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Accuracy of Seven Equations for Predicting 1-RM Performance of Apparently Healthy, Sedentary Older Adults

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This study compared the relative accuracy, similarity, and average error of 7 prediction equations (Brzycki, 1993; Epley, 1985; Lander, 1985; Lombardi, 1989; Mayhew, Ball, Arnold, & Bowen, 1992; O'Connor, Simmons, & O'Shea, 1989; Wathen, 1994) for estimating 1-repetition maximum (1-RM) performance of older sedentary adults using Hammer Strength Iso-Lateral resistance exercise machines. Data were collected from 49 apparently healthy volunteers (26 males, 23 females) aged 53.55 ± 3.34 (mean ± SD) years. 1-RM scores were obtained for biceps curl, chest press, high latissimus dorsi (lat) pull, incline chest press, leg curl, leg extension, low lat pull, leg press, shoulder press, and triceps extension. Repetitions to fatigue (RTF) for each exercise were determined by assigning each subject a percentage of his or her 1-RM ranging from 50% to 90%. Subjects performed as many repetitions as possible with the predetermined resistance. Predicted 1-RM (1-RMP) was evaluated by relative accuracy (correlation between 1-RM and 1-RMP), similarity (paired *t*-test between 1-RM and 1-RMP), and average error ($\text{sqrt}[\Sigma(1RMP - 1RM)^2/(n - 1)]$). Relative accuracy, similarity, and average error improved significantly and gender differences were minimal when RTF ≤ 10. Accuracy of prediction equations varied over different resistance exercises. The Mayhew, Ball, Arnold et al. (1992), Epley (1985), and Wathen (1994) formulas evidenced the lowest average error (AE) and highest relative accuracy over the resistance exercises examined; however, both absolute AE and AE expressed as a percent of mean 1-RM were quite high for all formulas over all exercises.

Key words: one-repetition maximum, prediction, resistance training

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Progressive declines in muscular strength, lean muscle mass, and bone mass are predictable consequences of aging; however, strong evidence exists that age-related declines in muscular strength and lean mass (Feigenbaum & Pollock, 1999) and bone mass (Layne & Nelson, 1999) can be impeded following periods of mechanical stress resulting from resistance training. In response to recommendations by the American College of Sports Medicine regarding the importance of resistance training (Kenney, 1995), health professionals are more frequently prescribing resistance training programs for older adults as an important component of an overall wellness and fitness program. Moreover, resistance training is included among the types of physical activity recommended by the World Health Organization's 1996 *Guidelines for Promoting Physical Activity Among Older Persons* (Chodzko-Zajko, 1997).

Resistance training can be beneficial for older adults who are a rapidly increasing segment of the American population; however, when prescribing a weight-training program for novices, how does an exercise specialist determine an ideal starting point for this population? Typically, a percentage (40% to 80%) of a one-repetition maximum (1-RM) is prescribed for each exercise (Stone, O'Bryant, & Garhammer, 1981). Because the guidelines set forth for older adults by the American College of Sports Medicine suggest moderate intensities for older adults, it is questionable whether it is safe to subject an untrained older adult to a 1-RM to determine maximal strength. Moreover, accurate determination of 1-RM requires "great concentration and entails considerable mental preparation by the lifter. Novice lifters may find this technique difficult because of an unaccustomed insecurity of handling heavy loads, inadequate spotting assistance, and fear of failure" (Mayhew et al., 1995, p. 108).

Numerous 1-RM prediction equations using repetitions to fatigue (RTF; Table 1) with submaximal weight have been developed and tested with high school-age, college-age, and middle-age active males and females. Researchers examining the utility and accuracy of these equations have focused almost exclusively on the use of free weights in the performance of two specific exercises, bench press and squat, although the applicability of four of these equations (e.g., Lander, 1985; Lombardi, 1989; O'Connor, Simmons, & O'Shea, 1989; Wathen, 1994) to other resistance exercises was not limited by the originators.

The accuracy of these equations has not been tested in older populations or over the wide range of weight–machine resistance exercises typically prescribed for older adults. Because accurate prediction of 1-RM strength is a critical component of a well-designed exercise program (Wathen, 1994), it would be beneficial for exercise specialists responsible for determining the proper prescription for weight lifting exercises if a 1-RM prediction equation could be identified that accurately predicts maximal strength based on submaximal weight and RTF over a wide range of exercises.

TABLE 1
Seven Equations for Predicting 1-RM

Author	*Equation*
Brzycki (1993)	$1RMP = \frac{W}{1.0278 - .0278 \cdot R}$
Epley (1985)	$1RMP = (0.33 \cdot R) \cdot W + W$
Lander (1985)	$1RMP = \frac{W}{1.013 - .0267123 \cdot R}$
Lombardi (1989)	$1RMP = (R^{0.1}) \cdot W$
Mayhew, Ball, Arnold, et al., (1992)	$1RMP = \frac{W}{(52.2 + 41.9e^{-0.55 \cdot R})/100}$
O'Connor et al. (1989)	$1RMP = (.025 \cdot R \cdot W) + W$
Wathen (1994)	$1RMP = \frac{W}{(48.8 + 53.8e^{-0.075 \cdot R})/100}$

Notes. R = number of repetitions; W = submaximal weight lifted per repetition.

Estimating maximal physical performance from a submaximal test is not a new concept. For example, Åstrand and Rhyming (1954) and Mahar, Jackson, and Ross (1985) used submaximal performance on a bicycle ergometer to predict maximal oxygen consumption. More recently, Plowman and Liu (1999) investigated the validity of the 1-Mile Run and progressive aerobic cardiovascular endurance run tests as predictors of VO_2 max for college-aged individuals. Validating the utility of submaximal tests as predictors of maximal performance involves examining the accuracy of prediction equations for specific populations, settings, and purposes.

Over the past 3 decades, interest in the prediction of 1-RM performance from a submaximal test has resulted in the formulation of several prediction equations that are presented in Table 1. These equations employ a relative endurance model based on a strong linear relation between the number of repetitions that can be completed and the percentage of 1-RM when the 1-RM percent is greater than 75% for the weight lifted (Sale & MacDougall, 1981). When percent of 1-RM is smaller than 75%, the relation becomes exponential in form. The method involves lifting a load lighter than 1-RM until exhaustion. The amount of weight lifted per each repetition of an exercise and the number of RTF are used to predict 1-RM. All the prediction equations presented in Table 1 are linear, with the exception of the Mayhew, Wathen, and Lombardi formulas, which are exponential.

Despite the popularity of these 1-RM prediction formulas, the developmental research that underpins many of the formulas is unclear and unpublished. For example, Lombardi's (1989) formula was based on curve fitting and "a lot of guesswork and a bit of intuition…that is, tinkering with the equation when I saw the data was [*sic*] off" (V. P. Lombardi, personal communication, June 23, 2000), whereas Lander's (1985) formula began as a "guess-timated" chart that was eventually published without the author's knowledge (J. Lander, personal communication, June 23, 2000). Many of the prediction formulas (Epley, 1985; Lander, 1985; O'Connor et al., 1989; Wathen, 1994) originated as charts published in resistance exercise textbooks or were used to train athletes. The prediction formulas were later extrapolated from the charts (J. Mayhew, personal communication, June 26, 2000). Brzycki's (1993) equation was extrapolated from a graph representing the relation between the percentage of maximum load and RTF based on Anderson and Haring's unpublished observations that Sale and MacDougall (1981) reported. That is, data points extrapolated from the graph and not a direct observation of subjects were used to derive the prediction equation. Brzycki pointed out that the relation between maximum load and RTF is "near linear" when RTF is ≤10; however, when RTF is >10 the relation is exponential. Therefore, Brzycki's 1-RM prediction equation is linear in form and is most accurate when RTF ≤ 10.

Of the seven 1-RM prediction equations considered in this investigation, only the Mayhew, Ball, Arnold, and Bowen (1992) equation was developed using published empirical evidence analyzed with recognized statistical methodology and research design. These authors used a derivation sample consisting of 184 males and 251 females enrolled in a college fitness course and various cross-validation samples, including 70 males and 101 females in a similar college fitness course, high school male athletes (n = 25) and nonathletes (n = 74), and college football players (n = 45) to develop a 1-RM prediction equation for the bench press using free weights. Finding no gender difference in prediction, a single exponential equation (Table 1) was developed with a correlation between 1-RM and predicted 1-RM (1-RMP) of .98 and standard error of estimate of 10.58 lb. In the cross-validation samples, correlations between 1-RM and 1-RMP ranged from .91 to .97. Mean differences between 1-RM and 1-RMP were not statistically significant, and the standard error of estimate ranged from 7.94 (college females) to 12.79 lb (high school, male nonathletes).

Several issues concerning the use 1-RM prediction formulas have been examined. Of primary concern is evidence that the degree of prediction accuracy depends on the particular formula used, type of lift, number of RTF employed, and the use of free weights compared with weight machines.

The accuracy of various 1-RM prediction formulas has been compared using populations of untrained, college-aged males and females (LeSuer, McCormick, Mayhew, Wasserstein, & Arnold, 1997; Mayhew et al., 1995); college-aged athletes (Mayhew et al., 1995; Ware, Clemens, Mayhew, & Johnston, 1995); moderately active males and females aged 30 to 66 years (LeSuer, McCormick, & Mayhew, 1995); resistance-trained, middle-aged males (Mayhew et al., 1995); high school males (Mayhew et al., 1995); and high school football players (Knoll, Cissell, Clemens, Ware, & Mayhew, 1995). Three groups of researchers (Knoll et al.; LeSuer et al., 1995, 1997) examined all seven equations used in this investigation, whereas Mayhew et al. (1995) compared all but the Wathen formula, and Ware et al. (1995) compared all but the Wathen, O'Connor, and Lombardi formulas. The results have been mixed. Both Mayhew et al. (1995) and LeSuer et al. (1995) concluded that the Brzycki formula provided the least amount of error, particularly when RTF ≤ 10; however, Mayhew et al. (1995) noted that "care should be taken when predicting 1-RM strength from submaximal repetitions due to the possibility of large errors associated with the prediction equations" (p. 113). LeSuer et al. (1997) found the Mayhew and Wathen formulas to be the most accurate and also concluded that RTF ≤ 10 "can accurately predict 1-RM lifts" (p. 213). Ware et al. (1995) employed RTF ranging from 9 to 20 repetitions and found the greatest accuracy with the Mayhew formula. However, Ware et al. (1995) concluded that "higher repetitions-to-failure do not provide an accurate basis for judging strength levels in the bench press" (p. 103). In contrast, Knoll et al. reported an acceptably low degree of error using the Lombardi prediction and recommended use of RTF ≤12 for high school football players.

Although most researchers studying 1-RM prediction formulas have focused on the bench press, several other resistance exercises have been examined with less than encouraging results. Ware et al. (1995) reported moderately large to large errors in predicting squat strength in college football players and concluded that the Bryzcki, Epley, Lander, and Mayhew formulas were "not acceptable for estimating squat strength for repetitions-to-failure" (p. 102). The range of RTF used by Ware et al. was 11 to 25, which exceeds the RTF ≤ 10 recommended by others. Similar results for the squat and deadlift were reported by LeSuer et al. (1997) for untrained college-aged males and females enrolled in weight-training classes. All seven formulas significantly underestimated 1-RM deadlift performance, whereas only the Wathen formula accurately predicted squat 1-RM performance.

Less clear are results concerning the effect of training on estimation of 1-RM. Hoeger, Hopkins, Barette, and Hale (1990) provided evidence that for both men and women, training changes the relation between RTF and the percentage of 1-RM chosen for various resistance exercises. More specifically, Braith, Graves, Leggett, and Pollock (1993) reported that application of an equation to predict 1-RM maximal knee extension strength from 7 to 10 repetition maximum (RM) systematically overpredicted 1-RM in trained subjects compared with their 1-RM prediction in the untrained state. In contrast, Mayhew, Ball, and Bowen (1992) and Sebelski, Wilson, Mayhew, and Ball (1994) found no pretraining or posttraining change in the relation between the relative load chosen and RTF when performing the bench press. The discrepancy in results may be partly explained by the use of weight machines in the Hoeger et al. and Braith et al. investigations compared with use of free weights when the researchers found no effect of training (Knoll et al., 1995). In addition, Hoeger et al. reported that differences between trained and untrained subjects tended to be less in exercises employing large muscle groups like the bench press compared with small muscle group exercises like biceps curls. Therefore, Mayhew et al.'s and Sebelski et al.'s use of the bench press may explain, in part, their finding of no difference between trained and untrained states.

Finally, there is evidence that estimation of 1-RM using free weights differs from estimation using machine weight devices. In an examination of the YMCA bench press test (maximum number of repetitions lifting a submaximal weight), Kraus et al. (1996) reported that participants generally performed more RTF using a machine weight device compared with free weights. In addition, estimates of 1-RM using a machine weight device overpredicted 1-RM to a greater extent than predictions using free weights. Fleck and Kraemer (1997) hypothesized that

> in general, a certain percentage of the 1 RM with free-weight exercises will allow fewer repetitions than the same percentage of 1 RM on a similar exercise performed on a machine. This is most likely caused by the need for greater balance and control in space with free weights. (p. 100)

Although the choice of machine weight device or free weights affects the number of RTF performed by subjects, it appears that the relation between 1-RM and RTF remains unchanged (Bates, Bowen, Mayhew, & Visich, 1995). However, as Cosgrove and Mayhew (1997) pointed out, "Care should be taken in interchanging free weights and machine weights to estimate strength from RTF" (p. 26).

Because many beginners start resistance training with machine-based exercise, the purpose of this study was to examine the accuracy of seven existing prediction equations for estimating 1-RM performance from RTF in apparently healthy, older, sedentary adults using resistance exercise machines and a wide variety of resistance exercises. Prediction accuracy was examined using relative error, similarity statistics, and average error (AE).

METHODS

Subjects

Participants were apparently healthy, untrained, nonexercising volunteer adult males ($n = 26$) and females ($n = 23$) from Benton County, Oregon. The mean age (±1 *SD*) at the time of laboratory testing was 53.55 ± 3.34 years for the total sample, 54.22 ± 3.12 years for males, and 52.73 ± 3.22 years for females. Participants were classified as sedentary (not having participated in an exercise or resistance training program for the past 2 years) and were free of medications and hormone therapy.[1] All participants were

[1]Participants in this research were part of a 1-year training intervention study of the effects of two resistance training protocols on insulin-like growth factors, muscle strength, and bone mass in older adults. To determine whether the training protocols could offset declines in bone mass, women in this study were within 3 years postmenopause and were free of hormone therapy.

subjected to a comprehensive screening process that included a health questionnaire and written release from their family physician allowing them to participate in the study. Participants were screened by a health history questionnaire for chronic disease, orthopedic problems (significant disability of shoulder, knee, lower back, or hip), and alcohol consumption (>2 drinks per day). All participants were of White descent and came from middle to upper socioeconomic backgrounds. Participants were informed of the purpose, procedures, and potential risks of the study before signing an informed consent form. The research protocol was approved by the University Institutional Review Board for the Protection of Human Subjects.

1-RM

Prior to the start of the study, all participants attended six instructional sessions that focused on proper lifting technique, safety, and weight room etiquette. All training sessions were conducted at a local Gold's Gym using Hammer Strength Iso-Lateral resistance exercise machines (Hammer Strength, Cincinnati, OH). Minimal resistance was used during this phase.

Testing sessions were conducted under the close supervision of experienced personal trainers (two trainers per participant) to ensure proper technique, to provide positive verbal encouragement, to record all testing results, and to decrease the risk of injury. Personal trainers were college-level exercise and sport science students with at least 4 years of resistance training experience and who had successfully completed a 3-week training period with a National Strength and Conditioning Association certified specialist. Spotters assisted participants with the eccentric part of the lift to minimize the potential for muscle soreness. No physical assistance was given at any time to help participants complete the concentric phase of a repetition. Testing sessions were conducted over the same 2-week period, with each testing session lasting approximately 75 min. All testing sessions included a 10- to 15-min warm-up and a 5- to 7-min cool-down period consisting of aerobic exercise on either a motorized treadmill or StairMaster stair-stepping machine (StairMaster, Kirkland, WA). This was followed by 5 to 8 min of supervised stretching exercises for all major muscle groups.

Dynamic muscle strength was defined as the 1-RM or the maximum amount of weight that can be lifted one time with proper technique through a full range of motion. 1-RM was determined over the course of three testing sessions, with 1 day of complete rest between sessions. Testing was scheduled so that the synergist muscle group used for one assessment was not the primary muscle group during a subsequent exercise. During the first testing session, 1-RM values were obtained for the following exercises: chest press, high lat pull, and leg curl. In Session 2, leg press, shoulder press, and low lat pull-down 1-RM values were determined, whereas incline chest press, leg extension, biceps curl, and triceps extension 1-RM testing was performed during Session 3. Participants rested for 3 min between repetitions and for 5 min between exercises to allow for recovery of the anaerobic energy systems (Larsen, Potteigner, & Zebas, 1996).

For each exercise, the 1-RM protocol was as follows: After two warm-up sets of 10 to 12 repetitions using light resistance, each participant performed a single repetition with a weight he or she could lift through a complete range of motion. All machines and participant limb positions were adjusted to ensure proper technique throughout the full range of motion. At the conclusion of each successful lift, 5 to 20 lb were added, at the discretion of the personal trainer, for the next attempt. This procedure was repeated until the participant could no longer lift the weight (generally achieved in 4 to 6 attempts), and the greatest amount of weight lifted successfully (to the nearest pound) was recorded as the 1-RM.

RTF

RTF were determined over the course of three testing sessions, with 1 day of complete rest between sessions (Fry, Kraemer, van Borselen, & Lynch, 1994; Kraemer, Noble, Clark, & Culver, 1987). Participants were randomly assigned to 1 of 10 groups, and each group completed RTF for each of the 10 exercises. The order that the exercises were tested for each group was randomized, with no two groups following the same exercise order. Three exercises were tested during Sessions 4 and 5, and four exercises were tested on Session 6 of the study. Each of the 10 Hammer Strength exercises was randomly assigned one of the following percentages of the 1-RM: 50, 55, 60, 65, 70, 75, 80, 85, 90. Each participant completed a light warm-up set of 10 repetitions using 35% of their previously determined 1-RM for each exercise tested. A 1-min rest period was given at the conclusion of each warm-up set. During the testing trials, participants were asked to (a) perform as many repetitions as possible with the assigned resistance, (b) complete the concentric phase as explosively as possible, and (c) execute the eccentric phase under control (2 to 3 sec). For a repetition to be recorded, participants were required to take the resistance through a complete range of motion. A 10-min rest was provided between specific exercises in contrast to the 5-min rest used in the determination of 1-RM.

Statistical Analysis

Three statistics commonly employed in the 1-RM prediction literature were used to compare the accuracy of the seven 1-RM prediction equations. Pearson product–moment correlation coefficients between 1-RM and 1-RMP provide minimal evidence for the relative accuracy or the degree to which 1-RMP increases as 1-RM increases. Because relative accuracy does not assess the magnitude of the difference between 1-RM and 1-RMP, similarity statistics and AE were also computed. Similarity statistics use paired *t* tests to examine mean differences between 1-RM and 1-RMP for each prediction equation over each exercise. Small and statistically nonsignificant differences between 1-RM and 1-RMP are preferred. Similarity statistics must be interpreted with caution because the statistical power of paired *t* tests is affected by the correlation between variables. Therefore, large mean differences between 1-RM and 1-RMP could be statistically nonsignificant if the correlation between 1-RM and 1-RMP is low, whereas small mean differences could be statistically significant if the correlation between 1-RM and 1-RMP is high. In addition, small mean differences could result from a combination of 1-RMP values that overestimate 1-RM and values that underestimate 1-RM, resulting in no significant net mean difference. AE is an estimate of the average amount that 1-RMP differs from 1-RM. Because AE includes a comparison of 1-RM and 1-RMP for each participant in its computation, it is the most informative of the three statistics.[2]

Statistical analyses were completed for the total participant group, males, and females to compare results with the literature. Estimated 1-RM from the seven equations given in Table 1 were computed for each exercise using the Microsoft® *Excel97* spreadsheet (Microsoft Corporation, 1997). *Excel97* was also used to compute AE for each equation for each exercise according to Equation 1

$$AE = \sqrt{\frac{\Sigma(x - x')^2}{n - 1}} \tag{1}$$

where x represents actual 1-RM, x' represents 1-RM predicted from one of the formulas given in Table 1, and n is the sample size. Descriptive statistics for all variables, Pearson correlations between 1-RM and 1-RMP, and paired *t* tests comparing 1-RM and 1-RMP were computed using *SPSS 7.5 for Windows* (SPSS Inc., 1997). In addition, gender differences in relative accuracy were examined with a test of the difference between two correlations from independent samples (Hays, 1981).

RESULTS

Study results are presented in four sections: subject characteristics, relative accuracy of prediction equations, similarity statistics, and AE. Analyses are presented for the total sample, for males, and for females. In addition, because researchers have shown that the accuracy of 1-RM prediction equations is inversely related to number of RTF (e.g., Mayhew et al., 1995), subjects with

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[2]AE is a statistic commonly used to cross-validate prediction equations (see Jackson, 1989; Wood, 1989). The statistic has been given several names in the literature, including the cross-validation standard error (Jackson, 1989) and total error (Mayhew et al., 1995; Ware et al., 1995). The name AE was chosen for this study because it was deemed more intuitively descriptive than others.

RTF ≤ 10 were examined separately.[3] Variables with missing data are identified via footnotes in the tables.

Subject Characteristics

Table 2 presents descriptive statistics for the subject characteristics of age, body weight, and 1-RM for each exercise. The mean age (±1 *SD*) for the total sample was 53.55 ± 3.34 years, with a minimum age of 49 and a maximum age of 61. The males (54.22 ± 3.12 years) were slightly older than the females (52.73 ± 3.22 years). As expected, males (198.13 ± 35.21 lb) tended to be heavier than females (155.21 ± 25.68 lb) and exhibited higher 1-RM values for each exercise.

Relative Accuracy

Relative accuracy was examined by correlating 1-RMP with measured 1-RM using the Pearson product-moment correlation coefficient. A high positive correlation was expected, indicating that subjects with high 1-RM tended to have high values of 1-RMP and that those with low 1-RM tended to have lower values of 1-RMP. The relative accuracy coefficients over the full range of RTF are presented in Table 3.

With the exception of the Brzycki and Lander predictions for the leg press (r = .48 and .57, respectively) and triceps extension (r = .41 and .50, respectively), the lowest correlation for the total group in Table 3 was .81 (r^2 = .67), indicating a relatively strong positive relationship between 1-RM and 1-RMP over the full range of RTF trials. When RTF ≤ 10, the correlations over all formulas and exercises exceeded .90 (r^2 = .81) for the total group.

With few exceptions, higher correlations were evident for females for leg extension, leg press, high lat pull down, and triceps extension when compared with males over the full range of RTF trials; however, with the exception of the Bryzcki and Lander predictions of leg press 1-RM, the differences were not statistically significant (p > .05). Males had significantly (p ≤ .05) greater relative accuracy on the leg curl for all but the Lombardi and Mayhew predictions. When RTF ≤ 10 relative accuracy improved appreciably (r > .80) for both genders with the exception of the leg curl for females (range, –.06 to .01) and high lat pull down for males (range, .53 to .56). Males did not differ significantly (p > .05) from females when RTF ≤ 10, with the exception of the leg curl, which had very low correlations for females. The low leg curl correlations for females when RTF ≤10 can be attributed to the small sample size (n = 5).

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[3]Interpretation of all analyses involving RTF ≤10 must be viewed with caution because of the low sample size associated with some exercises, particularly leg curl (n = 5), leg press (n = 7), and high lat pull down (n = 6) for females and triceps extension (n = 9) for males.

TABLE 2
Descriptive Statistics for All Measured Variables[a]

	Minimum	*Maximum*	*M*	*SD*
Total Group (*N* = 49)				
Age (years)	49.00	61.00	53.55	3.34
Body weight (lb)[b]	106.29	285.61	176.83	36.62
BCRM (lb)	17.50	105.00	54.54	23.51
TERM	20.00	100.00	55.41	22.90
LLRM	65.00	300.00	159.69	71.07
HLRM[b]	70.00	250.00	149.17	54.75
SPRM	25.00	205.00	90.36	43.79
CPRM	35.00	245.00	120.77	54.85
ICRM	35.00	230.00	127.35	58.28
LCRM	40.00	240.00	121.22	44.38
LERM[b]	40.00	230.00	20.73	54.15
LPRM	90.00	590.00	293.76	115.92
Males (*n* = 26)				
Age	50.00	61.00	54.22	3.12
Body weight	126.10	285.61	198.13	35.21
BCRM	40.00	105.00	74.57	14.59
TERM	55.00	100.00	75.52	11.93
LLRM	120.00	300.00	217.92	47.91
HLRM[c]	130.00	250.00	198.26	29.45
SPRM	70.00	205.00	125.94	31.49
CPRM	95.00	245.00	167.39	34.51
ICRM	90.00	230.00	174.17	38.47
LCRM	100.00	240.00	155.63	34.81
LERM[c]	70.00	230.00	162.71	40.05
LPRM	180.00	590.00	367.71	106.84
Females (*n* = 23)				
Age	49.00	61.00	52.73	3.22
Body weight[d]	106.09	201.68	155.21	25.68
BCRM	17.50	50.00	33.07	8.05
TERM	20.00	60.00	34.43	9.88
LLRM	65.00	140.00	97.27	24.63
HLRM	70.00	150.00	100.68	21.40
SPRM	25.00	90.00	53.64	18.14
CPRM	35.00	105.00	71.70	17.62
ICRM	35.00	125.00	76.36	21.78
LCRM	40.00	110.00	85.00	16.18
LERM	40.00	140.00	78.64	27.70
LPRM	90.00	400.00	216.14	72.16

[a]Key for abbreviated variable names: first two to three letters denote exercise type where BC = biceps curl; TE = triceps extension; LL = low lat pull; HL = high lat pull down; SP = shoulder press; CP = chest press; IC = inclined chest press; LC = leg curl; LE = leg extension; LP = leg press; the last two letters denote 1-RM. [b]*N* = 48. [c]*n* = 25. [d]*n* = 22.

TABLE 3
Correlations[a,b] Between Predicted 1-RM and Actual 1-RM Over Full Range of RTF

	Brzycki	*Epley*	*Lander*	*Lombardi*	*Mayhew*	*O'Connor*	*Wathen*
Total group (*N* = 49)							
BC[c]	.91[a]	.96[a]	.92[a]	.93[a]	.95[a]	.95[a]	.96[a]
TE	.41[a]	.95[a]	.50[a]	.91[a]	.94[a]	.95[a]	.95[a]
LL	.94[a]	.95[a]	.94[a]	.92[a]	.93[a]	.94[a]	.94[a]
HL[d]	.87[a]	.95[a]	.89[a]	.91[a]	.93[a]	.94[a]	.94[a]
SP	.98[a]	.97[a]	.98[a]	.95[a]	.96[a]	.97[a]	.97[a]
CP	.96[a]	.96[a]	.96[a]	.92[a]	.94[a]	.95[a]	.96[a]
IC	.96[a]	.95[a]	.96[a]	.93[a]	.94[a]	.95[a]	.95[a]
LC	.81[a]	.93[a]	.84[a]	.89[a]	.91[a]	.92[a]	.92[a]
LE[e]	.83[a]	.90[a]	.84[a]	.90[a]	.90[a]	.90[a]	.91[a]
LP[d]	.48[a]	.92[a]	.57[a]	.89[a]	.91[a]	.91[a]	.91[a]
Males (*n* = 26)							
BC	.68[a]	.81[a]	.71[a]	.78[a]	.80[a]	.81[a]	.81[a]
TE	–.01	.78[a]	.03	.70[a]	.75[a]	.77[a]	.78[a]
LL	.85[a]	.82[a]	.85[a]	.75[a]	.79[a]	.80[a]	.82[a]
HL[f]	.49[a]	.77[a]	.54[a]	.69[a]	.73[a]	.75[a]	.76[a]
SP	.94[a]	.93[a]	.94[a]	.89[a]	.91[a]	.92[a]	.93[a]
CP	.86[a]	.85[a]	.86[a]	.73[a]	.78[a]	.80[a]	.85[a]
IC	.86[a]	.83[a]	.86[a]	.77[a]	.80[a]	.81[a]	.83[a]
LC	.83[a]	.86[a]	.85[a]	.77[a]	.81[a]	.84[a]	.85[a]
LE[g]	.64[a]	.78[a]	.66[a]	.77[a]	.78[a]	.78[a]	.78[a]
LP[f]	.27	.83[a]	.34[b]	.78[a]	.82[a]	.83[a]	.83[a]
Females (*n* = 23)							
BC	.39[b]	.90[a]	.47[b]	.84[a]	.87[a]	.89[a]	.89[a]
TE	.39[b]	.90[a]	.34	.86[a]	.88[a]	.89[a]	.87[a]
LL	.61[a]	.76[a]	.63[a]	.74[a]	.76[a]	.76[a]	.76[a]
HL	.71[a]	.89[a]	.74[a]	.80[a]	.85[a]	.87[a]	.87[a]
SP	.91[a]	.92[a]	.91[a]	.91[a]	.92[a]	.92[a]	.92[a]
CP	.86[a]	.87[a]	.87[a]	.84[a]	.85[a]	.86[a]	.86[a]
IC	.86[a]	.87[a]	.86[a]	.87[a]	.87[a]	.87[a]	.87[a]
LC	.16	.57[a]	.19	.56[a]	.58[a]	.58[a]	.58[a]
LE	.68[a]	.83[a]	.70[a]	.89[a]	.87[a]	.85[a]	.84[a]
LP	.71[a]	.90[a]	.74[a]	.88[a]	.90[a]	.90[a]	.90[a]

[a]Correlation significant from zero ($p \leq .01$, one-tailed). [b]Correlation significant from zero ($p \leq .05$, one-tailed). [c]BC = biceps curl; TE = triceps extension; LL = low lat pull; HL = high lat pull down; SP = shoulder press; CP = chest press; IC = inclined chest press; LC = leg curl; LE = leg extension; LP = leg press. [d]N = 48. [e]N = 47. [f]n = 25. [g]n = 24.

Similarity Statistics

Tables 4 and 5 include similarity statistics over the full range of RTF trials and for RTF ≤ 10, respectively. Type I error was set at $\alpha = .05$ (two-tailed). Therefore, $p \leq .05$ provided evidence for a lack of similarity.

TABLE 4
Paired *t* Tests Comparing 1-RM With Predicted 1-RM Over Full Range of RTF (Tabled Values are Mean Differences)

	Equation						
	Brzycki	*Epley*	*Lander*	*Lombardi*	*Mayhew*	*O'Connor*	*Wathen*
Total group (*N* = 49)							
BC[a]	–0.34	–3.43*	–0.33	–6.68*	–4.37*	–6.42*	3.28*
TE	19.13	–0.05	13.14	–6.42*	–2.89*	–4.17*	0.51
LL	0.12	–7.65*	0.35	–18.64*	–11.21	–17.14*	6.75
HL[b]	15.01*	–3.32	14.18*	–17.08*	–8.75*	–13.33*	3.38
SP	–8.34*	–10.24*	–7.99*	–14.03*	–10.94*	–14.50*	9.92*
CP	–11.61*	–15.80*	–11.28*	–22.24*	–17.14*	–21.55*	15.58*
IC	–16.49*	–17.48*	–15.88*	–22.22*	–18.36*	–23.38*	16.71*
LC	6.64	–9.14*	5.70	–20.19*	–13.61*	–17.02*	9.13*
LE[c]	–8.96*	–12.81*	–8.66*	–18.64*	–14.32*	–18.97*	12.23*
LP[b]	83.82*	–0.49	71.13*	–33.59*	–14.78*	–22.19*	1.82
Males (*n* = 26)							
BC[a]	–0.97	–4.67*	–0.88	–9.33*	–6.13*	–8.85*	4.36*
TE	38.52	–0.18	29.69*	–9.34*	–4.36*	–5.84*	0.97
LL	3.23	–7.21	3.55	–23.26*	–12.84*	–20.77*	5.64
HL[d]	15.82*	–3.22	15.16*	–18.68*	–8.89	–15.58*	2.95
SP	–7.77*	–11.42*	–7.37*	–17.26*	–12.72*	–17.53*	11.03*
CP	–13.96*	–20.72*	–13.60*	–30.48*	–23.19*	–29.03*	20.35*
IC	–21.25*	–22.49*	–20.41*	–28.99*	–23.76*	–30.65*	21.40*
LC	2.81	–11.06*	2.36	–23.48*	–15.83*	–20.68*	10.63*
LE[e]	–15.38*	–20.34*	–15.01*	–27.64*	–22.37*	–28.49*	19.44*
LP[d]	141.78	3.53	118.54*	–42.93*	–17.45	–25.30*	–1.05
Females (*n* = 23)							
BC[a]	0.38	–2.04*	0.29	–3.68*	–2.38*	–3.68*	2.05*
TE	–2.79	0.09	–5.58	–3.11*	–1.22	–2.28*	–0.02
LL	–3.39	–8.15*	–3.27	–13.43*	–9.36*	–13.02*	8.01*
HL	14.15*	–3.43	13.11*	–15.34*	–8.60*	–10.88*	3.84
SP	–8.99*	–8.90*	–8.69*	–10.39*	–8.93*	–11.07*	8.66*
CP	–8.96*	–10.23*	–8.65*	–12.93*	–10.30*	–13.10*	10.18*
IC	–11.11*	–11.79*	–10.76*	–14.58*	–12.26*	–15.15*	11.41*
LC	10.97	–6.97*	9.48	–16.46*	–11.09*	–12.87*	7.44*
LE	–2.27	–4.96	–2.03	–9.24*	–5.92*	–9.03*	4.70
LP	20.82	–4.86	19.60	–23.45*	–11.87	–18.80*	4.95

[a]BC = biceps curl; TE = triceps extension; LL = low lat pull; HL = high lat pulldown; SP = shoulder press; CP = chest press; IC = inclined chest press; LC = leg curl; LE = leg extension; LP = leg press. [b]*N* = 48. [c]*N* = 47. [d]*n* = 25. [e]*n* = 24.

*$p \leq .05$.

Over the full range of RTF trials (Table 4) for the total group, the Lombardi and O'Connor formulas showed a lack of similarity with relatively large and statistically significant mean differences over all exercises. The Mayhew formula had a lack of similarity for all but the low lat pull down. None of the seven formulas evidenced similarity for the shoulder press, chest press, inclined chest press, and leg extension. No single formula presented acceptable similarity over a wide range of exercises. The Wathen formula had relatively small and statistically nonsignificant mean differences for the leg press, high lat pull down, lower lat pull down, and triceps extension. The Lander and Brzycki formulas performed well for biceps curl, lower lat pull down, and leg curl. Both formulas exhibited relatively large and statistically nonsignificant mean differences for triceps extension compared with the rather small and statistically significant differences for triceps extension computed from the Lombardi, Mayhew, and O'Connor formulas. This paradox can be explained by the low correlations between 1-RM and 1-RMP (.41 and .50 for the Brzycki and Lander formulas, respectively) and illustrates the interpretation difficulties inherent in similarity statistics.

Across genders over the full range of RTF trials, males evidenced larger mean differences than females; none of the seven formulas had similarity for the shoulder press, chest press, and inclined chest press, and the Lombardi and O'Connor formulas had unacceptable similarity over the full range of exercises. No single formula showed similarity across all exercises for males; however, the Brzycki and Lander formulas exhibited smaller mean differences and similarity over more exercises for females.

When RTF ≤ 10 (Table 5), similarity statistics improved for some exercises, most notably triceps extension, leg press, lower lat pull down, and high lat pull down. This was true for most formulas, notably those of Mayhew and Epley. The Mayhew and Wathen formulas performed best for the total group with similarity for all but shoulder press, chest press, inclined chest press, and leg extension. Reducing RTF had little effect on the lack of similarity for shoulder press, chest press, inclined chest press, and leg extension across all formulas for the total group. For males, similarity improved for all formulas, particularly the Mayhew formula, which showed similarity over 8 of the 10 exercises. Reducing RTF for females had mixed results with a worsening of similarity in some cases (e.g., biceps curl and lower lat pull predicted by the Brzycki formula) and improvement in others (e.g., prediction using the Lombardi formula).

AE

AE determines the difference between 1-RM and 1-RMP for each participant and accounts for algebraic sign in its computation by squaring the error, therefore providing a more accurate estimation of error in predicting 1-RM. Tables 6 and 7 include AE for all formulas and exercises for the full range of RTF trials and for RTF ≤ 10, respectively. To assist in determining the practical significance of AE, Tables 8 and 9 provide AE expressed as a percentage of mean 1-RM for each formula and exercise

TABLE 5
Paired *t* Tests Comparing 1-RM With Predicted 1-RM When RTF ≤ 10 (Tabled Values are Mean Differences)

	Equation						
	Brzycki	*Epley*	*Lander*	*Lombardi*	*Mayhew*	*O'Connor*	*Wathen*
Total group							
BC[a] (*n* = 30)	–3.47*	–2.48*	–3.04*	–3.42*	–2.05	–4.71*	2.24
TE (*n* = 19)	–1.68	–0.67	–1.25	–1.67	–0.36	–3.09*	0.33
LL (*n* = 23)	–3.50	–0.39	–2.21	–3.09	–0.89	–6.96	–0.37
HL (*n* = 19)	–0.79	2.40	0.63	–1.13	3.36	–5.58	–3.49
SP (*n* = 32)	–9.74*	–7.79*	–8.99*	–8.68*	–6.74*	–11.13*	7.52*
CP (*n* = 29)	–12.67*	–10.11*	–11.69*	–11.14*	–8.11*	–13.55*	10.18*
IC (*n* = 34)	–16.88*	–14.41*	–15.91*	–16.12*	–13.55*	–19.47*	13.74*
LC (*n* = 15)	–7.45*	–4.81	–6.39	–6.72*	–3.76	–10.19*	4.17
LE (*n* = 31)	–15.43*	–13.18*	–14.49*	–15.67*	–12.63*	–18.58*	12.36*
LP (*n* = 17)	–8.68	–2.62	–6.18	–7.57	–0.49	–15.89*	0.92
Males							
BC (*n* = 14)	–5.24*	–0.98	–4.65	–5.54*	–3.57	–7.30*	3.56
TE (*n* = 9)	–2.30	–0.89	–1.72	–2.09	–0.40	–4.04	0.49
LL (*n* = 10)	6.37	10.33	8.20	5.27	11.18	–0.46	–11.94
HL (*n* = 13)	0.72	4.27	2.35	–0.14	5.17	–5.15	–5.61
SP (*n* = 16)	–8.84*	–6.05*	–7.75*	–7.46*	–4.60	–11.02*	5.63*
CP (*n* = 13)	–15.41*	–11.56*	–13.95*	–12.99*	–8.65	–16.78*	11.62*
IC (*n* = 19)	–20.09*	–16.87*	–18.80*	–19.49*	–15.95*	–23.94*	15.83*
LC (*n* = 10)	–4.43	–1.50	–3.21	–4.19	–0.66	–8.29	0.54
LE (*n* = 17)	–19.95*	–17.20*	–18.79*	–20.58*	–16.95*	–24.44*	15.92*
LP (*n* = 10)	–5.43	–0.35	–2.88	–9.56	–0.32	–17.24	–2.56
Females							
BC (*n* = 16)	–1.93*	–1.17	–1.63	–1.56	–0.72	–2.44*	1.09
TE (*n* = 10)	–1.12	–0.47	–0.82	–1.29	–0.33	–2.23	0.20
LL (*n* = 13)	–11.10*	–8.64	–10.22*	–9.51	–7.03	–11.95*	8.53
HL (*n* =6)	–4.08	–1.65	–3.10	–3.27	–0.60	–6.50	1.11
SP (*n* = 16)	–10.64*	–9.53*	–10.23*	–9.89*	–8.88*	–11.23*	9.42*
CP (*n* = 16)	–10.44*	–8.93*	–9.85*	–9.63*	–7.67*	–10.93*	9.01*
IC (*n* = 15)	–12.81*	–11.29*	–12.25*	–11.85*	–10.50*	–13.81*	11.08*
LC (*n* = 5)	–13.50*	–11.44*	–12.77*	–11.78*	–9.97*	–14.00*	11.45*
LE (*n* = 14)	–9.95*	–8.29*	–9.26*	–9.70*	–7.39*	–11.47*	8.03*
LP (*n* = 7)	–13.31	–5.86	–10.88	–4.74	–0.73	–13.96	5.90

[a]BC = biceps curl; TE = triceps extension; LL = low lat pull; HL = high lat pull down; SP = shoulder press; CP = chest press; IC = inclined chest press; LC = leg curl; LE = leg extension; LP = leg press.
*$p \leq .05$.

over the full range of RTF trials and for RTF ≤ 10, respectively. Table 10 includes the frequency and magnitude of overestimation (+) and underestimation (–) of 1-RM by 1- RMP for each formula across all exercises over the full range of RTF.

TABLE 6
Average Error (lb) Between Predicted 1-RM and Actual 1-RM Over Full Range of RTF

	Brzycki	*Epley*	*Lander*	*Lombardi*	*Mayhew*	*O'Connor*	*Wathen*
Total group (N = 49)							
BC[a]	9.82	7.58	9.18	10.70	8.66	9.67	7.55
TE	87.13	7.16	65.09	11.31	8.45	8.38	7.40
LL	25.22	24.89	24.72	33.73	28.11	29.77	24.98
HL[b]	32.78	18.32	30.38	29.05	22.53	22.95	19.23
SP	12.44	14.60	12.11	19.59	16.40	18.37	14.50
CP	19.10	22.26	18.68	30.72	25.48	28.12	21.87
IC	23.74	25.09	23.30	30.62	26.77	30.28	24.45
LC	29.27	19.15	26.59	28.96	23.14	24.37	19.68
LE[c]	31.95	26.51	30.87	30.06	27.26	30.07	25.98
LP[b]	283.95	48.44	223.62	63.41	51.39	52.15	48.53
Males (n = 26)							
BC	10.66	9.70	10.23	13.67	11.11	12.36	9.65
TE	115.98	8.99	79.43	14.53	10.74	10.57	9.28
LL	27.24	29.66	37.34	41.65	34.27	36.01	29.82
HL[d]	40.24	23.35	37.34	35.12	27.98	28.37	24.44
SP	13.18	16.99	12.78	24.15	19.81	22.03	16.92
CP	23.09	27.57	22.59	39.13	32.15	35.43	26.93
IC	28.91	30.96	28.37	38.35	33.33	37.73	30.10
LC	23.09	21.63	21.46	33.93	26.89	28.38	22.35
LE[e]	38.90	33.74	37.58	39.30	35.36	38.82	33.10
LP[d]	389.34	59.93	308.58	77.97	62.85	63.46	59.83
Females (n = 23)							
BC	8.78	4.00	7.83	5.72	4.49	5.14	4.02
TE	31.11	4.22	43.50	5.84	4.67	4.82	4.40
LL	22.73	18.05	21.75	21.52	18.88	20.56	18.01
HL	21.96	10.37	20.26	20.50	14.44	14.97	11.08
SP	11.55	11.30	11.29	12.57	11.38	13.06	11.14
CP	13.20	14.04	12.90	16.73	14.65	16.29	14.09
IC	16.00	16.04	15.71	18.30	16.47	18.54	15.79
LC	34.96	15.88	31.40	22.03	17.99	18.83	16.14
LE	22.50	15.77	21.78	15.33	14.62	16.57	15.36
LP	59.12	31.51	55.02	42.23	34.90	36.04	32.00

[a]BC = biceps curl; TE = triceps extension; LL = low lat pull; HL = high lat pull down; SP = shoulder press; CP = chest press; IC = inclined chest press; LC = leg curl; LE = leg extension; LP = leg press. [b]N = 48. [c]N = 47. [d]n = 25. [e]n = 24.

The most striking feature of Tables 6 and 7 is the large magnitude of AE over all exercises and formula (total group range of 7.16 to 283.95 lb), particularly for the leg press (total group range of 48.44 to 283.95 lb). Although AE decreased when RTF ≤ 10 (Table 7), the magnitude remained high (total group range over all exercises 4.29 to 31.54 lb). Across all exercises and both genders, the Wathen, Epley, and Mayhew formulas generally produced the lowest AE over the full range of RTF trials (Table

TABLE 7
Average Error (lb) Between Actual 1-RM and Predicted 1-RM When RTF ≤ 10

	Brzycki	*Epley*	*Lander*	*Lombardi*	*Mayhew*	*O'Connor*	*Wathen*
Total group							
BC[a] (*n* = 30)	7.28	6.84	7.05	7.58	6.83	8.13	6.77
TE (*n* = 19)	4.38	4.52	4.29	5.44	4.96	5.53	4.43
LL (*n* = 23)	20.22	20.04	20.22	18.82	19.54	19.00	20.82
HL (*n* = 19)	20.81	19.76	20.76	17.20	18.76	18.48	20.63
SP (*n* = 32)	12.54	11.19	11.98	11.97	10.84	13.57	11.06
CP (*n* = 29)	16.45	15.02	15.75	16.72	14.93	18.16	14.74
IC (*n* = 34)	24.08	22.38	23.41	23.76	22.04	26.02	21.92
LC (*n* = 15)	15.19	13.44	14.68	12.87	12.28	15.05	13.78
LE (*n* = 31)	24.05	22.72	23.48	24.32	22.58	26.28	22.25
LP (*n* = 17)	29.31	28.80	28.86	30.21	29.25	31.54	29.25
Males							
BC (*n* = 14)	9.88	9.39	9.60	10.50	9.51	11.21	9.22
TE (*n* = 9)	5.26	5.49	5.17	6.69	6.15	6.75	5.34
LL (*n* = 10)	20.79	21.36	21.26	17.78	20.72	17.03	22.96
HL (*n* = 13)	24.07	23.03	24.09	19.88	21.87	21.11	24.09
SP (*n* = 16)	12.37	10.57	11.60	11.75	10.26	13.84	10.45
CP (*n* = 13)	19.26	17.48	18.31	20.43	17.90	22.21	16.88
IC (*n* = 19)	28.18	26.17	27.35	28.21	25.95	30.94	25.52
LC (*n* = 10)	15.11	13.35	14.68	12.22	12.21	14.66	13.84
LE (*n* = 17)	29.41	27.92	28.75	29.84	27.84	32.18	27.33
LP (*n* = 10)	33.99	34.67	33.98	36.55	35.43	37.22	35.19
Females							
BC (*n* = 16)	3.75	3.26	3.56	3.32	2.88	3.74	3.39
TE (*n* = 10)	3.39	3.42	3.32	3.40	3.55	4.14	3.41
LL (*n* = 13)	19.77	18.96	19.38	19.58	18.58	20.39	19.01
HL (*n* = 6)	10.74	9.35	10.37	8.97	8.85	10.74	9.53
SP (*n* = 16)	12.70	11.78	12.36	12.19	11.39	13.31	11.65
CP (*n* = 16)	13.75	12.67	13.32	13.07	11.98	14.04	12.75
IC (*n* = 15)	17.57	16.35	17.18	16.47	15.77	17.95	16.26
LC (*n* = 5)	15.34	10.81	14.69	14.09	10.76	15.78	13.67
LE (*n* = 14)	15.19	14.01	14.71	15.11	13.71	16.49	13.77
LP (*n* = 7)	20.90	17.25	19.34	17.57	16.86	20.91	17.55

[a]BC = biceps curl; TE = triceps extension; LL = low lat pull; HL = high lat pull down; SP = shoulder press; CP = chest press; IC = inclined chest press; LC = leg curl; LE = leg extension; LP = leg press.

6). Additionally, over the full range of RTF trials, the Brzycki and Lander formulas showed extraordinarily high AE for the leg press and triceps extension exercises, particularly for males. When RTF ≤ 10, the AEs for all formulas were more comparable with slightly lower AE for the Mayhew, Wathen, and Epley formulas.

More revealing than AE is AE expressed as a percentage of mean 1-RM. Based on total group data over the full range of RTF trials (Table 8), a minimum of a 12% error was calculated for most formulas across all exercises (range of 12% to

TABLE 8
Average Error Expressed as the Percentage of Mean 1-RM Over Full Range of RTF

	Equation						
	Brzycki	*Epley*	*Lander*	*Lombardi*	*Mayhew*	*O'Connor*	*Wathen*
Total group (N = 49)							
BC[a]	18	14	17	20	16	18	14
TE	157	13	117	20	15	15	13
LL	16	16	15	21	18	19	16
HL[b]	22	12	20	19	15	15	13
SP	14	16	13	22	18	20	16
CP	16	18	15	25	21	23	18
IC	19	20	18	24	21	24	19
LC	24	16	22	24	19	20	16
LE[c]	26	22	26	25	23	25	22
LP[b]	97	16	76	22	17	18	17
Males (n = 26)							
BC	14	13	14	18	15	17	13
TE	154	12	105	19	14	14	12
LL	13	14	17	19	16	17	14
HL[d]	20	12	19	18	14	14	12
SP	10	13	10	19	16	17	13
CP	14	16	14	23	19	21	16
IC	17	18	16	22	19	22	17
LC	15	14	14	22	17	18	14
LE[e]	24	21	23	24	22	24	20
LP[d]	106	16	84	21	17	17	16
Females (n = 23)							
BC	27	12	24	17	14	16	12
TE	90	12	126	17	14	14	13
LL	23	19	22	22	19	21	19
HL	22	10	20	20	14	15	11
SP	22	21	21	23	21	24	21
CP	18	20	18	23	20	23	20
IC	21	21	21	24	22	24	21
LC	41	19	37	26	21	22	19
LE	29	20	28	19	19	21	20
LP	27	15	25	20	16	17	15

[a]BC = biceps curl; TE = triceps extension; LL = low lat pull; HL = high lat pull down; SP = shoulder press; CP = chest press; IC = inclined chest press; LC = leg curl; LE = leg extension; LP = leg press. [b]N = 48. [c]N = 47. [d]n = 25. [e]n = 24.

157%). Error for the triceps extension and leg press predicted by the Brzycki and Lander formulas ranged from 76% to 157%. The Wathen, Epley, and Mayhew formulas performed comparatively well (range of 12% to 23%) across all exercises over the full range of RTF trials.

TABLE 9
Average Error Expressed as the Percentage of Mean 1-RM When RTF ≤ 10

	Equation						
	Brzycki	*Epley*	*Lander*	*Lombardi*	*Mayhew*	*O'Connor*	*Wathen*
Total group							
BC (*n* = 30)	14	13	13	14	13	15	13
TE (*n* = 19)	07	08	07	09	08	09	07
LL (*n* = 23)	13	13	13	12	13	13	14
HL (*n* = 19)	12	11	12	10	11	11	12
SP (*n* = 32)	14	12	13	13	12	15	12
CP (*n* = 29)	15	14	14	15	14	17	13
IC (*n* = 34)	19	17	18	19	17	20	17
LC (*n* = 15)	12	10	11	10	10	12	11
LE (*n* = 31)	19	17	18	19	17	20	17
LP (*n* = 17)	10	10	10	10	10	10	10
Males							
BC (*n* = 14)	13	12	12	14	12	15	12
TE (*n* = 9)	07	08	07	09	09	09	07
LL (*n* = 10)	09	10	10	08	09	08	10
HL (*n* = 13)	12	12	12	10	11	11	12
SP (*n* = 16)	10	08	09	09	08	11	08
CP (*n* = 13)	12	11	11	13	11	14	11
IC (*n* = 19)	14	13	14	12	13	12	14
LC (*n* = 10)	10	09	10	08	08	10	09
LE (*n* = 17)	18	17	17	18	17	19	16
LP (*n* = 10)	10	10	10	11	10	11	10
Females							
BC (*n* = 16)	11	10	11	10	09	11	10
TE (*n* = 10)	09	09	09	09	09	11	09
LL (*n* = 13)	20	19	20	20	19	21	19
HL (*n* = 6)	09	08	09	08	08	09	08
CP (*n* = 16)	20	19	19	19	18	21	19
IC (*n* = 15)	24	22	23	22	21	24	22
LC (*n* = 5)	18	13	17	17	13	19	16
LE (*n* = 14)	18	16	17	18	16	19	16
LP (*n* = 7)	09	07	08	07	07	09	07
SP (*n* = 16)	24	22	23	23	21	25	22

[a]BC = biceps curl; TE = triceps extension; LL = low lat pull; HL = high lat pull down; SP = shoulder press; CP = chest press; IC = inclined chest press; LC = leg curl; LE = leg extension; LP = leg press.

When RTF ≤ 10 (Table 9), the error dropped substantially, ranging from 7% to 20% for the total group. Females had slightly higher error than males for the chest press, inclined chest press, low lat pull, leg curl, and shoulder press when RTF ≤ 10. Little difference was found in percentage of error among the formulas across all exercises.

Table 10 provides evidence for the degree to which the seven 1-RM prediction formulas tend to overestimate (+) or underestimate (–) actual 1-RM. Two

TABLE 10
Average Difference (lb) Between 1-RM and 1-RMP for Overestimates and Underestimates Over Full Range of RTF

	Brzycki		*Epley*		*Lander*		*Lombardi*		*Mayhew*		*O'Connor*		*Wathen*	
	+	–	+	–	+	–	+	–	+	–	+	–	+	–
Total group (*N* = 49)														
BC[a]	10[b]	5	5	6	9	5	4	9	5	7	5	8	5	6
	16[c]	33	11	38	16	33	10	39	12	37	6	41	13	36
TE	35	13	6	4	27	18	3	10	4	8	4	7	5	5
	33	16	21	18	34	15	14	35	19	30	11	38	21	28
LL	21	17	18	20	20	17	13	31	15	26	12	27	17	21
	22	27	16	33	23	26	14	35	18	31	12	37	18	31
HL[d]	25	16	12	14	26	13	10	26	13	19	9	20	12	15
	36	12	20	28	34	14	12	36	16	32	10	37	21	27
SP	4	11	4	12	4	10	2	15	3	13	0	15	4	12
	8	41	5	44	8	41	4	45	7	42	0	49	6	43
CP	9	16	5	19	184	61	4	26	4	23	4	23	5	19
	9	40	7	42	3	46	6	43	11	38	2	47	7	42
IC	8	22	8	23	8	21	7	27	11	23	5	27	9	22
	9	40	8	41	9	40	7	42	7	42	5	43	8	41
LC	26	12	8	17	24	12	6	26	10	20	6	21	10	17
	24	25	15	34	24	25	9	40	10	39	7	41	14	35
LE[e]	21	25	11	24	21	23	9	26	9	24	10	26	13	23
	15	33	13	35	14	34	8	40	12	36	7	40	12	36
LP[d]	141	47	43	41	125	44	22	67	37	52	32	52	45	42
	32	17	20	29	31	18	15	34	17	32	14	35	19	30

Males (n = 26)														
BC	11	7	7	8	10	7	6	13	7	10	7	11	7	8
	9	17	6	20	9	17	5	21	6	20	3	23	7	19
TE	58	6	6	7	43	7	3	15	5	11	5	9	7	7
	18	8	13	13	19	7	8	18	10	16	6	20	11	15
LL	26	16	22	25	24	17	16	44	21	34	16	34	24	24
	12	14	10	16	13	13	9	17	10	16	7	19	10	16
HL[f]	30	21	16	21	33	16	13	34	15	28	11	27	16	23
	18	7	12	13	16	9	8	17	11	14	7	17	13	12
SP	4	11	4	14	4	11	2	21	4	18	0	18	5	14
	6	20	4	22	6	20	4	22	6	20	0	26	4	22
CP	13	20	5	24	184	84	5	37	6	32	4	30	5	24
	5	21	3	23	3	46	4	22	6	20	1	25	3	23
IC	10	29	11	31	11	28	10	38	13	33	6	37	12	29
	5	21	5	21	5	21	5	21	5	21	4	22	5	21
LC	18	12	9	18	17	12	6	31	10	24	6	25	10	18
	13	13	7	19	13	13	5	21	6	20	3	22	7	19
LE[g]	28	33	13	32	27	32	11	36	12	32	12	36	13	31
	6	19	5	20	6	19	3	22	4	21	2	22	5	20
LP[f]	212	74	54	62	180	73	23	94	40	79	36	77	63	57
	18	8	12	14	18	8	9	17	11	15	9	17	10	16
Females (n = 23)														
BC	9	4	3	3	8	3	2	5	2	4	2	5	2	4
	7	16	5	18	7	16	5	18	6	17	3	18	6	17
TE	7	21	5	2	6	28	3	5	3	4	4	4	4	3
	15	8	8	15	15	8	6	17	9	14	5	18	10	13

(*continued*)

TABLE 10 (*Continued*)

	Brzycki		*Epley*		*Lander*		*Lombardi*		*Mayhew*		*O'Connor*		*Wathen*	
	+	–	+	–	+	–	+	–	+	–	+	–	+	–
LL	16	18	11	15	15	18	9	20	8	18	7	19	9	17
	10	13	6	17	10	13	5	18	8	15	5	18	8	15
HL	21	10	6	8	19	9	5	20	7	13	5	13	6	9
	18	5	8	15	18	5	4	19	5	18	3	20	8	15
SP	3	10	2	9	3	10	0	10	1	9	0	11	2	10
	2	21	1	22	2	21	0	23	1	22	0	23	2	21
CP	5	12	4	13	0	39	3	15	3	14	5	14	5	13
	4	19	4	19	0	23	2	21	5	18	1	22	4	19
IC	4	14	4	14	4	14	2	16	5	14	3	17	5	14
	4	19	3	20	4	19	2	21	2	21	1	21	3	20
LC	37	13	8	15	33	13	5	21	10	15	6	17	9	14
	11	12	8	15	11	12	4	19	4	19	4	19	7	16
LE	16	14	10	13	17	12	7	14	8	13	9	14	12	12
	9	14	8	15	8	15	5	18	8	15	5	18	7	16
LP	50	24	28	22	50	20	21	39	31	27	24	31	25	24
	14	9	8	15	13	10	6	17	6	17	5	18	9	14

[a]BC = biceps curl; TE = triceps extension; LL = low lat pull; HL = high lat pull down; SP = shoulder press; CP = chest press; IC = inclined chest press; LC = leg curl; LE = leg extension; LP = leg press.[b]Values in the first row represent the average difference (lbs) between 1-RM and 1-RMP. [c]Values in the second row are frequency counts of overestimates (+) and underestimates (-) of 1-RM. [d]$N = 48$. [e]$N = 47$. [f]$n = 25$.

statistics are provided in Table 10: frequency of overestimation and underestimation and the mean associated with each type of error. All formulas tended to underestimate 1-RM for the biceps curl, shoulder press, chest press, inclined chest press, and leg extension. The Brzycki and Lander formulas tended to overestimate 1-RM for triceps extension, high lat pull down, and leg press. Over all exercises, the O'Connor, Mayhew, Lombardi, and to a lesser extent the Wathen formulas tended to underestimate 1-RM. This pattern was most discernible in the total group and female sample.

DISCUSSION

Similar to Brzycki (1993), LeSuer et al. (1997), and Mayhew et al. (1995), prediction accuracy of 1-RM improved when RTF ≤ 10. Intuitively, as the number of RTF decreases (and conversely, the amount of weight lifted per repetition increases), the submaximal test becomes more akin to the 1-RM test, and greater congruence is expected. An additional explanation, however, may be hypothesized for the improvement. The formulas examined in this study, with the exception of the Mayhew, Lombardi, and Wathen equations, model the linear or straight-line relation between 1-RM and RTF. For example, Brzycki developed his formula on a "near linear relationship" between 1-RM and RTF based on Anderson and Haring's unpublished observations, which were reported in Sale and MacDougall (1981). The relation noted by Anderson and Haring was linear when RTF ≤10, but was nonlinear when RTF > 10. Brzycki modeled his equation on the linear portion of the relation; therefore, it is not surprising, as he noted, that his equation is more accurate when RTF ≤ 10. In contrast, the Mayhew and Lombardi formulas are exponential in form and take advantage of the nonlinear relation between 1-RM and RTF when RTF > 10.

Relative accuracy correlations obtained in this study were comparable to those reported for younger populations of males and females when predicting bench press (Knoll et al., 1995; LeSuer et al., 1997; Mayhew, Ball, Arnold, et al., 1992; Mayhew, Ball et al., 1992; Mayhew et al., 1995; Ware et al., 1995), squat (LeSuer et al., 1997; Ware et al.), and deadlift (LeSuer et al., 1997) and for an older population of males and females on the bench press (LeSuer et al., 1995). These findings provide minimal evidence for the accuracy of 1-RM prediction equations as they indicate that over a wide range of resistance exercises 1-RMP tended to increase as 1-RM increased.

Similarity statistics, coupled with both absolute and relative AE, present a different picture. These statistics are used to analyze the difference between 1-RM and 1-RMP means (i.e., similarity) and the mean of the individual differences between 1-RM and 1-RMP (i.e., AE). Similarity statistics revealed statistically significant mean differences between 1-RM and 1-RMP for the Lombardi and O'Connor formulas over all exercises. In addition, chest press, inclined chest press, and shoulder press evidenced a lack of similarity over all formulas. The utility of similarity statistics, however, is limited by (a) the failure to account for the reduction in overall mean error resulting from the "canceling" effect of combining overestimates and underestimates of 1-RM, and (b) the effect of correlations on the statistical power of the paired *t* test. In contrast, analysis of absolute and relative AE revealed relatively high error (relative AE ≥ 12% over the full range of RTF and ≥ 7% when RTF ≤ 10) in estimating 1-RM for all equations over all exercises. It is clear that analysis of AE provides a more precise picture of prediction accuracy.

With the exception of the Brzycki and Lander formulas for triceps extension, high lat pull down, and leg press, most formulas tended to underestimate 1-RM, a finding supported for the bench press by Mayhew, Ball, Arnold, et al. (1992) and Prinster, Mayhew, Arabas, Ware, and Bemben (1993). From a safety perspective, underestimation is preferable to overestimation of 1-RM; however, as noted previously here, the AE and relative AE analysis indicated a relatively high degree of inaccuracy in the estimation of 1-RM. This inaccuracy was most evident for the leg press, which would be unacceptably high for most applications.

Compared with males, data for females exhibited comparable relative accuracy, greater similarity, and lower AE over the full range of RTF trials; however, gender differences were minimized when RTF ≤10. Accounting for the gender difference is difficult over the full range of RTF. Analysis of the average percentage of 1-RM randomly assigned to males and females revealed that with the exception of the shoulder press and low lat pull exercise, females were assigned a slightly lower or the same average percent of 1-RM as males (Table 11). In addition, Table 11 shows that although the average number of RTF for females was slightly lower than males over the full range of RTF trials, generally, the average RTF across genders was similar.

Few published studies have compared accuracy of equations across gender. Mayhew, Ball, Arnold, et al. (1992) contrasted college-aged males and females while developing an exponential equation for predicting bench press 1-RM. Finding no significant differences in prediction equations for males and females, the researchers developed a single equation. Cross-validation indicated comparable relative accuracy and similarity across genders; however, females evidenced a slightly lower relative accuracy and slightly lower mean differences than males. Mayhew, Ball et al. (1992) compared bench press 1-RMP of college-aged males and females before and after training and reported no significant gender difference in relative accuracy, percentage of 1-RM, and number of repetitions. Because gender differences in this study were minimal when RTF ≤ 10, the use of gender-specific formulas is not recommended.

A question of some importance is the accuracy of 1-RM prediction equations across a range of resistance exercises. Ware et al. (1995) examined the accuracy of the Brzycki, Epley, Lander, and Mayhew formulas in predicting bench press

TABLE 11
Average Number of Repetitions for Repetitions to Fatigue (Minimum and Maximum Values in Parentheses)

	Unlimited Repetitions			*Repetitions ≤10*		
	Total Group	*Males*	*Females*	*Total Group*	*Males*	*Females*
BC[a]	11 (2, 30)	12 (3, 23)	10 (2, 30)	7 (2, 10)	7 (3, 10)	6 (2, 10)
TE	15 (3, 40)	16 (3, 350	14 (3, 40)	7 (3, 10)	7 (3, 10)	7 (3, 10)
LL	11 (1, 25)	11 (4, 20)	10 (1, 25)	6 (1, 10)	7 (4, 10)	6 (1, 10)
HL	14 (3,25)	12 (3, 25)	16 (3, 25)	7 (3, 10)	7 (3, 10)	7 (3, 10)
SP	9 (2, 21)	10 (3, 21)	8 (2, 18)	6 (2, 10)	7 (3, 10)	6 (2, 10)
CP	10 (1, 25)	11 (1, 20)	9 (1, 25)	5 (1, 10)	5 (1, 10)	5 (1, 10)
IC	9 (3, 18)	9 (4, 17)	9 (3, 18)	7 (3, 10)	7 (4, 10)	6 (3, 10)
LC	14 (2, 30)	13 (4, 25)	15 (2, 30)	6 (2, 10)	7 (4, 10)	5 (2, 9)
LE	10 (1, 25)	10 (4, 25)	10 (1, 21)	7 (1, 10)	8 (4, 10)	6 (1, 10)
LP	14 (3, 34)	15 (3, 34)	13 (4, 26)	7 (3, 10)	8 (3, 10)	5 (4, 10)

[a]BC = biceps curl; TE = triceps extension; LL = low lat pull; HL = high lat pull down; SP = shoulder press; CP = chest press; IC = inclined chest press; LC = leg curl; LE = leg extension; LP = leg press.

and squat 1-RM of 45 Division II college football players. The prediction of bench press 1-RM was more accurate than prediction of squat 1-RM. They concluded that none of the equations accurately predicted the squat; however, their subjects were permitted to choose submaximal weights, which resulted in an average of RTF > 10. More recently, LeSuer et al. (1997) investigated the accuracy of the Brzycki, Epley, Lander, Lombardi, Mayhew, O'Connor, and Wathen formulas for predicting 1-RM of bench press, squat, and deadlift of untrained male and female college-aged students. When predicting 1-RM for these three exercises, subjects were limited to submaximal weight resulting in RTF ≤ 10. Similar to this investigation, all formulas revealed acceptable relative accuracy across exercises ($r \geq .95$). Similarity statistics, however, showed that all equations significantly underestimated deadlift (LeSuer et al., 1997). The Mayhew and Wathen formulas most accurately predicted bench press 1-RM, whereas the Wathen formula most accurately predicted squat 1-RM. LeSuer et al. did not report AE statistics. In this investigation, the relative accuracy of all equations was acceptable across all exercises except leg curl for females and high lat pull down for males when RTF ≤ 10; however, similarity and AE statistics revealed differences in 1-RM equations across resistance exercises. In particular, chest press, inclined chest press, shoulder press, and leg extension revealed a lack of similarity over all equations. The Mayhew and Wathen formulas provided the lowest mean differences across all but inclined chest press, leg extension, and shoulder press when RTF ≤ 10. Analysis of AE relative to 1-RM indicated that the Brzycki and Lander formulas have an extraordinarily high error for triceps extension and leg press over the full range of RTF trials. When RTF ≤ 10, the relative error was more comparable for all formulas across all exercises. Interestingly, when RTF ≤ 10, triceps extension and leg press showed the lowest relative AE.

SUMMARY AND CONCLUSIONS

The major findings of this investigation were as follows:

1. Both absolute and relative AE were high over all formulas and exercises, therefore limiting the practical application of these formulas.
2. Relative accuracy, similarity, and AE of 1-RM prediction equations improved significantly when RTF ≤ 10.
3. The accuracy of 1-RM prediction equations varied over different resistance exercises.
4. The relative accuracy of 1-RM prediction equations was generally high over a wide range of resistance exercises when RTF ≤ 10.
5. Compared with males, females exhibited comparable relative accuracy, greater similarity, and lower AE over the full range of RTF trials; however, gender differences were minimal when RTF ≤ 10. Therefore, gender-specific formulas are not recommended.
6. The Mayhew, Epley, and Wathen formulas evidenced the highest relative accuracy and lowest AE over the exercises examined in this study. From a clinical perspective, the Mayhew formula may be preferred because it tended to underestimate 1-RM and thus reduces safety concerns.

Although the seven equations used in this study can accurately predict that if 1-RMP increases then 1-RM is likely to increase, a substantial amount of error exists when comparing actual 1-RM to 1-RMP. If the focus of research using 1-RMP is association among variables, then the high relative accuracy of the equations examined in this investigation indicates that they have some utility. From a clinical perspective, if the aim of prediction is to provide safe "ball-park" 1-RM values for older adults interested in starting a resistance training program, the Mayhew formula provides the most accurate predictions across gender and exercises when RTF ≤ 10.

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