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Prediction of One Repetition Maximum Strength From Multiple Repetition Maximum Testing and Anthropometry

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Abstract. Reynolds, J.M., T.J. Gordon, and R.A. Robergs. Prediction of 1 repetition maximum strength from multiple repetition maximum testing and anthropometry. *J. Strength Cond. Res. 20(3):584–592. 2006.*—The purpose of this study was to quantify the decrease in the load lifted from 1 to 5, 10, and 20 repetitions to failure for the flat barbell bench press (chest press; CP) and plate-loaded leg press (LP). Furthermore, we developed prediction equations for 1 repetition maximum (RM) strength from the multiple RM tests, including anthropometric data, gender, age, and resistance training volume. Seventy subjects (34 men, 36 women), 18–69 years of age, completed 1, 5, 10, and 20RM testing for each of the CPs and LPs. Regression analyses of mean data revealed a nonlinear decrease in load with increasing repetition number (CP: linear $S_{y.x}$ = 2.6 kg, nonlinear $S_{y.x}$ = 0.2 kg; LP: linear $S_{y.x}$ = 11.0 kg, nonlinear $S_{y.x}$ = 2.6 kg, respectively). Multiple regression analyses revealed that the 5RM data produced the greatest prediction accuracy, with R^2 data for 5, 10, and 20RM conditions being LP: 0.974, 0.933, 0.915; CP: 0.993, 0.976, and 0.955, respectively. The regression prediction equations for 1RM strength from 5RM data were LP: 1RM = 1.0970 × (5RM weight [kg]) + 14.2546, $S_{y.x}$ = 16.16 kg, R^2 = 0.974; CP: 1RM = 1.1307 × (5RM weight) + 0.6999, $S_{y.x}$ = 2.98 kg, R^2 = 0.993. Dynamic muscular strength (1RM) can be accurately estimated from multiple repetition testing. Data reveal that no more than 10 repetitions should be used in linear equations to estimate 1RM for the LP and CP actions.

Key Words. chest press, leg press, regression, fatigue, training

Introduction

The use of 1 repetition maximum (RM) testing in resistance training has been applied to quantify strength in order to prescribe training programs by health and fitness professionals, athletic trainers, rehabilitation specialists, and strength coaches. Research on 1RM testing began over 50 years ago (9), and the use of 1RM testing has become a reliable method of strength assessment in trained and untrained subjects (1, 4–6, 8, 17–23). However, for some populations, age and preexisting medical conditions may be contraindications to the safe completion of 1RM testing.

Investigators have identified the difficulty in completing 1RM testing on certain populations, and several 1RM strength prediction equations have been developed. However, some of these equations are only for specific exercises, such as the leg extension (1) or bench press (1, 4–9, 11, 15, 18–21, 23–26, 30), while others are only for certain populations, such as college-aged men (8, 21, 22, 24, 30). These equations are all based on having subjects lift the greatest load possible for a predetermined number of repetitions (such as in RM testing), a given load for as many repetitions as possible in a predetermined time frame, or with loads inducing fatigue within a specific range of repetitions. The range of repetitions used in such testing has been between 2 (6, 7) and 15 (21), with linear equations apparent for repetitions less than 10 and nonlinear equations available for repetition numbers up to 15 (19, 21).

Mayhew et al. (21) developed their nonlinear equation using data from multiple subjects who lifted a fixed weight repeatedly, recording as many correct repetitions of the bench press as possible in 1 minute, with a load of 55–95% (selected randomly by computer) of 1RM for each subject. The range of repetitions was based on the between-subject variability and the randomly assigned percentage of 1RM. Conversely, Lombardi (19) proposed a nonlinear equation in his textbook but provided no data, or evidence of data, from which this equation was developed. Consequently, there is no experimental evidence for a nonlinear relationship between the decrease in load lifted and repetition number for any given individual.

In addition to repetition number, other factors may affect the maximum amount of weight an individual can lift. Age, sex, ethnicity, limb lengths and circumferences, body mass, muscle mass, training routine and status, the rate of contractions, and the time distribution between concentric, eccentric, and recovery phases of a contraction cycle could all possibly influence the load able to be lifted for a specific number of repetitions.

Given the limited research of 1RM strength prediction for a variety of weight lifting exercises, and the absence of guidelines for using linear vs. nonlinear equations for 1RM strength prediction, additional research of 1RM prediction is needed. Furthermore, because of the limited number of independent variables used in past regression equations, it is possible that additional variables could improve the accuracy of 1RM strength prediction.

The purpose of this study was to (a) examine the relationship of decreases in the load lifted and increases in repetitions to failure, (b) determine if there are gender differences in the decrease in loads lifted from 1, 5, 10, and 20RM testing, (c) assess which of the loads lifted during 5, 10, and 20RM testing most accurately predicts 1RM strength, and (d) identify if the addition of anthropometry, gender, age, and training history data increases the accuracy of 1RM strength prediction in a large, diverse population.

We chose to study the leg press (LP) and chest press (CP) actions, as these have been included in past research and are common actions included in most resistance training programs.

Methods

Experimental Approach to the Problem

Our stated purpose and hypotheses required multiple types of research design, consisting of analysis of variance (ANOVA) (influence of repetitions to failure [1, 5, 10, 20] on the loads lifted and differences in loads lifted between men and women) and multiple regression (prediction of 1RM strength from multiple RM testing and anthropometry, gender, age, and training history).

Subjects

Seventy subjects (34 men and 36 women; 18–69 years of age) of varied resistance training experience were recruited from the university campus and from the surrounding community. Subjects were recruited using a convenience sampling technique. Prior to the start of the study, subjects completed a health history and resistance and aerobic training questionnaire. In addition, seated resting blood pressure was measured on the nondominant arm using manual sphygmomanometry.

Subjects were excluded based upon known disease or signs or symptoms of health-related problems that would interfere with their ability to complete the protocol or compromise their health, as recommended and detailed by the American College of Sports Medicine (2). For example, if a subject had more than one positive risk factor other than age (men >45, women >55 years; family history, cigarette smoking, hypertension, hypercholesterolemia, impaired fasting glucose, obesity, and sedentary lifestyle), the subject was excluded from participation in the study.

The research protocol was approved by the University Institutional Review Board. All details of the study were explained to each subject on an individual basis prior to reading of the informed consent and subsequent signing to confirm participation in the study. All exercise testing sessions were completed at the university recreational weight room or a community-based health club, both located at an altitude approximating 1,572 m (P_B ~635 mm Hg) and having identical equipment to that used in this research.

Procedures

After successful screening for inclusion and exclusion criteria and signing of the consent forms, subjects arrived for their next appointment at the university weight room or health club. Subjects were informed of the need to not train the muscles (or antagonists) to be assigned testing on a given day for at least 48 hours prior to the scheduled session. Height was measured while the subject was in mid-inspiration and barefoot. Body weight was measured to the nearest 0.1 kg on a precalibrated digital scale (Seca Corporation, Columbia, MD), and subjects were prepared for anthropometric and skinfold measurements. Subjects had the girth of their chest, upper arm, and upper thigh measured. Finally, subjects had 3 skinfold sites measured (chest, abdominal, and thigh for male; triceps, suprailiac, and thigh for women) to predict body density (17). Body density was converted into a population-specific equation (14) to estimate percentage body fat based on a 2-component model, from which data for fat-free mass (FFM) was calculated.

A standard 22-kg (45-lb) barbell and a nonadjustable Cybex weight bench (Cybex International, Inc., Medway, MA) were used for the bench press exercise (chest press, CP). A nonadjustable Cybex plate-loaded squat press (we will refer to this as the plate-loaded leg press) was used for the LP exercise. All equipment was identical in both testing locations.

Two 1-hour testing sessions consisting of 4 maximum resistance bouts were conducted on each subject. During the first testing session, each subject completed a 20RM and a 10RM for the LP and CP. Loads were initially estimated based on researcher experience and feedback from verbal questions pertaining to training history. Subsequent loads were based on the following estimations obtained from a collection of past research (1, 7, 26)—5RM ~80% 1RM, 10RM ~70% 1RM, 20RM ~60% 1RM. Each subject reached muscular failure for each RM, and the last completed weight was recorded for the RM. Partial repetitions (incomplete extension) did not count as an RM. If a subject had to redo a given repetition number for a given condition, as a result of ease in obtaining the desired repetitions or failure to attain the repetition number, a 5-minute rest period was given and the condition was attempted again at an altered load. No subject had to perform a given repetition number test condition more than 3 times. Each subject performed the LP exercise, rested for 5 minutes, and then performed the CP exercise. A total of 10 minutes of rest was given between each set before the subject was asked to repeat the same exercise regimen again for a different RM. The second session consisted of a 5RM and a 1RM for the same 2 exercises, and these loads were again based on their 20 and 10RM loads, based on estimates obtained from past research, as previously explained.

A Timex portable metronome (Timex Corp., Middleburg, CT) was used to standardize the 20RM, 10RM, and 5RM for each subject. The metronome was set at 60 $b \cdot min^{-1}$, and the subject was asked to perform each phase (concentric and eccentric) of the repetition in cadence with the metronome, resulting in a repetition rate of 30 per minute (12, 13). Although such a constrained lifting cycle is atypical, it was required to ensure similarity between subjects and trials for all repetitions. For the CP, subjects had to touch the top of their chest with the barbell for each complete repetition. For the LP, a goniometer was used to ensure that each subject attained a 90° angle during the eccentric phase and attained full extension during the concentric phase. Consequently, failure was defined as the inability to contract to full extension for both the LP and CP exercises. One week separated the first and second sessions. Subjects that were unable to adhere to the guidelines of the first and second test sessions were retested.

Statistical Analyses

All data were entered into spreadsheet software (Excel; Microsoft Corporation, Seattle, WA). For the training questionnaire, responses were coded based on the number of repetitions completed each week for each of the LP and CP exercises. For example, a subject who trained for 5 sessions per week, with 4 sets of 10 repetitions for the LP and 3 sets of 8 repetitions for the CP, scored 200 and 120 for LP and CP, respectively. We did not include the loads lifted during training within training volume, as this aspect of strength was provided by the RM data with the multiple regression analyses. As such, training volume then became a unique variable with minimal theoretical co-linearity to strength.

The spreadsheet data were imported into a statistical software program (Statistica; StatSoft, Tulsa, OK) as well as a curve-fitting program (Prism; Graphpad Software, San Diego, CA) for subsequent analyses.

Mixed-design ANOVA (2 [gender] × 2 [action] × 4 [RM condition]) was used to determine if there were gender differences in the change in strength across RM conditions and for a significant interaction between CP and LP. When interactions were significant, simple main effects analyses were completed, followed by Tukey's tests to assess specific mean differences.

The linear or nonlinear profile of strength and RM condition for each action was assessed using linear and nonlinear (mono- and 2-function exponential decay) curve fitting. The strength of the correlations (linear and nonlinear) was quantified by the correlation coefficient (r), explained variance (r^2), and standard error of estimate ($S_{y.x}$).

Multiple regression analyses were used to explain the variance in the predicted 1RM, using the independent variables of gender, age, height, weight, lean body mass, body fat percentage, arm girth, chest girth, thigh girth, and the 5RM, 10RM, and 20RM for the specific action. Stepwise regression was performed because of the lack of prior research that has evaluated the additional independent variables used in this study. The same procedures were used for 1RM prediction equations based on 10 and 20RM data. Normality of the residuals was assessed through raw residual plots for each of the independent variables using the action-specific 1RM data as the dependent variable.

Linear regression was used to determine correlations and resulting residuals from measured and predicted 1RM strength for the cross-validation group using the equations from this study. The same procedures were used to assess the accuracy of predicted 1RM strength using previously published 1RM prediction equations.

The subject number (70) was determined to be appropriate using a priori power estimates based on the recommendation of at least 10 subjects per independent variable (IV) when conducting biomedical or physiological research involving human subjects. As we anticipated approximately 5 IVs for each equation, this required us to have at least 50 subjects. We continued subject recruitment through 70 subjects to gain further improvements in statistical power in multiple regression research. The use of an additional cross-validation group further increased the meaningfulness of our findings. Such a large sample size provided excellent statistical power for ANOVA-based statistical procedures, providing a power of 0.9 for mean differences of 59 and 18 kg for the LP and CP, respectively (1-tailed t-test at $p \leq 0.05$). In reality, statistical power was far greater for all ANOVA analyses (ability to detect a smaller mean difference as significant) as a result of the repeated-measures nature of the research design.

The cross validation of the prediction equations was accomplished using 20 additional subjects for the 5RM condition for LP and CP. Statistical significance was accepted at $p \leq 0.05$. All mean data (text, tables, and figures) are presented as mean ± standard deviation (SD).

TABLE 1. Descriptive characteristics of the subjects (mean ± SD).*

Variable	Total (N = 70)	Men (N = 34)	Women (N = 36)
Age (y)	30.6 ± 11.2	30 ± 11	31 ± 11
Height (cm)	173.3 ± 9.4	180.7 ± 5.9	166.3 ± 6.1
Weight (kg)	73.8 ± 16.7	85.0 ± 15.2	63.4 ± 9.9
FFM (kg)	60.4 ± 14.2	72.82 ± 8.82	48.87 ± 6.18
%BF	18.0 ± 8.0	13.2 ± 7.3	22.6 ± 5.6
Arm girth (cm)	32.2 ± 5.3	35.7 ± 4.9	28.9 ± 3.2
Chest girth (cm)	98.5 ± 11.5	106.2 ± 10.5	91.3 ± 6.7
Thigh girth (cm)	55.0 ± 6.1	57.1 ± 6.5	53.1 ± 4.9
1RM LP/FFM	4.3 ± 1.1	4.45 ± 1.20	4.18 ± 1.93
1RM CP/FFM	1.1 ± 0.6	1.30 ± 0.37	0.84 ± 0.19
1RM LP (kg)	264.1 ± 101.4	719 ± 224	450 ± 112
1RM CP (kg)	67.0 ± 34.5	209 ± 64	90 ± 22

* FFM = fat-free mass; %BF = % body fat; 1RM = 1 repetition maximum; LP = leg press; CP = chest press.

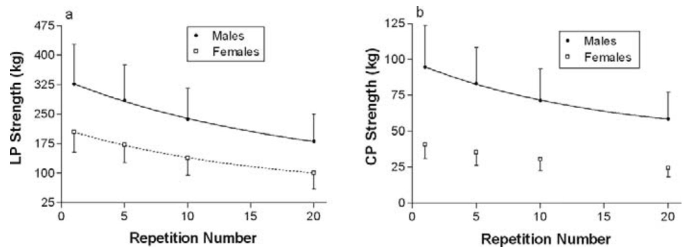

FIGURE 1. Three-way interaction (gender × repetitions to failure [RM] × action) for strength. (a) Women decreased less in chest press (CP) strength than men across RM conditions. (b) Women also decreased less in leg press (LP) strength than men. However, compared to CP strength, there were larger decrements across LP RM conditions for both men and women. All means are significantly different from each other.

RESULTS

Subjects

The physical characteristics of the participants (N = 70) are presented in Table 1. As evidenced by the range of data, the sample was heterogeneous. The average participant was a resistance trained individual, participating in their own weight-training program 1–3 days per week. The subjects comprised 34 men and 36 women, and training status consisted of 16 untrained, 37 circuit weight-trained, and 17 volume-trained (split body, >4 days per week). Each of the 5RM LP and CP data residuals (compared to 1RM data) were normally distributed based on plots of raw residuals superimposed to the normal curve.

Interactions Between Gender, RM, and Action

The mixed-design 3-way ANOVA revealed significant 2-way (gender × RM, gender × action, action × RM) and 3-way (gender × RM × action) interactions (all $p < 0.0001$) (Figure 1a,b). Obviously, LP strength was greater than CP across all RM values, and for both genders. Men were stronger than women, and this was more often the case for CP than for LP. In addition, both men and women exhibited a larger decrement in strength with increasing RM for the LP than for the CP. The decrement in strength across RM values was less for women than men for both actions.

To assess whether these gender and RM differences resulted from the 1RM strength differences between genders and actions, we also completed 2 analysis of covariance (ANCOVA) analyses (for LP and CP) using the action-specific 1RM data as the covariate. For both LP and CP, the ANCOVA did not alter the significance for any

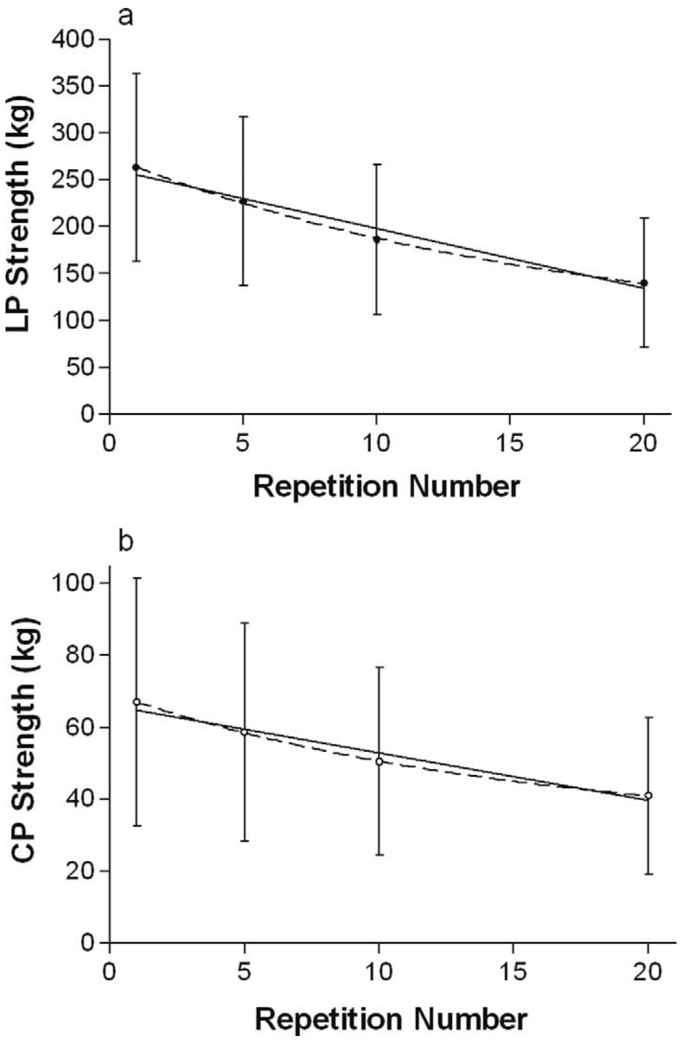

FIGURE 2. The mean strength data of all subjects ($n = 70$) presented with linear (solid line) and nonlinear (dotted line) regression lines. (a) Leg press (LP) data. (b) Chest press (CP) data.

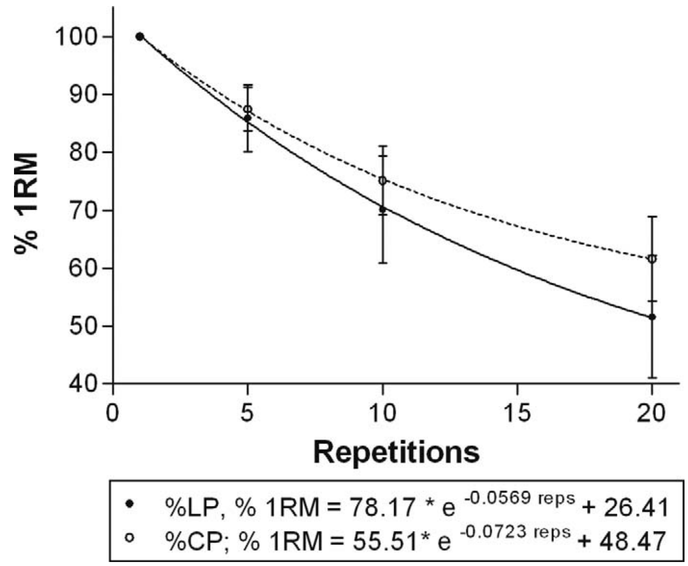

FIGURE 3. The mean relative strength data of the subjects of the combined regression and cross-validation groups ($n = 90$) for leg press (LP) and chest press (CP) data. The equations provided can be used, when the 1 repetition maximum (1RM) is known, to estimate the %1RM load based on any number of repetitions.

main effect or interaction from the ANOVA analyses, indicating that the absolute 1RM strength differences between genders did not contribute to gender differences in the magnitude of load decrement across RM values.

Linearity vs. Nonlinearity of the RM Data

The gender-combined data sets for LP and CP mean data were best fit by a nonlinear model (Figure 2), with $S_{y.x}$ criterion for assessing goodness of fit being LP: linear $S_{y.x} = 11.2$, nonlinear $S_{y.x} = 2.4$ kg ($p = 0.014$); CP: linear $S_{y.x} = 2.6$, nonlinear $S_{y.x} = 0.2$ kg ($p = 0.018$).

When the data were expressed as relative decrements from the 1RM (Figure 3), the nonlinear change in load is also seen, and the mean values for each %RM condition were LP of 85.91, 70.10, and 51.58% for the 5, 10, and 20RM, respectively. For CP, the values were 87.45, 75.65, and 61.61%, respectively. See Figure 3 for the specific equations for estimating loads to be used for a given number of repetitions based on the %1RM.

Univariate Regression Analyses

Chest Press and Leg Press. The univariate correlations that existed between the maximum repetition ranges and maximum strength for LP and CP are presented in Table 2. High correlations existed between all strength measures, yet there was a consistent decrease in correlation to 1RM as the RM increased for both CP and LP. Training volume had low correlations to 1RM for both LP and CP.

TABLE 2. Correlation matrix for leg press (LP) and chest press (CP) strength and pertinent variables ($N = 70$).*

Variable	20RM	10RM	5RM	1RM
LP				
Training	0.22	0.21	0.21	0.23
20RM	1.00	0.98	0.97	0.96
10RM		1.00	0.99	0.97
5RM			1.00	0.99
1RM				1.00
Gender	0.59	0.62	0.63	0.61
Age (y)	−0.40	−0.33	−0.33	−0.34
Height (cm)	0.47	0.49	0.48	0.47
Weight (cm)	0.59	0.63	0.61	0.58
LBM (kg)	0.71	0.75	0.74	0.71
Thigh girth (cm)	0.54	0.59	0.60	0.59
CP				
Training	0.13	0.13	0.12	0.13
20RM	1.00	0.99	0.99	0.98
10RM		1.00	0.99	0.99
5RM			1.00	1.00
1RM				1.00
Gender	0.78	0.79	0.79	0.79
Age (y)	−0.38	−0.38	−0.35	−0.35
Height (cm)	0.55	0.57	0.58	0.59
Weight (kg)	0.51	0.53	0.54	0.56
LBM (kg)	0.73	0.74	0.76	0.77
Arm girth (cm)	0.61	0.62	0.65	0.66
Chest girth (cm)	0.56	0.57	0.59	0.60

* RM = Repetition maximum; LBM = lean body mass.

Anthropometric Variables. The univariate correlations that existed between anthropometric variables and max-

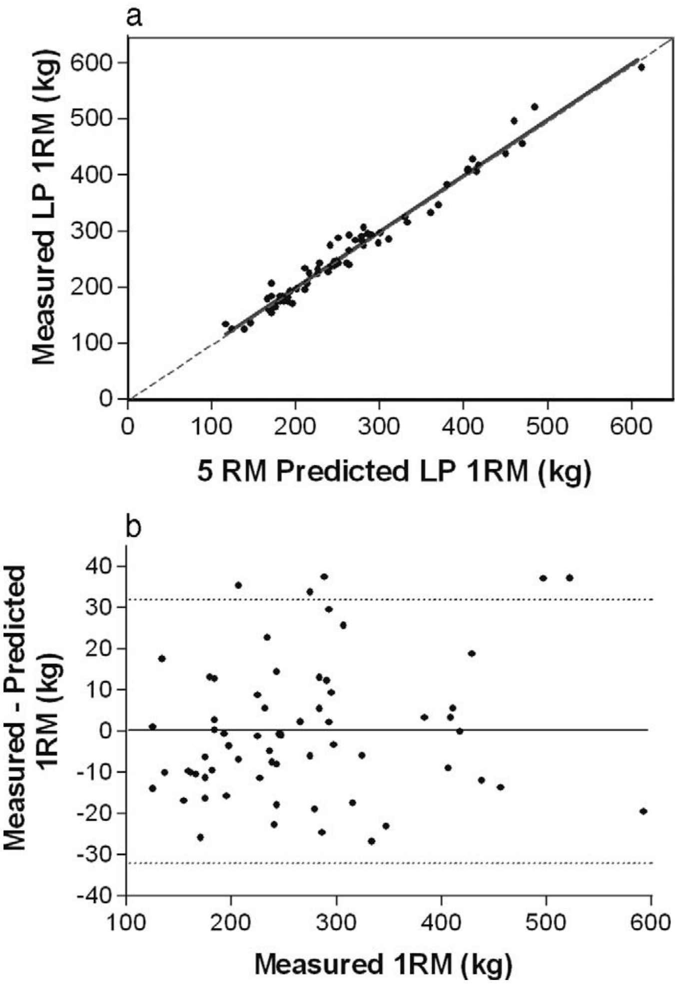

FIGURE 4. (a) Predicted vs. measured 1 repetition maximum (1RM) leg press (LP) strength. (b) The residuals resulting from the prediction of 1RM LP strength from 5RM LP strength data. The solid line represents the mean residuals (0.01 kg), and the dotted lines represent ±2 standard deviations (*SD*) (±32.08 kg).

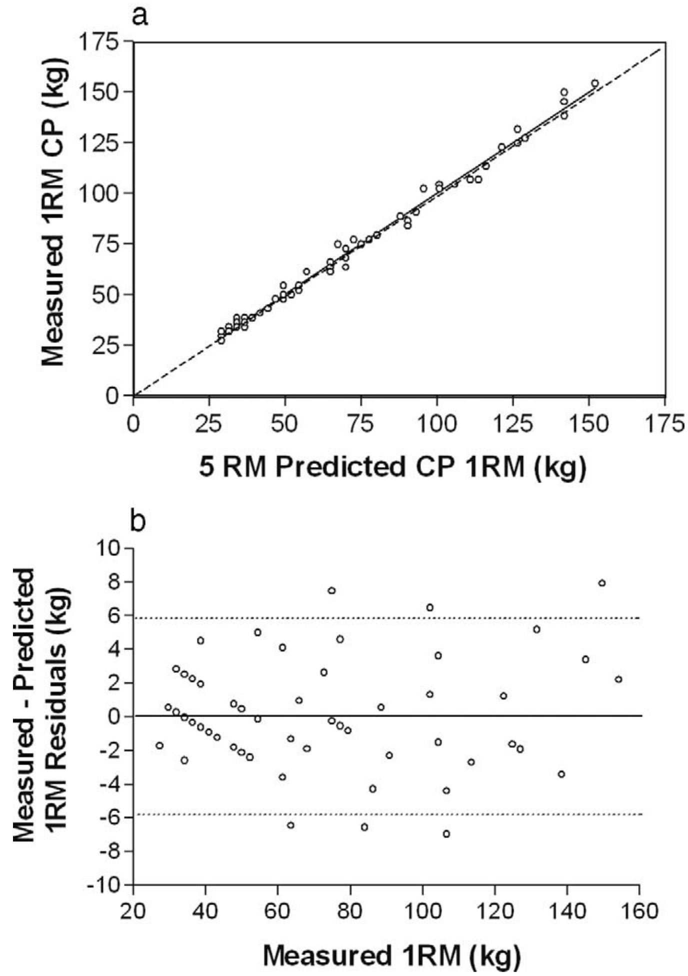

FIGURE 5. (a) Predicted vs. measured 1 repetition maximum (1RM) chest press (CP) strength. (b) The residuals resulting from the prediction of 1RM CP strength from 5RM CP strength data. The solid line represents the mean residuals (0.00 kg), and the dotted lines represent ±2 standard deviations (*SD*) (±5.92 kg).

imum strength for LP and CP are also presented in Table 2. 1RM strength decreased with increasing age and was moderately correlated with each of the remaining variables. As expected, FFM had the highest correlation to 1RM for LP, whereas gender and FFM revealed similar high correlations for the CP. Arm girth was more highly correlated to all RM strength scores than thigh girth was to LP RM strength scores.

Multiple Regression Analyses

Leg Press. Forward stepwise multiple regression analysis resulted in only one significant variable (5RM) entering into a prediction equation. We also performed the multiple regression analyses using each of the 10 and 20RM variables. These results produced the following equations and results: 5RM: 1.09703 (5RM) + 14.2546, R^2 = 0.974, $S_{y.x}$ = 16.16 kg; 10RM: 1.2091 (10RM) + 38.0908, R^2 = 0.933, $S_{y.x}$ = 26.13 kg; 20RM: 1.3870 (20RM) + 69.2494, R^2 = 0.915, $S_{y.x}$ = 29.41. Compared to the 5RM prediction, the error (based on $S_{y.x}$) associated with using each of the 10 and 20RM equations is considerably large. Figure 4a presents the relationship between measured and predicted 1RM LP strength (using 5RM), and Figure 4b presents the distribution of residuals resulting from the prediction.

Chest Press. Forward stepwise multiple regression analysis resulted in one significant variable (5RM) entering into a prediction equation. We also performed the multiple regression analyses using each of the 10 and 20RM variables. These results produced the following equations and results: 5RM: 1.1307 (5RM) + 0.6998, R^2 = 0.993, $S_{y.x}$ = 2.98 kg; 10RM: 1.2321 (10RM) + 0.1752 (FFM) − 5.7443, R^2 = 0.976, $S_{y.x}$ = 5.38 kg; 20RM: 1.5471 (20RM) + 3.834, R^2 = 0.955, $S_{y.x}$ = 7.36. As for the LP, CP 1RM prediction error increased with increasing repetition numbers, but to a lesser extent. Figure 5a presents the relationship between measured and predicted 1RM CP strength (using 5RM), and Figure 5b presents the distribution of residuals resulting from the prediction.

Cross-Validation Group. Prediction equations have an inflated accuracy when based solely on the data from which the equations were derived. To reveal a more realistic error of prediction, cross-validation groups are recommended. We recruited an additional 20 subjects to create a cross-validation group, and we took care to provide a range of pertinent strength and demographic charac-

TABLE 3. Descriptive characteristics of the subjects in the cross-validation group (n = 20).*

Variable	Mean ± *SD*	Range
Age (y)	12.8 ± 12.8	20–53
Height (cm)	175.3 ± 10.5	163.5–195.1
Weight (kg)	17.4 ± 17.4	53.5–107.1
LBM (kg)	14.9 ± 14.9	44.1–83.0
%BF	8.5 ± 8.5	5.6–37.4
Arm girth (cm)	5.1 ± 5.1	26.6–45.7
Chest girth (cm)	11.6 ± 11.6	82.7–116.3
Thigh girth (cm)	8.7 ± 8.7	36.0–69.3
1RM LP/LBM	302.7 ± 1.5	2.0–7.5
1RM CP/LBM	4.1 ± 0.4	0.6–1.8
1RM LP (kg)	255.4 ± 118.7	133.9–469.6
1RM CP (kg)	63.2 ± 36.7	29.5–142.9

* LBM = lean body mass; %BF = % body fat; 1RM = 1 repetition maximum; LP = leg press; CP = chest press.

TABLE 4. Summary of the regression analyses for 1 repetition maximum (1RM) leg press (LP) and 1RM chest press (CP) using the cross-validation data set.*

	R	R^2	$S_{y.x}$	Residuals
LP				
5RM equation	0.994	0.988	13.51	−0.47 ± 13.26
10RM equation	0.981	0.962	23.79	−2.36 ± 24.65
20RM equation	0.962	0.926	33.08	−4.33 ± 33.80
CP				
5RM equation	0.999	0.998	1.80	−0.52 ± 1.75
10RM equation	0.995	0.991	3.64	−1.34 ± 3.80
20RM equation	0.992	0.984	4.82	−2.63 ± 5.13

* Residuals (kg) = measured − predicted.

teristics that represented our initial subject population. The descriptive characteristics of the cross-validation group are presented in Table 3.

Use of the LP and CP prediction equations revealed slightly decreased prediction error compared to the original (n = 70) data set, with the results for both LP and CP presented in Table 4. Figure 6a presents the relationship between measured and predicted 1RM LP strength using 5RM data, and Figure 6b presents the distribution of residuals resulting from the prediction. Similarly, Figure 7a presents the relationship between measured and predicted 1RM CP strength using 5RM data, and Figure 7b presents the distribution of residuals resulting from the prediction.

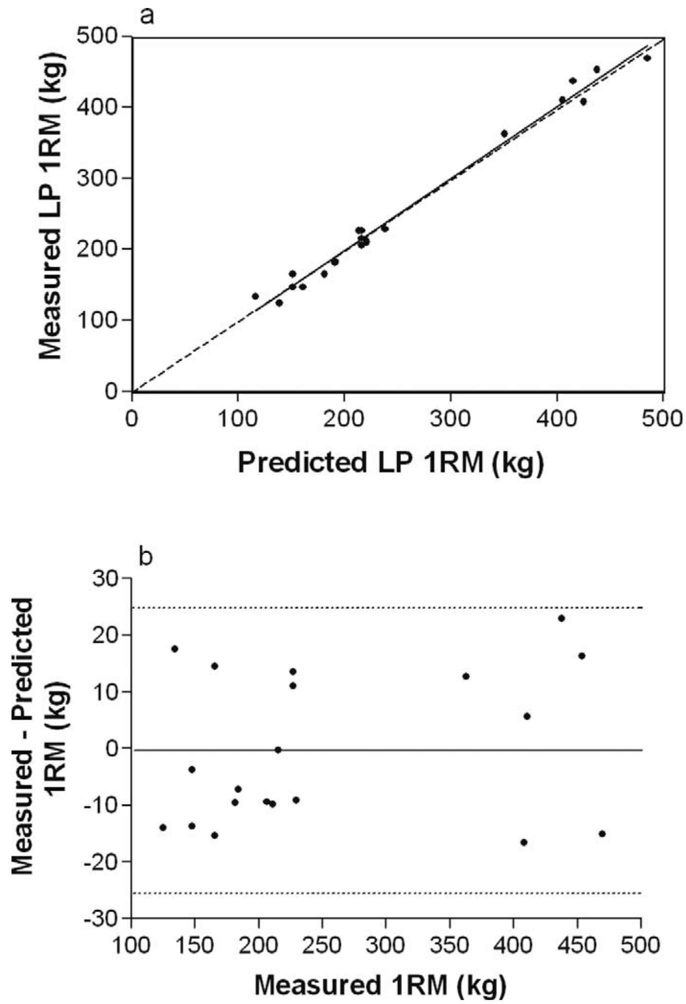

FIGURE 6. Data from the cross-validation group (n = 20). (a) Predicted vs. measured 1 repetition maximum (1RM) leg press (LP) strength. (b) The residuals of the predicted (from the 5RM equation) and measured 1RM LP strength. The solid line represents the mean residuals (−0.47 kg), and the dotted lines represent ±2 standard deviations (*SD*) (±26.52 kg).

Comparison to Other Prediction Equations

In order to compare the prediction accuracy of our equations to past research, we compared our prediction equations to 6 different linear prediction equations and 2 nonlinear prediction equations for our cross-validation data set. The equations and resulting goodness-of-fit criteria are presented in Table 5.

Our equation was evaluated at the 5 and 10RM values for both LP and CP as a result of the nonspecific nature of the RM condition for many of the other prediction equations. For previously published equations, the authors' recommendations were strictly followed, and RM values were used that applied to these alternate equations.

All of the linear prediction equations using the 5RM data functioned with similar accuracy for the LP and CP. However, our equations, and those of Abadie (1) and Epley (11), had the smallest mean residuals, with only a slight trend for overestimation. The equations of Brzycki (7), Lander (18), and O'Connor (26) all underestimated LP strength. All equations were less accurate when the 10RM rather than 5RM data was used. The nonlinear equations of Lombardi (19) and Mayhew (21) were less accurate than all linear equations.

Test–Retest Reliability

Twenty additional subjects were used for the test–retest reliability. These subjects were also of varied training status and of identical gender distribution, but they were younger, ranging from 19 to 42 years of age. Data collection occurred in a manner identical to that of prior descriptions, but testing was only done on the 5RM condition. The intraclass correlation coefficient was computed as the correlation between repeated test scores (Statistica), and such test–retest correlations for the LP and CP were 0.999 and 0.999, respectively. The proportion of subjects that scored the identical load for LP and CP were 65 and 60%, respectively, with ranges of residuals being

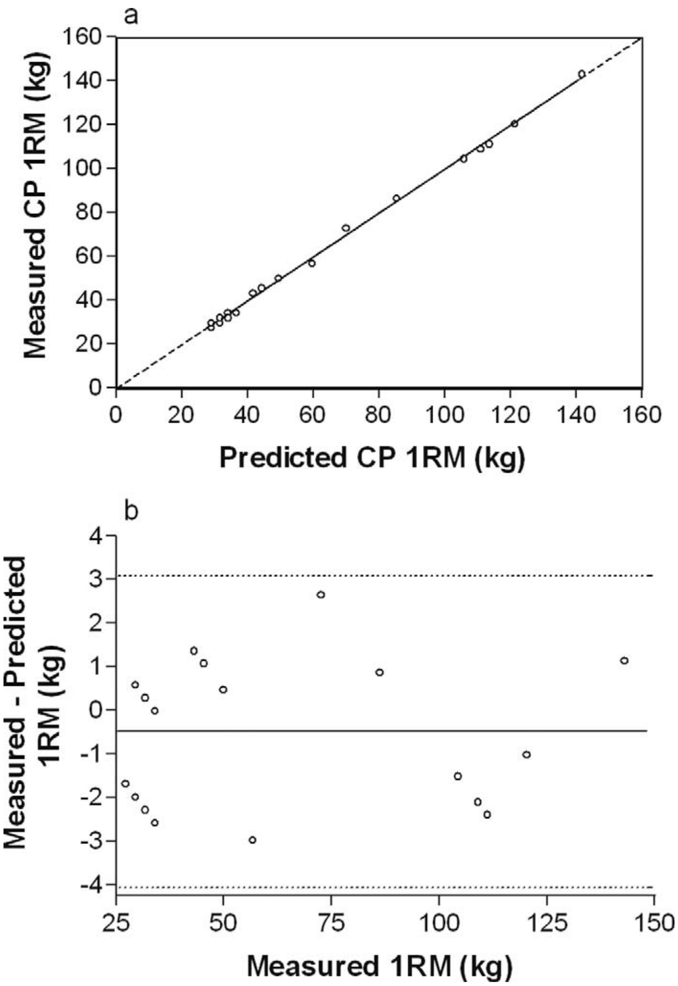

Figure 7. Data from the cross-validation group (n = 20). (a) Predicted vs. measured 1 repetition maximum (1RM) chest press (CP) strength. (b) The residuals of the predicted (from the 5RM equation) and measured 1RM CP strength. The solid line represents the mean residuals (−0.52 kg), and the dotted lines represent ±2 standard deviations (SD) (±3.54 kg).

5 to 10 and 2 to 5 kg, respectively. The mean errors for the LP and CP were both ±0.5%.

Discussion

We reported a nonlinear relationship between strength and increasing repetitions to failure for both LP and CP. Women were less strong than men, and they were more so for CP than for LP exercises. For both LP and CP, the most accurate prediction of strength occurred from a 5RM test, with the accuracy of prediction worsening with increasing repetitions to failure. Addition of anthropometric, gender, and training volume variables to the prediction equations did not significantly improve the accuracy of prediction.

Our data clearly reveal the trend for a nonlinear decrease in strength with increasing repetitions to failure. Surprisingly, we have been the first to document such a trend. However, Mayhew et al. (21) reported a nonlinear equation to estimate 1RM for the bench press from the number of repetitions performed in 1 minute. Lombardi (19) published a book with a nonlinear equation with application to all weight-training actions, but there was no citation to published research.

These findings have application to both the prediction of 1RM and the designation of weight to lift for a given number of repetitions. We illustrated the latter concept in Figure 3 and provided prediction equations based on this relative (%RM) data. For example, if the 1RM and number of training repetitions are known, the load to be lifted can be calculated using the action-specific prediction equations. For example, for a LP 1RM of 300 kg, the load to be lifted for sets of 10 repetitions is calculated to be 212 kg. For a CP 1RM of 150 kg, the load to be lifted for sets of 10 repetitions is calculated to be 113 kg. For comparison, the table of Landers et al. (18) yields a LP load of 225 kg and a CP load of 112 kg. The equation of Mayhew et al. (21) for CP load estimation yields a load of 115 kg. Interestingly, our CP equation produces similar results to the studies of Landers et al. and Mayhew et al., but our LP equation produces meaningfully different data. The only other research study on this topic was that of Abadie et al. (1). However, these authors solely presented 1RM prediction equations and did not reassess their data to evaluate %RM loads.

Research of RM strength testing has mainly focused on the need to predict the 1RM (1, 4, 6–9, 18, 20–23, 25, 29, 30). Our results revealed acceptable prediction accuracy for 1RM for each of the LP and CP. For example, our regression predictions for the LP and CP resulted in similar prediction accuracy for the original 70 subjects, as well as for the 20 subjects used in the cross-validation group. This consistency reaffirms the accuracy of our equations. We have been the only investigators to use a cross-validation group, which we also used to cross-validate all prior prediction equations (Table 5). The data from Table 5 reveals that our equation and that of Abadie et al. (1) are the most accurate for LP. Conversely, our equation and those of Bryzcki (7) and O'Connor et al. (26) are the most accurate for the CP.

The inability of anthropometric variables, as well as gender and training volume, to improve the prediction accuracy of LP and CP 1RM was unexpected. These findings indicate that each of these variables is either unrelated to 1RM strength (e.g., training volume) or is so interrelated to strength (gender and all anthropometric variables) that the 5RM data sufficiently accounts for its contribution to the explanation of between-subject variance in 1RM strength. This is fortunate from the perspective of the strength coach or personal trainer, who can be assured that accurate 1RM strength prediction is as simple as applying a known 5RM strength value to a simple equation or to charts derived from these equations. If loads to be used are required to be lower in testing, then prediction can still occur using our 10 and 20RM test equations.

Rest periods between sets determine how quickly an individual will recover from the previous bout of exercise. Although we did not experimentally assess differences in the rest interval, the variable duration of the rest interval used by investigators warrants comment on this topic. In this study, 5-minute rest periods were used for the LP and CP exercises. Furthermore, a warm up period of 5 minutes was used to transition subjects from the CP action to the LP action. In prior research, there have been varying practices for these rest periods. Some investigators employed a 2-minute rest period (1, 5), others utilized

TABLE 5. Linear and nonlinear 1 repetition maximum (1RM) prediction equations, with data from regression analyses using the cross-validation data set.*

Author	Prediction equation	R^2	$S_{y.x}$
Linear			
Reynolds (N = 70)	Varied subject population 1RM LP = (1.09703 × [5RM, kg]) + 14.2546 1RM CP = (1.1307 × [5RM, kg]) + 0.6998		
5RM LP		0.988	13.23
10RM LP		0.962	21.64
5RM CP		0.998	1.78
10RM CP		0.991	3.49
Abadie (1) (N = 30)	Women, college aged 1RM = 7.24 + (1.05 × weight lifted)		
5RM LP		0.988	13.74
10RM LP		0.962	20.41
5RM CP		0.998	1.67
10RM CP		0.990	3.00
Bryzcki (7) (N = ?)	Population unknown 1RM = (Weight lifted/(1.0278 − [0.0278 × No. of reps])		
5RM LP		0.988	13.56
5RM CP		0.998	1.79
Epley (11) (N = ?)	Population unknown %1RM = ([0.033 × reps] × rep wt.) + rep wt.		
5RM LP		0.988	14.05
5RM CP		0.998	1.85
Lander (18) (N = ?)	Population unknown %1RM = 101.3 − (2.67123 × reps)		
5RM LP		0.988	13.71
10RM LP		0.962	24.00
5RM CP		0.998	1.81
10RM CP		0.990	3.84
O'Connor (26) (N = ?)	Population unknown %1RM = (0.025 × [rep wt. × reps]) + rep wt.		
5RM LP		0.988	13.56
10RM LP		0.962	22.37
5RM CP		0.998	1.79
10RM CP		0.990	3.58
Nonlinear			
Lombardi (19) (N = ?)	Population unknown 1RM = (No. of reps$^{0.1}$) × (weight lifted)		
5RM LP		0.988	14.16
10RM LP		0.962	22.54
5RM CP		0.998	1.87
10RM CP		0.990	3.60
Mayhew (21) (N = 434)	185 college men; 251 college women %1RM = 52.2 + 41.9$e^{-0.055 \times reps}$		
5RM LP		0.988	14.35
10RM LP		0.962	23.44
5RM CP		0.998	1.89
10RM CP		0.990	3.75

* LP = leg press; CP = chest press. Guidelines for authors' equations: Bryzcki and Epley = <10 reps; Abadie = 5–10 reps; Lombardi = <11 reps; Mayhew et al. = <15 reps; Lander and O'Connor = not specified.

a 5-minute rest period (9), and still others have used a variable 1–3- or 3–5-minute rest period (21, 23, 24).

Rest periods of less than 5 minutes are likely to be too short. Muscle creatine phosphate recovery reveals a dual exponential curve having a fast and slow component (3, 27). The fast component of creatine phosphate recovery is complete within less than 2 minutes and represents 80–90% of complete creatine phosphate recovery (3, 27). Additionally, the slow component may require up to 45–90 more seconds after the fast component (3, 27). Both components of creatine phosphate recovery are slowed with increasing acidosis (3). We would encourage other investigators, as well as strength coaches and trainers, to adhere to the 5-minute rest interval between sets in RM testing.

Based on the results in this study, the following conclusions were drawn: (a) 1RM strength, compared to a multiple repetition maximum load, is a nonlinear relationship, in which the magnitude of the decline in load becomes smaller with increasing repetitions used in RM testing; (b) Women are less strong than men, and this is more often the case for the CP than for the LP exercises; (c) Of the 5, 10, and 20RM, the best repetition maximum range to use for prediction of 1RM strength in the LP and CP exercises is the 5RM; (d) In order to increase accuracy, prediction equations must be exercise specific; (e) The most accurate equations to predict 1RM strength for the LP are ours and those of Abadie et al. (1). The most accurate equations to predict 1RM strength for the CP are ours and those of Bryzcki (7) and O'Connor et al. (26); and (f) Our data can also be used to predict the load needed for efforts to failure for specific repetition conditions for LP and CP.

Practical Applications

It is important that practitioners use prediction equations for specific actions. We used the free-weight barbell bench press for the CP action and the Cybex plate-loaded leg press for the LP action. As the CP action used free weights, the range of contraction and rate or contraction variables are all that are required for correct application of the prediction equations. However, there are different types of LP equipment in weight rooms, and we discourage any application of our equations to multiple RM testing for prediction of 1RM on equipment other than the Cybex plate-loaded LP, or when contraction or rest durations that differ from 1-second concentric, 1-second eccentric pattern are used.

When assessing 5RM prediction of 1RM, care should be given to the quality of repetitions during the 5RM. For example, based on our equations, a ±5-kg error in 5RM load calculates to a 1RM prediction error of 19.7 kg for the LP and 6.3 kg for the CP. Clearly the 5RM test needs to be conducted with strict attention to methodological detail. Once the 1RM is known (whether measured or predicted), our equations can be used to estimate the load needed for sets to failure for a specific repetition number.

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