increasing body of evidence supporting that the optimal load for PPO during the JS occurs at the lowest loads used, even in trained professional rugby union players. Such information is useful for the strength & conditioning coach seeking to train at the optimal load for PPO during the JS, although there are good arguments supporting training at a range of loads, and hence velocities, specific to the sport. This study illustrates how peak VGRF and peak BV are affected over such a range of loads accordingly, such that trainers can make more informed decisions. This study also demonstrates that it is feasible and safe to fully characterise the PPO, BV and VGRF across a full range of loads up to 100% 1-RM during a single session. However, based on existing evidence, for accuracy it is recommended that a combination of force plate and linear position transducer are used and for safety a magnetic braking unit can also be employed. Such data enables the strength & conditioning coach to assess individual strengths and weaknesses across the force-velocity relationship, such that programs can be tailored accordingly, as well as accurately monitoring the effectiveness of varying interventions across the range.

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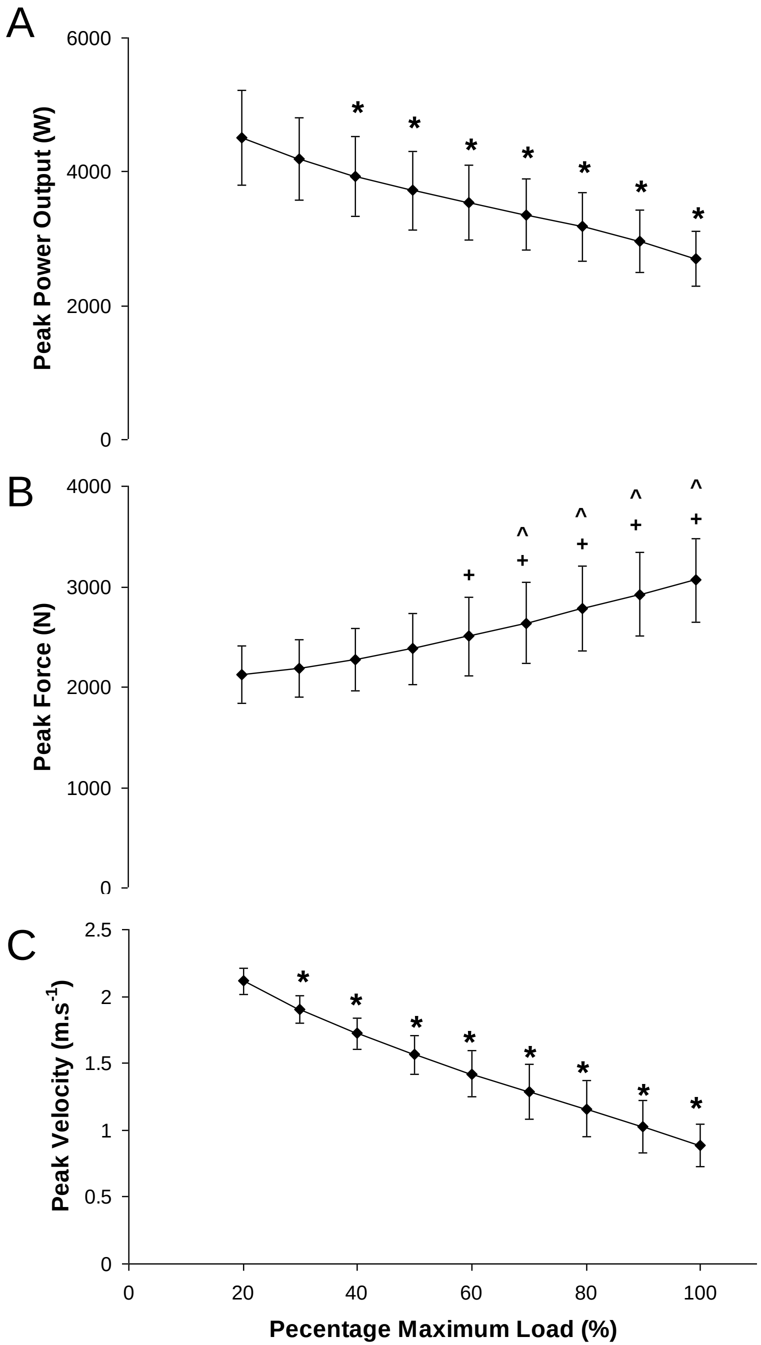
Figure Legend

FIGURE 1 - Interpolated Peak Power Output (Panel A), Peak Vertical Ground Reaction Force (Panel B) and Peak Bar Velocity (Panel C) vs. Percentage Maximum Load during loaded jump squats at incremental loads. * indicates PPO or peak BV significantly lower than at 20% Load, $P < 0.01$. + indicates Force significantly greater than at 30% Load, $P < 0.001$. ^ indicates Force significantly greater than at 20% Load, $P < 0.001$.

Figure



A
6000
4000
2000
0
Peak Power Output (W)
B
4000
3000
2000
1000
0
Peak Force (N)
C
2.5
2
1.5
1
0.5
0
Peak Velocity (m.s-1)
0
20
40
60
80
100
Pecentage Maximum Load (%)