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Title: The Relationship between Maximum Pull-up Repetitions and First Repetition Mean Concentric Velocity

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Preferred Running Head: Pull-up Repetition Velocity Relationship

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Abstract

Mean concentric velocity (MCV) of exercise execution has been used by strength and conditioning professionals to improve exercise technique, provide accurate feedback, and predict exercise one repetition maximum. There is still limited research on velocity based training and currently only one research study on the pull-up exercise. The primary purpose of this research was to determine if the maximum number of pull-ups an individual can perform can be predicted by the MCV of a single pull-up repetition. Forty-nine healthy men and women were recruited who reported they could do at least two pull-ups. Each subject performed a standardized warm up, then a single pull-up repetition, followed by one set of pull-up repetitions to failure. The GymAware PowerTool, a linear position transducer (LPT), was used to measure the MCV of each pull-up repetition. Both the MCV of the single repetition and first repetition of the set to failure were recorded, and the greater of the two was used in later analysis. Weighted least squares linear regression was used to estimate the relationship between the single repetition MCV and maximum amount of pull-up repetitions. We observed a statistically significant linear relationship between the maximum number of pull-ups and the MVC of a single pull-up repetition ($y= -6.661 + 25.556x$, $R^2 = 0.841$). Prediction of maximum pull-up number by a single repetition rather than testing maximal pull-up number may improve efficiency and effectiveness of exercise testing batteries for military, police, and other populations.

Keywords: Physical Fitness Testing, GymAware PowerTool, Repetition Maximum Testing, Velocity-Based Training, Body-Weight Exercises,

INTRODUCTION

Velocity based training (VBT) is a type of resistance training that uses velocity measurements to assign training loads and monitor changes in performance (16). Exercise velocity is often measured using a linear position transducer, such as the GymAware PowerTool, which has been established as a valid and reliable device (6, 8, 11, 16). When attached to a person or piece of exercise equipment, a linear position transducer provides displacement-time data, which can be converted into velocity and acceleration. A variable of interest for VBT is the mean concentric velocity (MCV), which is the average velocity of the concentric phase of an exercise. MCV is an accurate way to determine the ability of the subject to move the load explosively through the concentric phase (13). The MCV of exercise execution has been used by strength and conditioning professionals to improve exercise technique, provide accurate feedback, and predict exercise one-repetition maximum (1-RM) (17). Currently, there is still limited research on VBT and only one study has evaluated the velocities of the pull-up exercise (22).

Physical performance testing is done on a regular basis in large organizations such as military, firefighters, police officers, and other services for regular assessment and for pre-employment fitness testing. Performing well on these tests is important for these populations not only for job performance, but also for job promotion and retention (4, 19, 23). One common test for upper body strength in these populations is the maximum repetition pull-up test.

While occasional use of the maximum pull-up test is unavoidable due to the necessity of regular testing to meet fitness standards, overly frequent testing has several potential drawbacks including: increased time required for testing, particularly for large groups, recovery time, and interruptions to training. Indirect methods of testing are a potential solution, provided that those methods are quick to administer, efficient, and able to accurately predict the performance measures of interest.

While pull-ups are generally scored by counting the maximum number of valid repetitions, the 1 repetition maximum (1-RM) of a pull-up is also sometimes tested directly, or can be estimated by establishing a load-velocity profile (22). 1-RM can be estimated for a variety of exercises (9, 10, 20, 21), by having subjects lift increasingly heavy loads using maximal effort, from which a prediction equation is created from the velocities obtained at each load. Additionally, the number of repetitions performed to failure at a given load (repetition maximum, RM) can also be used to estimate a person's 1-RM of an exercise (15). If both velocity at a given load and repetitions-to-failure are both related to 1-RM, it is plausible that velocity of a single maximum-effort repetition is also related to maximum repetitions-to-failure with a given load.

If pull-up repetitions to failure are related to mean concentric velocity (MCV), prediction of maximal pull-up number from MCV would be possible using a prediction equation, thus simplifying regular assessment of maximal pull-up number and potentially improving the efficiency of testing tactical populations. Therefore, the purpose of the experiment was to determine if the maximum number of pull-ups an individual can perform can be predicted by the

MCV of a single pull-up repetition. We hypothesized a positive linear relationship between first repetition MCV and maximum pull-up repetitions.

METHODS

Experimental Approach to the Problem

This study was designed to evaluate if the MCV of a single repetition can be used to predict the maximum pull-up repetitions an individual can perform. After a standardized warm up, recreationally trained athletes performed a single pull-up repetition and one set of pull-ups to failure, with MCV measured using the GymAware PowerTool. A linear regression model was implemented to predict maximum pull-up count from the single repetition MCV.

SUBJECTS

Fifty-six recreationally trained men and women recruited for this study, who, prior to the day of testing, were injury free, they had not performed upper body resistance training within the last 48 hours, and reported that they could perform at least two pull-ups. In our pilot testing, we found that subjects often over-estimated their ability to do pull ups under our strict technique criteria, thus only testing subjects who reported they could do two pull ups ensured we were more likely to get at least one correctly executed pull up in testing. Still, seven participants were excluded from the final analysis because they could not complete at least one repetition using the standardized pull-up technique, were not currently injury-free, or had not rested their upper body for 48 hours prior to testing. Forty-nine subjects were included in the final analysis (entire group:

age 24.3 ± 4.4 y, height 171.5 ± 8.0 cm, weight 77.9 ± 12.5 kg). Forty-two males (age: 24.4 ± 4.5, height: 173.3 ± 6.9 cm, weight: 79.5 ± 12.4 kg) and seven females (age: 24.1 ± 4.5 y, height: 160.5 ± 5.4cm, weight: 68.3 ± 8.5 kg) participated in this study. This study was approved by the California State University, Monterey Bay Committee for the Protection of Human Subjects. All subjects were informed of study procedures and signed informed consent documents prior to participation.

PROCEDURES

Prior to testing, height, body mass, age, number of years training pull-ups, and self-estimated maximum pull-up count were recorded. Standardized instructions on pull-up technique were given prior to initiation of the standardized warm up. Subjects were instructed to use an overhand grip with hands placed slightly wider than shoulder width. Each repetition would begin at a dead hang (elbows fully extended, shoulders fully flexed, and shoulder girdle elevated) with legs placed behind the body, ankles crossed and knees flexed. Once in the correct starting position, subjects were to perform the concentric phase of the pull-up explosively, without swinging or kicking the legs. The concentric phase ended once the subjects chin passed the pull-up bar. Immediately after the concentric phase was completed, subjects were instructed to perform the eccentric phase of lowering their body back to the starting position at a comfortable speed. Subjects paused roughly 1 second between repetitions.

Subjects then began the warm up protocol using an assisted pull-up machine. The warm up consisted of: 2 sets of 5 repetitions at 50% body weight, 1 set of 3 repetitions at 75% body weight, and 1 set of 1 repetition at 100% body weight. A rest period of 90-120 seconds was given between each set. Standard pull-up technique was instructed and reinforced throughout the warm up. Following the warm up, subjects rested 20 minutes, then performed a set of one repetition and a set of pull-ups to failure, separated by 2 minutes of rest.

The MCV of each repetition of the single repetition and set of pull-ups to failure were measured using the GymAware PowerTool (Kinetic Performance, ACT, Australia). The GymAware PowerTool was anchored to the top of the pull-up rig, centered on the pull-up bar and attached to the front of a weight belt tightly fastened around the waist of the subject. The GymAware PowerTool has been previously found valid and reliable (6, 8, 11, 16). A webcam (HD Pro Webcam C920, Logitech Inc., Lausanne, Switzerland) was positioned at the same height as the pull-up bar to confirm pull-up repetitions were performed to standard. After all measurements were recorded, MCV of the single repetition pull-up or first repetition of the maximum set to failure was used depending on which MCV was greater.

STATISTICAL ANALYSES

We first considered a simple linear model $Y = \beta_0 + \beta_1 X + \varepsilon$ to predict the maximum repetitions (response Y) based on the MCV (explanatory X). To test for a potential heteroscedasticity (i.e. , violation of the constant variance assumption), we implemented the Breusche-Pagan (BP) test (3). Briefly, the BP test determines whether the variability of the response variable (maximum repetitions) linearly increases with respect to the explanatory variable (MCV).

In the presence of the heteroscedasticity, we would use the weighted least-square estimation (WLSE) by weighting data points proportional to the inverse of MCV. This weighting scheme allows data points with less variability to have greater contribution in the estimation of model parameters β_0 and β_1. In the case of heteroscedasticity, the WLSE provides more precise estimation than the ordinary least square estimation without changing the interpretation of the model parameters.

We then considered sex (denoted by Z) and determined whether it would be a useful predictor of the maximum repetitions in the presence of MCV in the model. We considered adjusted model $Y = \beta_0 + \beta_1 X + \beta_2 Z + \varepsilon$ and multiplicative model $Y = \beta0 + \beta_1 X + \beta_2 Z + \beta_3 XZ + \varepsilon$, where $Z = 1$ indicates male and $Z = 0$ indicates female. To test statistical significance for sex to be included in the model and to select a parsimonious model, we used critical p-value of $p \geq 0.05$ and the Akaike Information Criterion (AIC) (1). The AIC balances between the model-fit and the model complexity. A smaller AIC value is preferable for model selection.

With the sample size of the current study, use of the conventional method of validation (partitioning the entire dataset into a training set for model creation and the other part of the dataset into a validation set for model assessment) was not optimal due to the limited number of samples. Instead, we performed a 5-fold cross-validation and calculated the mean square error (MSE) (2, 14, 24). Briefly, the MSE measures the prediction error by considering both bias and variance. A large bias means that the average prediction error is toward one direction (i.e. under-estimation or over-estimation), and a large variance means a lack of precision (i.e. too high variation) in the prediction. To perform this method of cross-validation, we randomly partitioned the data into five subsamples (of sizes 10, 10, 10, 10, and 9 because the sample size was 49). Of the five subsamples, four subsamples were used as training data and the remaining subsample was used as validation data in a rotating fashion. We rotated each subsample into training and validation sets, with each subset serving as validation data exactly one time each, then averaged the resulting MSE of each rotation of the cross-validation procedure.

In addition to the primary objective of this study, the velocity of repetitions was plotted against the number of repetitions until failure of the set (e.g. 3 repetitions until failure means that after performing 3 repetitions, the subject would fail on the next repetition). The velocity of the last repetition was deemed the minimum velocity threshold (MVT)(5). We estimated a linear relationship using a linear mixed-effects model to account for subject-specific trajectory of the velocity with respect to repetitions (18).

RESULTS

Subjects performed 11.3±5.6 pullups (range 1-25).

BP TEST AND WLSE

The BP test suggested that the variability of maximum repetitions increases linearly with respect to MCV as shown in Figure 1. The figure provides estimated simple linear model y = -6.661 + 25.556 x which is estimated by the WLSE. The relationship seemed fairly linear with R^2 = .841 and AIC = 229.53.

Testing for Sex as an Additional Predictor

When we considered the adjusted model $Y = \beta_0 + \beta_1 X + \beta_2 Z + \varepsilon$, we could not reject $\beta_2 = 0$ with p-value .875, and AIC = 236.77. When we considered the multiplicative model $Y = \beta_0 + \beta_1 X + \beta_2 Z + \beta_3 XZ + \varepsilon$, we could not reject $\beta_3 = 0$ with p-value .453 and AIC = 238.15. Both p-values and AIC values indicated that the simple linear model with the WLSE is most plausible (i.e. not including sex in the model). Figure 2 provides observed data points with sex-specific lines $y = -4.062 + 19.381\,x$ for female and $y = -6.913 + 25.938\,x$ for male under the multiplicative model, but we had a lack of evidence and therefore decided against use of the sex-specific models.

Insert Figure 1 and 2 about here

Cross-Validation

When we implemented the 5-fold cross validation, the calculated MSEs were 6.83, 7.11 and 8.44 under the simple linear model, the adjusted model, and the multiplicative model, respectively. The simple linear model had both the lowest MSE and AIC score, indicating that of the candidate models, it was the best performing. The average deviation in the cross-validation prediction was about 2.07 under the simple linear model. In other words, when we predicted the maximum repetitions based on an observed value of MCV, the average absolute distance between the observed maximum repetitions and the predicted maximum repetitions was estimated as 2.07. All numerical results related to the predictive performance from the three candidate models are summarized in Table 1, and all results related to estimated model parameters are summarized in Table 2.

Table 1 about here

Modelling the Velocity of Each Repetition by Repetitions to Failure

Repetition MCV and repetitions to failure is represented in Figure 3. Under the linear mixed-effects model, the estimated linear relationship is y = 0.337 + 0.0356 x, R^2 = 0.70 (conditional R^2 = .93), and SEE = 0.054. Under this model, the marginal R^2 = 0.70 is interpreted as the proportion of variance in MCV explained by repetitions to failure based on the estimated population-level line, and the conditional R^2 = .93 is interpreted as the proportion of variance explained based on both population- and individual-level lines. The linear mixed-effects model is able to estimate each individual trajectory of MCV with respect to the repetitions to failure, so the conditional R^2 = 0.93 (which accounts for both population- and individual-levels) is greater than the marginal R^2 = 0.70 (which accounts for population-level only). The MVT was 0.339 ± 0.147 m•s^{-1}, range: 0.11 – 0.73 m•s^{-1}, coefficient of variation (COV): 43.4%.

Figure 3 about here

DISCUSSION

The findings of this study confirmed our hypothesis that there would be a positive linear relationship between first repetition MCV and maximum pull-up repetitions. Previous studies have demonstrated that 1-RM can be predicted using load and velocity. This load-velocity relationship has been studied using various upper body exercises (e.g. Smith machine bench press, free-weight bench press, loaded pull-up) and the 1-RM prediction equations generally have a high degree of prediction accuracy (12, 21, 22). Additionally, 1-RM can be predicted by the number of repetitions to failure performed at a given load (17). If repetitions to failure and load, and velocity of a repetition and load, can be used to predict 1-RM, it is logical to assume that repetitions to failure and velocity of a repetition might be related. The findings of the present study confirm that there is a strong linear relationship between repetitions to failure and first repetition velocity. For certain exercises in which the goal is to maximize repetitions performed rather than maximize the load (i.e. bodyweight exercises like the pull-up and push-up), prediction of repetitions to failure may be more important than prediction of 1-RM.

Replacing maximum repetition testing with the one rep MCV test may allow coaches working with tactical populations to more efficiently estimate the maximum repetitions their athlete can perform. A recent meta-analysis suggested that training to failure is of no greater benefit than training short of failure for strength development (7). Considering this meta-analysis, a technique that enables a coach to regularly assess her or his athletes without the necessity of going to failure may be of advantage.

Another potential drawback of maximum repetition testing is the amount of time needed to perform the test itself. MCV testing of a single repetition may allow for more efficient testing of large groups of people, such as military personnel or sports teams, by reducing testing time per person. With the time saved, more time and effort could potentially be devoted to training. Additionally, with the small time needed for testing the MCV of a single repetition, this could potentially be used as a method for regular monitoring of changes in pull-up performance. If the prediction is stable over time, increases in single repetition velocity could be indicative of improvements in maximal pull-up number.

While studies have reported the load-velocity relationship for a single period (cross-sectional studies), few studies have evaluated the stability of the load-velocity relationship over time (22). Sanchez-Moreno, et al. (22) found that the load and mean propulsive velocity relationship for the pull-up exercise was stable over 12 weeks of training. The study by Sanchez-Moreno, et al. (22) gives some evidence that the velocity-maximum repetition relationship may also be stable over time and after training. However, prediction of 1-RM using submaximal loads has been found to be somewhat unstable when used before and after a period of training (17), therefore, the stability of prediction equations over time from the present study should be evaluated in future research. Additionally, testing the stability of the prediction equations with different populations could provide more definitive results should different populations affect the accuracy of the prediction equation over time.

Some research has indicated that the accuracy of 1-RM prediction from RM differs based on the number of repetitions used to predict the 1-RM (e.g. 5RM versus 10RM), generally indicating that the greater the number of repetitions used as the RM, the less accurate the prediction (17). This finding is supported by the statistically significant Breusche-Pagan test for heteroscedasticity of the current study. Because the aim of the current study was to predict maximum pull-up repetitions, different amounts of error with different repetition counts (i.e. heteroscedasticity) make the prediction of max repetitions from first repetition MCV inherently difficult, particularly for subjects who can perform a high number of repetitions. In the present study we addressed the varying error by using weighted least-squares regression, which may be a solution for future studies. Additionally, future studies might attempt to figure out ways of reducing heteroscedasticity, such as by reducing the heterogeneity of the tested population. In other words, more similar populations might decrease the proportionally-increasing error of prediction, thus making the prediction models more accurate.

There are a variety of performance differences between men and women (25). However, whether or not these performance differences affect the RM and 1-RM relationship, or affect the load-velocity and 1-RM relationship, is not clear. Mayhew, et al. (17) found that there were some problems with applying 1-RM prediction equations from male populations in female populations, but equations for men could generally be used with women. Agreeing with Mayhew, et al. (17), we found that there was not sufficient justification to either include sex as an additional predictor in our model or create a unique model specifically for males and females. However, given the small number of females included in our prediction model, it is warranted in future studies to specifically evaluate the effect of inclusion of sex in prediction models for maximum repetitions, to further assess the possibility of using the same prediction equations for males and females.

While examining MVT was not a central focus of this study, we were interested to examine it in a bodyweight exercise where high numbers of repetitions to failure were possible. The MVT is the MCV of the last repetition prior to failure (e.g. the 5th repetition of a 5 RM, or the 12th repetition of a 12 RM) (13). Interestingly, the range of MVTs obtained in our study (0.11 – 0.73 $m•s^{-1}$, COV of 43.4%) was greater than that of another study examining the pull-up (0.08-0.32 $m•s^{-1}$, 0.20 ± 0.05 $m·s^{-1}$, COV of 25.0%) (22), although this other study reported those measures during a 1-RM, rather than the last repetition prior to failure as in the present study. There is some disagreement as to the similarity of the MVT across loads (5, 20). It is possible that the minimum velocity to complete a repetition may vary between subjects with greater numbers of repetitions, as has been observed in this study. Another possibility is that the variability observed in the MCV of the last repetition is due to some other factor related to subjects of the current study, such as variability in limb length (i.e. greater limb lengths would necessitate large ranges of motion and may thus influence velocity).

One limitation of the present study is the variability in training background of the included subjects. While all subjects were currently training in some capacity, and performed pull-ups or pull-downs on a regular basis (≥1 time per week), there was a large variety in actual pull-ups performed (range 1-25). This may be indicative of a variety of what each participants' current training habits were, and resulted in a wide range of ability and may be a potential source for both the heteroscedasticity and the absolute average prediction error of 2.07 repetitions. Future studies should use subjects with a more homogenous training background to hopefully limit the variability. Another limitation of this study is the fact that the age range of participants (18-37) may be lower than the entire age range of the fire/law enforcement/military population. For this test to be applicable to the broader range of employees in these sectors, future research should evaluate a broader range of ages more representative of the employee pool.

PRACTICAL APPLICATIONS

For recreationally active trainees, the maximum number of pull-ups someone can perform shares a strong relationship to how quickly that person can do a single repetition, thus maximum pull-up repetitions can be predicted from the mean concentric velocity of a single repetition. A practitioner may use the MCV of a single repetition as an indirect measure of progress in a population interested in improving maximum pull-up count. The short duration of testing also indicates this test may be warranted as a regular performance monitoring tool for upper body strength and endurance development. Use of this test may provide a useful test of upper body ability in younger (18-37y) employees in the military, fire, and police sectors, as well as for potential workers in these sectors hoping to meet the physical standards necessary to gain employment.

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Tables

Table 1. Three statistical models considered.

Model	Parameterization	AIC	Mean square error in prediction	Average deviation in prediction
Simple linear model	$Y = \beta_0 + \beta_1 X + \varepsilon$	229.53	6.83	2.07
Adjusted model	$Y = \beta_0 + \beta_1 X + \beta_2 Z + \varepsilon$	236.77	7.11	2.14
Multiplicative model	$Y = \beta_0 + \beta_1 X + \beta_2 Z + \beta_3 XZ + \varepsilon$	238.15	8.44	2.21

* The simple linear model was selected as the best predictive model among the three models considered.

Table 2. Parameter estimates, standard errors, and p-values under the three models compared.

Model	Parameter	Estimate	Standard Error	p-value
Simple linear model	β_0	-6.6613	1.0845	< 0.0001
	β_1	25.5560	1.6223	< 0.0001
Adjusted model	β_0	-6.6724	1.1041	< 0.0001
	β_1	25.4729	1.9185	< 0.0001
	β_2	0.0811	0.9717	0.9339
Multiplicative model	β_0	-4.0624	3.1816	0.2082
	β_1	19.3808	7.2232	0.0102
	β_2	-2.8503	3.4889	0.4183
	β_3	6.5570	7.4938	0.3862

Figures

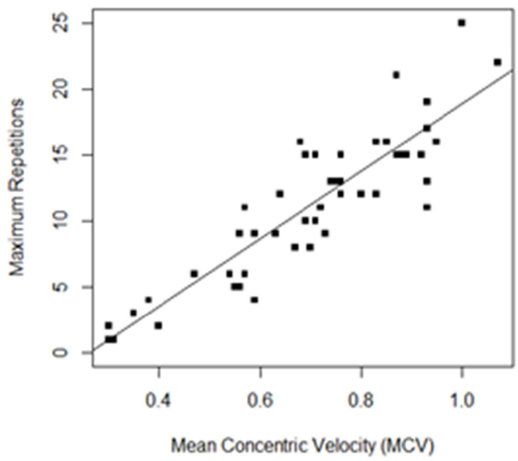

Figure 1. Maximum number of repetitions versus mean concentric velocity. The estimated linear relationship is y = -6.661 + 25.556 x, where x is the MCV and y is the maximum repetitions.

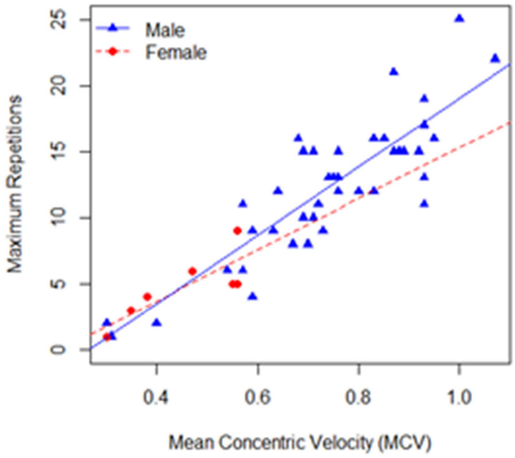

Figure 2. Maximum number of repetitions versus mean concentric velocity by sex (circular dots for female and triangular dots for male). The estimated sex-specific linear relationships are y = -4.062 + 19.381 x for female (dotted) and y = -6.913 + 25.938 x for male (solid), where x is the MCV and y is the maximum repetitions.

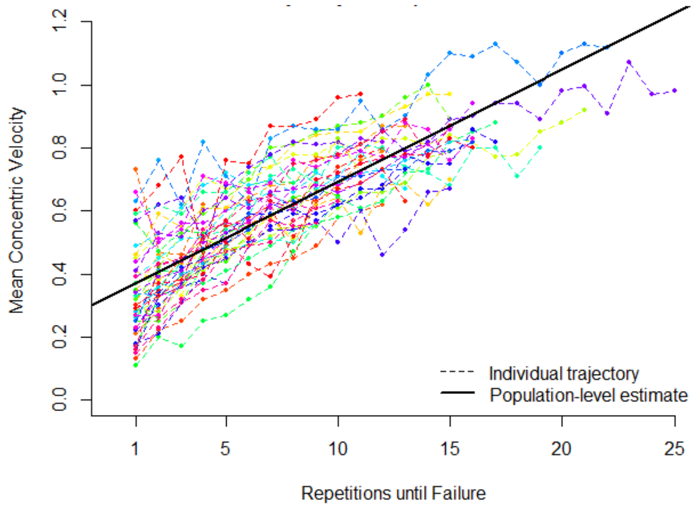

Figure 3: The MCV of each repetition plotted against how close that repetition is to the final repetition (e.g. 5 reps until failure, 4 reps until failure).