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Authors: Mario Muñoz-López¹, David Marchante¹, Miguel A. Cano-Ruiz¹, José López Chicharro² and Carlos Balsalobre-Fernández³

Affiliations: ¹Powerexplosive Center, Madrid, Spain. ²Complutense University of Madrid, Madrid, Spain. ³Department of Sport Sciences, European University of Madrid, Spain.

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LOAD, FORCE AND POWER-VELOCITY RELATIONSHIPS IN THE PRONE PULL-UP EXERCISE

Mario Muñoz-López¹, David Marchante¹, Miguel A. Cano-Ruiz¹, José López Chicharro² & Carlos Balsalobre-Fernández³

¹Powerexplosive Center, Madrid, Spain
²Complutense University of Madrid, Madrid, Spain
³Department of Sport Sciences, European University of Madrid, Spain

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Corresponding author
Carlos Balsalobre-Fernández
Department of Sport Sciences, European University of Madrid, Spain
Address: C/ Tajo, Villaviciosa de Odón 28670, Madrid, Spain
Telephone: +34 606798498
E-mail: carlos.balsalobre@icloud.com
ABSTRACT

Purpose: To analyze the load, force and power-velocity relationships, as well as to determine the load that optimizes power output on the pull-up exercise. Methods: Eighty-two resistance trained males (Age = 26.8 ± 5.0 yrs.; Pull-up 1RM – normalized per kg of body mass– = 1.5 ± 0.34) performed two repetitions with 4 incremental loads (ranging 70-100%1-RM) in the pull-up exercise while mean propulsive velocity (MPV), force (MPF) and power (MPP) were measured using a linear transducer. Relationships between variables were studied using first and second order least-squares regression, and subjects were divided into three groups depending on their 1-RM for comparison purposes. Results: Almost perfect individual load-velocity (R² = 0.975 ± 0.02), force-velocity (R² = 0.954 ± 0.04) and power-velocity (R² = 0.966 ± 0.04) relationships, which allowed to determine the velocity at each %1-RM as well as the maximal theoretical force (F0), velocity (V0) and power (Pmax) for each subject were observed. Statistically significant differences between groups were observed for F0 (p<0.01) but not for MPV at each %1-RM, V0 or Pmax (p>0.05). Also, high correlations between F0 and 1-RM (r = 0.811) and V0 and Pmax (r = 0.865) were observed. Finally, we observed that the load that maximized MPP was 71.0 ± 6.6 %1-RM. Conclusions: The very high load-velocity, force-velocity and power-velocity relationships allows to estimate 1-RM by measuring movement velocity, as well as to determine maximal force, velocity and power capabilities. This information could be of great interest for strength and conditioning coaches who wish to monitor pull-up performance.

KEYWORDS: resistance training; monitoring; biomechanics; physical performance
INTRODUCTION

Resistance training has been previously reported to improve health, fitness and performance \(^1\)–\(^3\). In order to optimize the response to resistance training, monitoring training load has been suggested as a key factor; specifically, training intensity is generally acknowledged as the most important variable to produce the desired neuromuscular adaptations \(^4\),\(^5\). In this sense, strength and conditioning coaches often faces an issue when designing resistance training programs, that’s it, how to objectively quantify and prescribe intensity in resistance exercises. The most common method to quantify intensity is the measurement of the 1-Repetition maximum (1-RM, i.e., the load that can be lifted just once) \(^6\),\(^7\); however, in the recent years less demanding methodologies have emerged as an alternative to the 1-RM paradigm \(^8\)–\(^10\). Among them, movement velocity was shown to be an accurate, effective and non-fatiguing method to quantify relative intensity in resistance exercises \(^8\),\(^11\),\(^12\). This method is based on the load-velocity relationship observed in different resistance exercises, by which the load (in terms of %1-RM) is highly related to the velocity at which that load is lifted \(^11\),\(^12\). Thus, the measurement of movement velocity has successfully been probed to estimate the 1-RM and each of its percentages on different resistance exercises such as bench-press \(^11\), bench-pull \(^13\), squat or leg press \(^12\).

In addition to the measurement of the load-velocity relationship, several studies have analyzed the well-known force and power-velocity relationships in order to understand the maximal force, velocity and power capabilities of the athletes \(^14\)–\(^16\). Thus, the analysis of the maximal theoretical force (F0), velocity (V0) and power (Pmax), and the slope of the force-velocity profile has been shown to be of great interest to study the maximal neuromuscular capabilities in different exercises \(^15\),\(^17\). For example, Pmax and the slope of the force-velocity profile have been probed to significantly influence the ballistic performance in vertical jumping \(^18\). Also, a very high relationship between F0 and 1-RM has been recently observed in the
bench-press exercise\textsuperscript{19}. Finally, the load that maximizes power output has been extensively studied in different exercises, since that load has been commonly used to improve ballistic performance\textsuperscript{7,20,21}. Thus, the analysis of individual force-power-velocity characteristics could be of great interest for coaches and sport practitioners.

However, research has shown that load-velocity, force-velocity and power-velocity relationships are specific of each exercise\textsuperscript{12,15,21}, meaning that the velocity associated at each \%1-RM, as well as the load that maximizes power output or the maximal expressions of F0 and V0 depend on the movement pattern and muscle groups used\textsuperscript{12,21}. Therefore, more research is needed in order to analyze the load, force and power-velocity relationships in other common resistance exercises. Specifically, one of the most used multi-joint, closed-chain, upper-body resistance exercises, the prone pull-up, has not been analyzed yet in this sense. The prone pull-up has been used to assess the strength of the upper limbs in different populations such as fitness practitioners\textsuperscript{22}, firefighters\textsuperscript{23}, swimmers\textsuperscript{24} or climbers\textsuperscript{25}. However, to our knowledge, there are no studies in the literature that analyze the specific relationships between load, force, power and velocity on the prone pull-up exercise. Consequently, the aim of the present study is to analyze the load, force, power-velocity relationships in this exercise.

**METHODS**

**Subjects**

Eighty-two resistance-trained males, with more than 4 years of experience in the prone pull-up exercise, participated in this study (N = 82 men; Age = 26.8 ± 5.0 yrs., Height = 1.80 ± 0.1m; Body mass = 81.6 ± 9.3 kg; Pull-up 1RM – normalized per kg of body mass = 1.47 ± 0.19). Participants were divided into three groups according to their normalized weighted pull-up 1-RM (1-RM/kg); group 1 (G1: N = 27; 1-RM/kg < 1.4), group 2 (G2: N=27; 1-RM/kg < 1.52) and group 3 (G3: N = 28; 1-RM/kg > 1.52).
No physical limitations or musculoskeletal injuries that could affect testing were reported. To join the study, each participant needed to perform a minimum of 15 repetitions to failure in the un-weighted prone pull-up exercise and train the weighted prone pull-up exercise at least once per week for the last 6 months. The study complained with the Declaration of Helsinki and all participants signed informed-consent forms before participation. The study was approved by the institutional review board.

**Design**

Least-squares regression analysis aiming to identify the load, force and power-velocity relationships was conducted. All participants performed a 4-loads incremental test in the prone pull-up exercise with loads ranging 70-100% of their 1RM (considered as body mass plus external load) while mean propulsive velocity (MPV), force (MPF) and power (MPP) were being registered at a sampling frequency of 1000Hz using the *Smartcoach Power Encoder* linear position transducer (LPT) (Smartcoach Europe, Stockholm, Sweden). The software of the LPT determined the propulsive phase of each repetition as the part of the concentric phase in which measured acceleration was higher than g (i.e. a > 9.81 m/s²) as described elsewhere. MPF was indirectly calculated from propulsive velocity using the well-known *impulse-momentum* theorem as follows:

\[
F = m \times (v_f - v_0) / t
\]

where \( F \) is MPF (in N), \( m \) the system mass (i.e. body mass plus external load, in kg), \( v_f \) is the final velocity of the propulsive phase (in m/s), \( v_0 \) is the initial propulsive velocity of the concentric phase (in m/s) and \( t \) is the duration of the propulsive phase (in s). Finally, MPP was computed as the product of MPF and MPV: \( MPP = MPF \times MPV \). The load that maximized MPP was also registered accordingly. Each participant performed 2 repetitions with each load, and the one with higher MPV was registered.
Furthermore, individual force-velocity and power-velocity relationships were used in order to determine theoretical maximal force (F0), velocity (V0) and power (Pmax) production, which represent the maximal neuromuscular capabilities of the participants. The values of F0 and V0 were calculated as the y-intercept and x-intercept of the force-velocity linear regression, and Pmax was computed as \( P_{\text{max}} = F_0 \cdot V_0 / 4 \) as described elsewhere. It should be noted that Pmax is a theoretical expression of the maximal power capabilities of the subject, while maximal MPP is the actual maximal power attained within the incremental test.

**Methodology**

**Body measures**

At the beginning of the testing session, height was measured to the nearest 0.5 cm during a maximum inhalation using a wall-mounted stadiometer (Seca 202, Seca Ltd, Hamburg, Germany). Then, body mass was measured using the Jata 531 scale (Jata S.A., Bizcaia, Spain).

**Pull-up incremental test**

One week prior to the testing session, a familiarization session was conducted so that participants could get used to isoinertial testing. After conducting a proper 15-minutes warm-up consisting on dynamic stretching and preparatory exercises (i.e., glenohumeral joint external rotations, scapular retraction and 1 set of 5 un-weighted prone pull-ups), athletes performed 4 different sets on the prone pull-up exercise. Initial external load was set at 0kg (i.e., un-weighted prone pull-up), and it was incremented until the 1-RM (i.e., weighted prone pull-up) was reached. The magnitude of the increment in the external load was based in the drop of velocity from the previous set, so that each set could be performed at least 0.1m/s slower than the previous set. If the 1-RM was not reached in the 4th set, an additional set with 5-10% more kg was performed. Consequently, the loads used ranged 70-100% 1RM approximately. Two
repetitions were performed with each load and the one with higher MPV was recorded. Sets where separated by 3 minutes of passive rest.

The pull-up was performed with a prone grip and hands were separated by a distance equivalent to participant’s acromion-to-acromion length. In order to consider a repetition valid, the participant needed to start the movement hanging in the bar with the elbows fully extended and the feet in the air with the knees flexed and the hip in neutral position. After holding that position for 2 seconds, participants were encouraged to perform the pull-up as fast as possible until their chins were above the bar.

Weight plates were located in the ventral section of the coronal plane using a specific belt (Maniak Fitness, Málaga, Spain). The cable of the LPT was fixed to the rear label of participants’ shorts at the sacral vertebrae height because of its proximity to the Center of Mass and to avoid any contact with the weight plates.

**Instrumental**

The *Smartcoach Power Encoder* (Smartcoach Europe, Stockholm, Sweden) LPT was used to register MPV (in m/s), MPF (in N) and MPP (in W) at a sampling frequency of 1kHz. Butterworth filtering was used by this instrument to smooth the data. The LPT was placed in the floor below participants’ Center of Mass so its cable could be aligned with the Z-axis (i.e., vertical position) following the criteria described by the manufacturer. Then, the LPT was connected to the *Smartcoach 5.0.0* software which was installed on a personal computer running the Windows 10 operating system and all the data were exported to a spreadsheet for further analyses.

**Statistical analysis**

Standard statistical methods were used for calculation of means and SDs. The normality of the data was analyzed using the Kolmogorov-Smirnov test. To analyze the load-velocity (i.e. %1-RM-MPV) and force-velocity relationship (i.e. MPF-MPV), first order least-squares
regression was used, and to analyze the power-velocity relationship (i.e. MPP-MPV), second order least-squares regression was used.

One-way ANOVA with Bonferroni post hoc comparisons was used to detect potential differences between groups in the studied variables, as well as to analyze differences between power output with different loads. Finally, the relationships between variables were calculated using Pearson’s product–moment correlation coefficient and bootstrapping (N= 1000) determined the 95% Confidence Interval (CI). The level of significance was set at .05, and the IBM® SPSS® V.23 software (IBM Co., USA) was used for the analyses.

RESULTS

Load-velocity relationship

When analyzing individual load-velocity profiles for each participant, an almost perfect relationship between %1-RM and MPV was observed in all cases (Mean (SD) from individual values: $R^2 = 0.975 \pm 0.02$, SEE = $0.035 \pm 0.02$ m/s). Moreover, the slope ($s = -0.017 \pm 0.004$) and intercept ($i = 1.933 \pm 0.44$ m/s) of the load-velocity relationship were similar for all participants. See Figure 1 for more details.

When using each participant’s regression equation to estimate MPV for a certain %1-RM, an almost perfect correlation, with no significant differences was observed between the estimated and actual MPV for each %1-RM used in the incremental tests ($r = 0.987 \pm 0.01$, Mean difference = $0.033 \pm 0.07$ m/s, $p = 1.00$).

Force-power-velocity relationships

Almost perfect relationships between mean propulsive force (MPF) and MPV ($R^2 = 0.954 \pm 0.04$), and mean propulsive power (MPP) and MPV ($R^2 = 0.966 \pm 0.04$) were observed for each participant. Using the force-velocity and power-velocity relationships, descriptive data
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for F0, V0, Pmax and the slope of the force-velocity profile were calculated for each participant. See Figure 2.

There were no statistically significant differences between groups of strength for V0 or Pmax as revealed by the one-way ANOVA (p> 0.05). However, significant differences were observed for F0 (p< 0.001) and the slope of the force-velocity profile (p< 0.05). See Table 1 for more details. Finally, it was observed that the load that maximized MPP was 71.0 ± 6.6 %1-RM i.e., the first load of the incremental test in most cases. The absolute value of maximal mean power output was 645.4 ± 171.4 W. See Figure 2 for more details.

*Correlations between variables*

Finally, high, significant correlations were observed between 1-RM and F0 (r = 0.811, CI: 0.623-0.930, p< 0.001) and V0 and Pmax (r = 0.865, CI: 0.801-0.917, p< 0.001). See Figure 3.

**DISCUSSION**

The results of our study showed a very close individual load-velocity (R² = 0.975 ± 0.02) relationship. Given the very high correlation between MPV and the load at which that velocity was produced, individual regression equations allowed to estimate the velocity at which each percentage of the 1-RM was performed. Moreover, no significant differences (0.046 ± 0.27 m/s, p = 1.00) were observed between the estimated and actual velocity performed with the loads used in the incremental test. Therefore, results in our study showed that the load used in the prone pull-up exercise can be accurately determined by measuring the velocity at which that load is moved. This is in line with previous research that found similar, very high correlations between load (in terms of %1-RM) and movement velocity in different exercises such as bench press ¹¹, bench-pull ¹³ or squat ¹². However, unlike previous research that showed an almost perfect fit (R² > 0.98) when velocities at each %1-RM from each
participant were computed in the same regression equation \(^1\), we observed a much lower value \((R^2 = 0.780)\), meaning that an individual regression equations, and not a global one, should be used to estimate the %1-RM of each participant. This could be due to a particularity of the prone pull-up exercise: unlike other exercises where the athlete mainly faces the load that represents the barbell and plates, the prone pull-up exercise is demanding with a load as low as 0kg of external load (i.e., the un-weighted pull-up) due to subject’s own body mass. Thus, subjects with higher 1-RM find easier to perform the exercise without any load and, consequently, can produce higher velocities. In fact, the one-way ANOVA showed significant differences in the MPV of the unweighted pull-up as detailed in Table 1 \((p<0.001)\). However, when a maximal lift is performed (i.e., 100% 1-RM) all participants produced the same velocity (in our study the velocity at 1-RM = 0.26 ± 0.05), which confirms previous research that showed that velocity at 1-RM is very stable and doesn’t depend on athletes’ fitness \(^8,11,12\). For this, to accurately determine the percentage of 1-RM from movement velocity, individual analysis to determine the athlete’s own load-velocity profile is highly recommended.

Also, very high force-velocity \((R^2 = 0.954 ± 0.04)\), and power-velocity \((R^2 = 0.966 ± 0.04)\) relationships, which allowed the calculations of F0, V0 and Pmax were observed. Thus, our study confirmed that the very high, linear force-velocity relationship and the very high quadratic power-velocity relationship observed in different activities \(^1\) are also present in the prone pull-up exercise. There is an increasing interest in the analysis of the force-power-velocity relationships since F0, V0 and Pmax have been proposed to represent the maximal theoretical neuromuscular capabilities of the athletes \(^14,15\). For example, vertical jump performance was shown to be significantly influenced by participants’ Pmax \(^18\), while bench press 1-RM has shown to be very highly correlated with F0 \(^19\). Therefore, the analysis of the force-power-velocity relationships has been proposed to provide interesting additional information on the athletes’ neuromuscular performance for different activities such as jumping
This is the first study that analyzed the force-power-velocity relationships in the prone pull-up exercise. Also, to the best of our knowledge, this study shows for the first time normative values of F0, V0 and Pmax for resistance-trained males in this exercise. However, one important limitation should be noted when analyzing the force-power-velocity characteristics in the pull-up exercise, that’s it, the instrumental used to measure force. The gold standard for the measurement of force are force platforms since they register the reaction forces applied to the ground directly. Meanwhile, linear transducers estimate force using the impulse-momentum theorem, providing an indirect measurement of force in the basis of system mass and changes in velocity. Thus, to obtain a direct measurement of force in this exercise, a special device that would register “bar reaction forces” should be used; however, to the best of our knowledge, such device doesn’t exist yet. Therefore, until technology provides a direct measurement of force in the pull-up exercise, the force (and consequently, power) measures obtained with a linear transducer should be interpreted with caution.

Interestingly, none of the variables analyzed in the force-power-velocity relationships differed among groups of strength with the exception of F0 (p<0.001) and the slope of the force-velocity profile (p<0.05) which were higher and lower, respectively, in G3 with respect to the other two groups. Therefore, it seems that while strongest athletes had significantly higher values of F0, none Pmax nor V0 were different from less strong subjects. In this sense, it was observed that F0 and 1-RM were significantly correlated (r = 0.811), as well as Pmax and V0 (r = 0.865), but no other pair of variables. Thus, it seems that high values of 1-RM are related with high values of F0, but not with high V0 or Pmax. Therefore, considering our results, athletes who wish to develop their 1-RM in the prone pull-up exercise might benefit from increasing their maximal force capabilities, while those who want to increase their maximal power might need to focus on developing maximal velocity.
Developing maximal power output is, in fact, one of the most common goals in strength and conditioning since ballistic performance has shown to be influenced by muscular power in several activities such as sprinting, jumping, lifting or tackling, among others. Thus, there is a large body of research investigating which range of loads produce the higher maximal power output, since it was proposed that training with the maximal power load could have superior benefits to increase power production. For example, a recent meta-analysis on the maximal power load on upper-body exercises has shown that power output on the bench press exercise is maximized with loads ranging 30-70% 1-RM. However, to date, no research has described the range of loads that maximize the power output in the prone pull-up exercise. In this sense, our study shows that, in most cases, the load that produced the greatest power output was the first load on the incremental test which corresponded to 71.0 ± 6.6% 1-RM. It should be noted that this value corresponds to the maximal MPP production within the incremental test, while Pmax (which is calculated from F0 and V0 as described in the methods section) is a theoretical expression of the maximal power production capabilities of the subject. In this sense, it was observed that the value of Pmax, derived from the force-power-velocity relationships was higher than the actual maximal MPP produced in the incremental test (747.4 ± 232.9 vs. 645.4 ± 171.4 W). Thus, we can conclude that the lightest load on the incremental test (i.e. the unweighted pull-up) is not enough to express the absolute maximal power capabilities of the subjects and, consequently, Pmax would only be reached with an assistance that would reduce the body weight of the athlete and, therefore, could allow a highest movement velocity.

To the best of our knowledge, this is the first study which analyzes the load-force-power-velocity relationships in the prone pull-up exercise.
PRACTICAL APPLICATIONS

First, results in our study showed that there is an almost perfect relationship between the load (in terms of %1-RM) and mean propulsive velocity in the prone pull-up exercise. Thus, strength and conditioning coaches who wish to monitor training intensity when prescribing the prone pull-up exercise might benefit from measuring movement velocity, because it would allow to know athlete’s 1-RM without conducting an actual 1-RM test; however, individual load-velocity profiles should be used for accurate estimations. Second, it was observed that the load that produced higher power outputs was about 71.0 %1-RM in most cases (i.e., un-weighted pull-up), although this value was lower than the maximal theoretical power (Pmax) derived from the force-power-velocity relationships. Therefore, if absolute maximal power capabilities are to be developed, subjects should use an assistance that would reduce body weight and, therefore, could produce higher movement velocities. Also, Pmax was shown to be highly correlated with maximal velocity (V0) but not to maximal force (F0). Therefore, athletes who wish to focus on power development might benefit from training with no load, or very light loads moved at high speeds to produce high power outputs. Finally, it was observed that 1-RM was highly related with F0, meaning that if maximal force capability is to be developed, athletes should probably focus on increasing their maximal load in the prone pull-up exercise.

CONCLUSIONS

Very high load-velocity, force-velocity and power-velocity relationships which allows to estimate training intensity (in terms of %1-RM) by measuring movement velocity, and to estimate the maximal force (F0), velocity (V0) and power (Pmax) capabilities were observed in the prone pull-up exercise. Our results could have potential practical applications for strength and conditioning coaches who wish to use the prone pull-up exercise in their training programs.
ACKNOWLEDGEMENTS

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REFERENCES


Figure 1. Load-velocity linear regression from a typical participant.
Figure 2. Force-velocity linear regression and power-velocity quadratic regression. Data represents average values from the whole group.
Figure 3. Correlation between A) F0 and 1-RM/kg and B) Pmax and V0.
### Table 1: Mean and standard deviations values for F0, V0, Pmax, slope of the force-velocity relationship, mean propulsive velocity without an external load and mean propulsive velocity at typical percentage of the 1-RM (calculated from individual regression equations)

<table>
<thead>
<tr>
<th>Measure</th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0 (N/kg) *</td>
<td>14.8 ± 2.1</td>
<td>16.3 ± 1.1</td>
<td>19.0 ± 2.6</td>
<td>16.7 ± 2.6</td>
</tr>
<tr>
<td>V0 (m/s)</td>
<td>2.4 ± 0.9</td>
<td>2.2 ± 0.4</td>
<td>2.0 ± 0.8</td>
<td>2.2 ± 0.7</td>
</tr>
<tr>
<td>Pmax (W/kg)</td>
<td>8.6 ± 2.8</td>
<td>9.1 ± 1.9</td>
<td>9.6 ± 3.1</td>
<td>9.1 ± 2.7</td>
</tr>
<tr>
<td>F-V Slope *</td>
<td>-7.4 ± 4.1</td>
<td>-7.5 ± 1.8</td>
<td>-10.4 ± 3.4</td>
<td>-8.5 ± 3.5</td>
</tr>
<tr>
<td>MPV UP (m/s)*</td>
<td>0.61 ± 0.12</td>
<td>0.80 ± 0.1</td>
<td>0.81 ± 0.15</td>
<td>0.73 ± 0.16</td>
</tr>
<tr>
<td>MPV @80%1-RM (m/s)</td>
<td>0.61 ± 0.09</td>
<td>0.61 ± 0.09</td>
<td>0.56 ± 0.12</td>
<td>0.59 ± 0.1</td>
</tr>
<tr>
<td>MPV @85%1-RM (m/s)</td>
<td>0.52 ± 0.07</td>
<td>0.52 ± 0.08</td>
<td>0.49 ± 0.1</td>
<td>0.51 ± 0.09</td>
</tr>
<tr>
<td>MPV @90%1-RM (m/s)</td>
<td>0.43 ± 0.06</td>
<td>0.44 ± 0.07</td>
<td>0.41 ± 0.09</td>
<td>0.43 ± 0.07</td>
</tr>
<tr>
<td>MPV @95%1-RM (m/s)</td>
<td>0.34 ± 0.04</td>
<td>0.35 ± 0.06</td>
<td>0.33 ± 0.07</td>
<td>0.34 ± 0.06</td>
</tr>
<tr>
<td>MPV @100%1-RM (m/s)</td>
<td>0.25 ± 0.03</td>
<td>0.26 ± 0.06</td>
<td>0.25 ± 0.04</td>
<td>0.26 ± 0.05</td>
</tr>
</tbody>
</table>

*p < 0.001; F0 = maximal theoretical force production at 0 velocity; V0 = maximal theoretical velocity at 0 force; Pmax = theoretical maximal power output; F-V slope = slope of the force-velocity linear relationship; MPV @ = mean propulsive velocity at each percentage of 1-RM; UP = unweighted pull-up (i.e. 0kg of external load)