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Cross-validation of Equations for Estimating Pre-training, Post-training, and Training-induced Changes in Leg Extension 1-Repetition Maximum

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Abstract Eight previously published equations (EQs) that estimate 1-repetition maximum (1-RM) from repetitions to failure (RTF) were cross-validated for estimating pre-training, post-training, and training-induced changes (post-training minus pre-training) in leg extension (Leg Ext) 1-RM. Thirty-one recreationally active men (age: 20.8±1.5 years; body mass: 81.7±14.6 kg) trained 3 days per week for 8 weeks with 1 bilateral Leg Ext set to failure at ~80% 1-RM. The subjects performed Leg Ext 1-RM and RTF tests at pre-training and post-training. The pre-training and post-training RTF were performed at ~80% pre-training 1-RM and the values were input into the EQs for estimating the 1-RM values. The measured changes in 1-RM and RTF from pre-training to post-training were analyzed with paired *t*-tests. The cross-validation statistical analyses included paired *t*-tests for the constant error, correlation coefficient, standard error of the estimate, and total error (TE). Training significantly increased ($p <$ 0.001) Leg Ext 1-RM (pre-training: 126.9±25.2 kg; post-training: 161.6±24.6 kg) and RTF (pre-training: 9.8±2.7 repetitions; post-training: 19.9±7.6 repetitions) by 34.6 kg and 10.1 repetitions, respectively. The cross-validation analyses indicated that an exponential EQ (Estimated 1-RM = $\text{RTF}^{0.1}$•weight lifted) exhibited the lowest TE (3.9 kg) for estimating pre-training 1-RM, however, all EQs exhibited high TE values for estimating post-training 1-RM (21.9 to 606.3 kg) and changes in 1-RM values (24.0 to 603.1 kg) relative to the mean measured values of 161.5 kg and 34.6 kg, respectively. Therefore, this exponential EQ is recommended for estimating a pre-training Leg Ext 1-RM with 4 to 17 RTF in recreationally active men, but none of the EQs in the present study are recommended for estimating post-training Leg Ext 1-RM or changes in Leg Ext 1-RM values with post-training RTF ranging from 11 to 37 RTF.

Keywords: *prediction, error, accuracy, muscular strength, resistance training, repetitions to failure*

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1. Introduction

One of the primary goals of resistance training is to increase muscular strength [1]. A 1-repetition maximum (1-RM), which is the maximum amount of weight that can be lifted in a single repetition through a full range of motion, is the most common test used for measuring dynamic constant external resistance (DCER) muscular strength [2], and thus, can be used to track training-induced changes in DCER strength (i.e., post-training 1-RM minus pre-training 1-RM). Performing a 1-RM, however, may not be practical or warranted in certain situations [3,4,5,6,7,8]. For example, 1-RM testing may detract time and effort away from training sessions [3,4,6,8], especially when testing multiple movements or subjects, because it is a trial-and-error method often involving multiple warm-up sets and 1-RM attempts with 2 to 4 minutes of rest between 1-RM attempts [7,9]. In addition, 1-RM testing involves lifting near-maximal, maximal, and supramaximal weights (i.e., failed 1-RM attempts), which may increase the concerns of injury risk among practitioners and/or subjects [3,4,5,6,8]. Therefore, a popular alternative to 1-RM testing has been to estimate 1-RM values from a single set of repetitions to failure (RTF) performed at submaximal weights [3,4,5,6,7,8,9]. Although estimating 1-RM based on the load-velocity relationship using devices that measure velocity has also gained popularity [10], using RTF to estimate 1-RM may be more practical for practitioners and/or subjects who do not have access to or the financial means for devices that measure velocity.

Various sources, including published papers [5] [11-20], books [21,22,23,24], and a 1-RM estimation chart [25], have proposed 1 or more equations (EQs) to estimate 1-RM values from RTF performed at submaximal weights ranging from 20 to 95% 1-RM. Most of these EQs were derived for the bench press movement [11-20], however, some EQs have been developed for other movements, including the leg extension (Leg Ext) [14,15], arm curl [14,15], leg press [20], leg curl [15], lat machine pulldown [15], inclined press [14], and triceps extension [14]. In contrast, several "generic" EQs have also been proposed, which can be defined as EQs from sources that did not specify their use for a particular movement and provided limited information regarding their derivation methodology [5,21,22,23,24,25].

Cross-validation procedures have been used to quantify the accuracy of EQs for estimating 1-RM values from RTF for various movements when applied to samples that are independent of the sample used to derive the EQs [4,8,26,27,28,29,30,31]. The independent cross-validation samples can be from the population used to derive the EQ or different populations to determine the external validity of the EQs [4,8,26,27,28,29,30,31]. For example, Wood et al. [31] cross-validated 6 generic EQs and 1 bench press-specific EQ for estimating 1-RM values of various movements, including the Leg Ext, in older, sedentary men and women. Furthermore, cross-validation procedures have also been used to quantify the accuracy of EQs for estimating pre-training, post-training, and training-induced changes in bench press 1-RM values [6,8,32]. Previous studies, however, have not cross-validated generic and Leg Ext-specific EQs for estimating pre-training, post-training, and absolute training-induced changes in Leg Ext 1-RM values in young, recreationally active [33] men. Therefore, the purpose of the present study was to cross-validate 5 generic EQs and 3 Leg Ext-specific EQs (Table 1) for estimating pre-training, post-training, and absolute training-induced changes in Leg Ext 1-RM values in young, recreationally active men. Based on previous findings [6,8,31,32], it was hypothesized that the EQs would vary in accuracy for estimating pre-training, post-training, and training-induced changes in Leg Ext 1-RM values.

2. Materials and Methods

2.1. Subjects

Thirty-one men (mean ± SD: age = 20.8 ± 1.5 years, height = 180.8 ± 7.7 cm, body mass = 81.7 ± 14.6 kg) volunteered to participate in this study. The subjects were recreationally active [33] and reported no lower body pathologies that would affect their Leg Ext performance. The subjects reported participating in the following activities and sports for at least 1 day per week: Resistance training (*n* = 20); running (*n* = 15); walking (*n* = 10); basketball (*n* = 2); biking (*n* = 2); soccer (*n* = 1); rowing (*n* = 1); martial arts (*n* = 1); and yard work (*n* = 1). The study was approved by the Institutional Review Board for Human Subjects (IRB Approval #: 20210721118FB). All subjects signed a written Informed Consent form and completed a Health History Questionnaire before any testing.

2.2. Study Design

Before training, the subjects visited the laboratory on 2 separate occasions, separated by at least 24 hours. The first visit was an orientation and familiarization session where demographic information was collected, and the subjects were familiarized with the bilateral Leg Ext testing and resistance training procedures. For the second visit, the subjects completed a pre-training Leg Ext 1-RM and an RTF test, separated by at least 5 minutes of rest. The pre-training Leg Ext RTF test was performed with a weight that was approximately 80% of their pre-training 1-RM. Following the second visit, with at least 24 hours of separation, the subjects visited the laboratory for their first training session. All training sessions consisted of 2 warm-up sets and 1 working set for the Leg Ext movement. The subjects trained for 3 days per week for 8 weeks. At least 24 hours after the final training session, the subjects completed post-training Leg Ext 1-RM and RTF tests, separated by approximately 5 minutes of rest. The post-training RTF was performed with the same weight as the pre-training RTF test (~80% pre-training 1-RM). The number of RTF and weight used for the RTF test were input into the EQs (Table 1) to estimate the subjects' pre-training and post-training Leg Ext 1-RM values. All Leg Ext testing and training were performed on a Cam Series Leg Extension and Curl (Body-Solid, GCEC340B) with free weights (Figure 1). The present study's design allowed for the cross-validation of estimated pre-training, post-training, and absolute training-induced changes in Leg Ext 1-RM values from RTF.

Table 1. The equations used in the cross-validation analyses, and the sources' derivation methodologies

Equation Number	Source	Equation	Sample	Movement	Range of RTF	*r*	SEE (kg)
1	Beam and Adams [21]	$W / ((100 - (RTF \cdot 2.5)) / 100)$	N.A.	N.A.	N.A.	N.A.	N.A.
2	Dohoney et al. [14]	$82.07 + (0.76 \cdot W) + (5.66 \cdot RTF)$	Untrained men (*n* = 34)	Leg Ext	4 – 6	0.82	26.3
3	Dohoney et al. [14]	$95.0 + (0.65 \cdot W) + (8.52 \cdot RTF)$	Untrained men (*n* = 34)	Leg Ext	7 – 10	0.76	30.1
4	Julio et al. [15]	$-0.46 + (0.79 \cdot RTF) + (1.08 \cdot W)$	Recreationally trained men (*n* = 20)	Leg Ext	1 – 19	0.97	3.9
5	Lander [25]	$W / (1.013 - 0.0267123 \cdot RTF)$	N.A.	N.A.	N.A.	N.A.	N.A.
6	Lombardi [22]	$RTF^{0.1} \cdot W$	"Intermediate and advanced trainees" (*n* = N.A.)	N.A.	N.A.	N.A.	N.A.
7	O'Connor et al. [23]	$(W \cdot 0.025 \cdot RTF) + W$	N.A.	N.A.	N.A.	N.A.	N.A.
8	Wathen [24]	$W / ([48.8 + 53.8e^{-0.075 \cdot RTF}] / 100)$	N.A.	N.A.	N.A.	N.A.	N.A.

Ext = extension, N.A. = not available from the source, RTF = repetitions to failure, SEE = standard error of the estimate, W = weight (kg) used during the repetitions to failure.

2.3. Procedures

2.3.1. 1-Repetition Maximum Testing

Before performing any Leg Ext repetitions, the subjects' maximum Leg Ext heights were assessed with a ruler taped to a tripod to ensure they moved through a full range of motion. The subjects were asked to fully extend their legs without hyperextending, and a researcher adjusted the tripod so that the ruler rested on top of the shin pad. This method provided consistent assessments between subjects and across time (Figure 1). The present study followed the National Strength and Conditioning Association's protocol for 1-RM testing [7]. The subjects warmed up with a lightweight that easily allowed for 5 to 10 repetitions. After 1 minute of rest, the subjects performed another warm-up set of 3 to 5 repetitions with a 14 to 18 kg increase in weight. Following 2 minutes of rest, the subjects performed 2 to 3 estimated near-maximal load repetitions with a 14 to 18 kg increase in weight. After 2 to 4 minutes of rest, the first 1-RM attempt was performed with an increase of weight of 14 to 18 kg. If the subjects completed a successful repetition, they were given 2 to 4 minutes of rest before performing another attempt with an increase in weight of 14 to 18 kg. In contrast, if the subjects failed the attempt, they were given 2 to 4 minutes of rest before performing another repetition with a decrease in weight of 7 to 9 kg. A repetition was considered successful if the Leg Ext machine's shin pad touched the ruler (Figure 1).

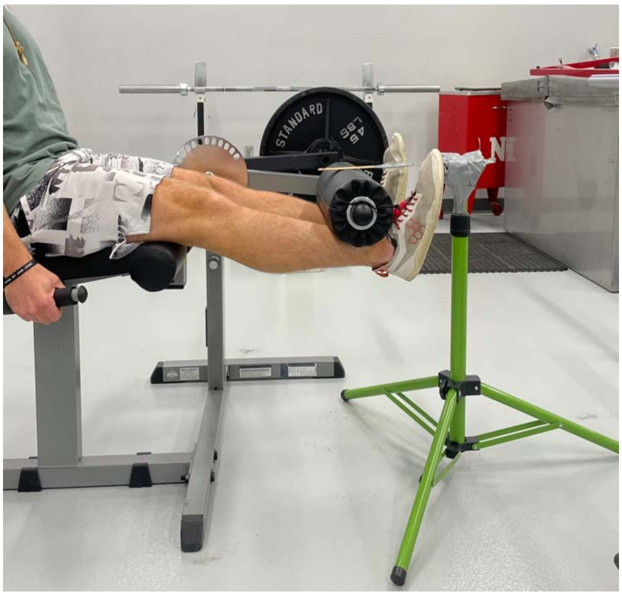

Figure 1. The bilateral leg extension setup that was used for testing and training

2.3.2. Repetitions to Failure Testing

The pre-training and post-training RTF tests were both performed at approximately 80% pre-training 1-RM. The same success indicators as the 1-RM testing were used for counting repetitions during the RTF testing. The subjects were instructed not to rest at the starting position between repetitions for more than approximately 1 to 2 seconds. The test was stopped if the subjects rested for more than approximately 3 seconds between repetitions, volitionally ended the test, or failed to complete 2 consecutive repetitions.

2.3.3. Resistance Training Intervention

The Leg Ext training intervention was 3 days per week for 8 weeks. The subjects were required to complete at least 20 training sessions to be included in this study. All training sessions consisted of 2 warm-up sets and 1 working set. For the first training session, the first and second warm-up sets consisted of 8 repetitions performed at approximately 50 and 70% pre-training 1-RM, respectively. The working set consisted of RTF at approximately 80% pre-training 1-RM and the same procedure as the RTF testing was used for counting the number of RTF. Throughout the training program, if the subjects completed 8 to 10 RTF, 11 to 15 RTF, or >15 RTF for the working set, the subsequent training session's weights for the warm-up and working sets were increased by 4.5 kg, 6.8 to 9.1 kg, or 11.3 to 13.6 kg, respectively. In contrast, if the subjects completed less than 8 RTF for the working set, the subsequent training session's weights for the warm-up and working sets were unchanged.

2.3.4. Equations for Estimating 1-Repetition Maximum

Eight EQs (Table 1) that estimate 1-RM from RTF were selected for this study [14,15,21,22,23,24,25]. Lander [25] and Wathen [24] provided 1-RM charts without a specific EQ, but their EQs were obtained from other sources [4,8,26,30,31]. The EQs used a linear (EQs 1-5 and 7) or exponential (EQs 6 and 8) model to estimate 1-RM. Equations 2-4 were derived specifically for the Leg Ext movement. In contrast, EQs 1 and 5-8 were from sources, such as books [21,22,23,24] or a published 1-RM chart [25], that provided limited information regarding the derivation of the EQ (see Table 1). Equations that were derived specifically for movements other than the Leg Ext were not included in this study [11,12,13,16,17,18,19,20].

2.4. Statistical Analyses

Absolute changes in the measured Leg Ext 1-RM, % 1-RM of the RTF weight, and number of RTF values from pre-training to post-training were analyzed with paired *t*-tests. Estimated pre-training 1-RM, estimated post-training 1-RM, and estimated absolute training-induced changes in 1-RM values were statistically cross-validated by examining the following: constant error (CE = differences between estimated and measured means) using a paired *t*-test; correlation coefficient (*r*); standard error of the estimate (SEE); and total error (TE), using equation (1).

$$TE = \sqrt{\frac{\Sigma\left(Estiamted\ Value - Measured\ Value\right)^2}{Sample\ Size}} \tag{1}$$

The following guidelines [34] were used for classifying the *r* values: Poor ($r < 0.40$); fair ($r = 0.40$ to 0.59); good ($r = 0.60$ to 0.74); and excellent ($r = 0.75$ to 1.00). The accuracy of the estimated values was determined with the following cross-validation criteria [35–38]: (a) mean estimated and measured values should be close (i.e., CE should be close to zero); (b) there should be close agreement between estimated and measured SD values; (c) a low SEE value is desirable; and (d) TE values should be calculated since they reflect the combined errors associated with the CE and SEE and quantify the error around the line of identity for estimated and measured values. Although all criteria were considered, primary consideration was given to TE for determining the accuracy of an EQ, because Sinning et al. [38] suggested that TE is the single, best criterion for determining true differences between estimated and measured values. Statistical significance was determined with an alpha level of $p \le 0.05$. All data were analyzed using IBM Statistics version 29 (Armonk, NY).

3. Results

The absolute changes in the measured Leg Ext 1-RM, % 1-RM of the RTF weight, and the number of RTF from pre-training to post-training are presented in Table 2. Leg Ext 1-RM and number of RTF significantly ($p < 0.001$) increased from pre-training to post-training, while % 1-RM of the RTF weight significantly ($p < 0.001$) decreased from pre-training to post-training.

The summary of the results for the cross-validation of estimated pre-training Leg Ext 1-RM is presented in Table 3. Six EQs (EQs 1-3, 5, 6, and 8) significantly ($p < 0.001$ to $p = 0.044$) overestimated pre-training Leg Ext 1-RM, with CE values ranging from 1.4 kg (EQ 6) to 118.0 kg (EQ 3), while EQ 4 underestimated pre-training 1-RM ($p < 0.001$; CE = -9.0 kg). Equation 7 exhibited no significant difference between the mean estimated and measured pre-training 1-RM ($p = 0.558$; CE = 0.7 kg). Equations 1 and 4-8 exhibited excellent correlations between estimated and measured pre-training 1-RM ($r = 0.91$ to 0.99), while EQ 3 and EQ 2 exhibited fair ($r = 0.56$) and good ($r = 0.74$) correlations, respectively. The SEE and TE values for all EQs' estimates of pre-training 1-RM ranged from 2.7 kg (EQ 4) to 21.3 kg (EQ 3) and 3.9 kg (EQ 6) to 120.5 kg (EQ 3), respectively. The differences between the estimated and measured SD values for pre-training 1-RM ranged from -3.1 kg (EQ 4) to 5.3 kg (EQ 5).

For the post-training assessments (Table 4), EQs 1-3 overestimated ($p < 0.001$ to $p = 0.007$) Leg Ext 1-RM, with CE values ranging from 98.3 kg (EQ 1) to 169.7 kg (EQ 3), while EQs 4, 6, and 7 underestimated ($p < 0.001$ to $p = 0.017$) Leg Ext 1-RM, with CE values ranging from -35.6 kg (EQ 4) to -9.4 kg (EQ 7). Equations 5 and 8 exhibited no significant difference between the mean estimated and measured post-training 1-RM (EQ 5: $p = 0.068$, CE = 198.2 kg; EQ 8: $p = 0.50$, CE = 2.7 kg). Equations 4-8 exhibited good correlations between estimated and measured post-training 1-RM ($r = 0.71$ to 0.75), while EQs 1-3 exhibited poor to fair correlations ($r = 0.22$ to 0.40). The SEE and TE values for all EQs' estimates of post-training 1-RM ranged from 16.5 kg (EQ 4) to 24.9 kg (EQ 5) and 21.9 kg (EQ 8) to 606.3 kg (EQ 5), respectively. The differences between the estimated and measured SD values for post-training 1-RM ranged from -4.2 kg (EQ 4) to 559.1 kg (EQ 5).

For the absolute training-induced changes in 1-RM values (Table 5), EQs 1-3 significantly overestimated ($p < 0.001$ to $p = 0.013$) the mean change in 1-RM, with CE values ranging from 22.8 kg (EQ 2) to 88.3 kg (EQ 1), while EQs 4, 6, and 7 underestimated ($p < 0.001$ to $p = 0.016$) the mean change in 1-RM, with CE values ranging from -26.6 kg (EQ 4) to -10.1 kg (EQ 7). Equations 5 and 8 exhibited no significant difference between the mean estimated and measured change in 1-RM (EQ 5: $p = 0.083$, CE = 187.5 kg; EQ 8: $p = 0.085$, CE = -7.5 kg). Equations 1-4 exhibited fair correlations between the estimated and measured absolute changes in 1-RM values ($r = 0.44$ to 0.51), while EQs 5-8 exhibited poor correlations ($r = 0.15$ to 0.33). The SEE and TE values for all EQs' estimates of the absolute training-induced changes in 1-RM values ranged from 17.8 kg (EQs 2-4) to 20.4 kg (EQ 6) and 24.0 kg (EQ 7) to 603.1 kg (EQ 5), respectively. The differences between the estimated and measured SD values for the absolute changes in 1-RM values ranged from -15.1 kg (EQ 6) to 568.8 kg (EQ 5).

Table 2. Performance characteristics of the subjects ($n = 31$)

	Pre-training		Post-training				
Variable	Mean ± SD	Range	Mean ± SD	Range	*t*	*p*-value	Absolute Change
Leg Extension 1-RM (kg)	126.9 ± 25.2	53.3 – 172.4	161.5 ± 24.6	111.1 – 213.2	9.48	<0.001	34.6
RTF weight (kg)[†]	102.4 ± 20.1	43.8 – 138.4	102.4 ± 20.1	43.8 – 138.4	–	–	–
% 1-RM of the RTF weight	80.7 ± 0.7	80.0 – 83.3	63.6 ± 9.7	33.9 – 73.8	-9.79	<0.001	-17.1
Number of RTF	9.8 ± 2.7	4 – 17	19.9 ± 7.6	11 – 37	7.25	<0.001	10.1

1-RM = 1-repetition maximum, RTF = repetitions to failure

[†] The post-training RTF was performed with the same weight as the pre-training RTF.

Table 3. Results of the cross-validation analyses for estimating pre-training leg extension 1-repetition maximum

Equation Number	Measured Pre-training 1-RM (mean ± SD)	Estimated Pre-training 1-RM (mean ± SD)	CE	*t*	*p*-value	*r*	SEE	TE
1	126.9 ± 25.2	136.8 ± 30.0	9.9	4.53	<0.001	0.92	10.3	15.6
2	126.9 ± 25.2	215.2 ± 22.9	88.3	28.17	<0.001	0.74	17.2	90.0
3	126.9 ± 25.2	244.9 ± 27.9	118.0	26.21	<0.001	0.56	21.3	120.5
4	126.9 ± 25.2	117.9 ± 22.1	-9.0	-12.46	<0.001	0.99	2.7	9.9
5	126.9 ± 25.2	137.7 ± 30.5	10.8	4.54	<0.001	0.91	10.9	16.9
6	126.9 ± 25.2	128.3 ± 25.9	1.4	2.10	0.044	0.99	3.6	3.9
7	126.9 ± 25.2	127.6 ± 26.5	0.7	0.59	0.558	0.97	6.4	6.5
8	126.9 ± 25.2	137.1 ± 29.3	10.2	6.07	<0.001	0.95	7.9	13.8

1-RM = 1-repetition maximum; CE = constant error; SEE = standard error of the estimate; and TE = total error values are expressed in kg.

Table 4. Results of the cross-validation analyses for estimating post-training leg extension 1-repetition maximum

Equation Number	Measured Post-training 1-RM (mean ± SD)	Estimated Post-training 1-RM (mean ± SD)	CE	*t*	*p*-value	*r*	SEE	TE
1	161.5 ± 24.6	259.7 ± 191.0	98.3	2.92	.007	0.22	24.4	208.7
2	161.5 ± 24.6	272.6 ± 40.3	111.1	16.26	<0.001	0.40	23.0	117.2
3	161.5 ± 24.6	331.2 ± 61.6	169.7	15.87	<0.001	0.28	24.0	179.5
4	161.5 ± 24.6	125.9 ± 20.4	-35.6	-12.11	<0.001	0.75	16.5	39.1
5	161.5 ± 24.6	359.7 ± 583.7	198.2	1.90	0.068	0.71	24.9	606.3
6	161.5 ± 24.6	137.0 ± 26.3	-24.5	-7.07	<0.001	0.72	17.5	30.9
7	161.5 ± 24.6	152.1 ± 31.0	-9.4	-2.54	0.017	0.75	16.6	22.4
8	161.5 ± 24.6	164.2 ± 33.2	2.7	0.683	0.50	0.75	16.7	21.9

1-RM = 1-repetition maximum; CE = constant error; SEE = standard error of the estimate; and TE = total error values are expressed in kg.

Table 5. Results of the cross-validation analyses for estimating the absolute change in leg extension 1-repetition maximum

Equation Number	Measured Absolute Change in 1-RM (mean ± SD)	Estimated Absolute Change in 1-RM (mean ± SD)	CE	*t*	*p*-value	*r*	SEE	TE
1	34.6 ± 20.3	122.9 ± 194.9	88.3	2.63	0.013	0.44	18.6	204.0
2	34.6 ± 20.3	57.3 ± 44.0	22.8	3.33	0.002	0.51	17.8	43.8
3	34.6 ± 20.3	86.3 ± 66.2	51.7	4.91	<0.001	0.51	17.8	77.5
4	34.6 ± 20.3	8.0 ± 6.1	-26.6	-8.21	<0.001	0.51	17.8	31.9
5	34.6 ± 20.3	222.0 ± 589.1	187.5	1.79	0.083	0.33	19.5	603.1
6	34.6 ± 20.3	8.7 ± 5.2	-25.9	-7.12	<0.001	0.15	20.4	32.6
7	34.6 ± 20.3	24.5 ± 17.2	-10.1	-2.55	0.016	0.32	19.6	24.0
8	34.6 ± 20.3	27.0 ± 16.5	-7.5	-1.78	0.085	0.20	20.3	24.4

Absolute change in 1-RM = post-training 1-repetition maximum minus pre-training 1-repetition maximum; CE = constant error; SEE = standard error of the estimate; and TE = total error values are expressed in kg.

4. Discussion

The present study used cross-validation procedures to provide unique information regarding the accuracy and magnitude of error of 5 generic EQs and 3 Leg Ext-specific EQs (Table 1) for estimating pre-training, post-training, and absolute training-induced changes in Leg Ext 1-RM values in young, recreationally active men. In the present study, most EQs (EQs 1-3, 5, 6, and 8) overestimated pre-training Leg Ext 1-RM (Table 3). In contrast, EQ 4 underestimated pre-training Leg Ext 1-RM, and EQ 7 exhibited no significant systematic error between the estimated and measured Leg Ext 1-RM values. These findings were not consistent with those of Wood et al. [31], who reported that EQs 5, 6, and 7 underestimated Leg Ext 1-RM and EQ 8 overestimated Leg Ext 1-RM in sedentary older men, which may be attributable to age-related differences in muscular endurance [39,40]. Equation 2 and EQ 3 are Leg Ext-specific EQs, but exhibited large CE values (88.3 to 118.0 kg, respectively), likely due to the present study including pre-training RTF values (4 to 17 RTF) outside the ranges for which the EQs were derived (EQ 2: 4 to 6 RTF; EQ 3: 7 to 10 RTF). Thus, the current findings indicated that the accuracy of EQ 2 and EQ 3 was greatly compromised for RTF values greater than 6 and 10 repetitions, respectively, and therefore, should not be used in those situations. All EQs, except for EQ 2 and EQ 3, exhibited excellent correlations (r = 0.91 to 0.99) between estimated and measured Leg Ext pre-training 1-RM (Table 3). Furthermore, EQ 6 demonstrated the lowest TE value of 3.9 kg for estimating pre-training Leg Ext 1-RM, which represented 3.1% of the mean measured pre-training 1-RM of 126.9 kg. Notably, EQ 6 is a generic EQ that uses an exponential model to estimate 1-RM. Although the pattern of the relationship (linear versus curvilinear) between % Leg Ext 1-RM and RTF has not been established, Reynolds et al. [20] reported a negative, exponential relationship between % leg press 1-RM and RTF within the range of 1 to 20 RTF. Thus, future studies should determine if the relationship between % Leg Ext 1-RM and RTF is linear or curvilinear across a wide range of RTF values.

Most EQs either underestimated (EQs 4, 6, and 7) or overestimated (EQs 1-3) post-training Leg Ext 1-RM, while EQ 5 and EQ 8 exhibited no significant differences between the mean estimated and measured post-training 1-RM values (Table 4). Equation 5 demonstrated a large CE value of 198.2 kg because 9 subjects with high post-training RTF values between 23 and 37 RTF had unrealistic overestimations of post-training Leg Ext 1-RM values that ranged from 109.7 to 3,243.9 kg, respectively. Furthermore, the r values for the relationship between the estimated and measured post-training Leg Ext 1-RM values ranged from poor to good (r = 0.22 to 0.75). In addition, for all EQs, the TE value relative to the mean measured value ([TE / mean measured value]•100) was higher for the post-training 1-RM estimates (Table 4) than for the pre-training 1-RM estimates (Table 3). Therefore, the EQs in the present study were less accurate at estimating post-training 1-RM than pre-training 1-RM, likely due to differences in RTF values between the pre-training (4 to 17 RTF) and post-training (11 to 37 RTF) assessments. These results supported previous reports [30,31,41] of greater accuracy in estimating 1-RM when using weights that resulted in lower RTF values (≤10 RTF) than higher RTF values (>10 RTF). Furthermore, EQ 8 demonstrated the lowest TE value (21.9 kg) for estimating post-training 1-RM. Similar to the pre-training 1-RM estimates, these findings indicated that an exponential model most accurately estimated post-training Leg Ext 1-RM values. The TE value for EQ 8's estimates of post-training 1-RM values, however, represented 13.6% of the mean measured post-training 1-RM value of 161.5 kg, which was approximately 4 times greater than the estimates from EQ 6 for the pre-training 1-RM values (TE = 3.1% of the mean measured pre-training 1-RM).

Similar to the post-training 1-RM estimates (Table 4), most EQs either underestimated (EQs 4, 6, and 7) or overestimated (EQs 1-3) the absolute training-induced changes in Leg Ext 1-RM, while EQ 5 and EQ 8 exhibited no significant difference between the mean estimated and measured absolute training-induced changes in Leg Ext 1-RM values (Table 5). In addition, EQ 5 exhibited a large CE (187.5 kg) due to the unrealistic overestimations from the post-training 1-RM estimates. Furthermore, the EQs demonstrated poor to fair (r = 0.15 to 0.51) relationships between estimated and measured absolute changes in 1-RM values, and the TE values relative to the mean measured absolute change in 1-RM of 34.6 kg ranged from 69.4% to 1,743.1%. Therefore, none of the EQs in the present study accurately estimated absolute training-induced changes in Leg Ext 1-RM values, likely because the high range of post-training RTF values resulted in inaccurate estimates of post-training Leg Ext 1-RM values.

The present study's findings were limited to young, recreationally active men. Future studies should cross-validate EQs for estimating pre-training Leg Ext 1-RM, post-training Leg Ext 1-RM, and training-induced changes in Leg Ext 1-RM values for use with other populations, including male and female athletes and older adults. In addition, for post-training RTF testing, future cross-validation studies should use heavier weights that would result in fewer RTF than the present study to determine if the EQs can more accurately estimate post-training Leg Ext 1-RM and absolute training-induced changes in Leg Ext 1-RM values. Furthermore, future cross-validation studies should compare generic EQs (not specified for a particular movement) versus movement-specific EQs (derived for a specific movement) with varying movements (bench press, leg press, squat, etc.) and/or exercise equipment (free-weights versus various types of machines) to examine their generalizability and external validity for estimating pre-training 1-RM, post-training 1-RM, and absolute training-induced changes in 1-RM values.

5. Conclusions

The cross-validation analyses in the present study indicated that EQ 6 most accurately estimated pre-training Leg Ext 1-RM. None of the EQs, however, provided accurate estimates of post-training Leg Ext 1-RM or absolute training-induced changes in Leg Ext 1-RM. Therefore, EQ 6 is recommended for estimating a pre-training Leg Ext 1-RM in young, recreationally active men with weights resulting in 4 to 17 RTF, but none of the EQs cross-validated in the present study are recommended for estimating a post-training Leg Ext 1-RM or training-induced changes in Leg Ext 1-RM with post-training RTF values ranging from 11 to 37 RTF.

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Statement of Competing Interests

The authors have no competing interests.

List of Abbreviations

1-RM = 1-Repetition Maximum

DCER = Dynamic Constant External Resistance

RTF = Repetitions to Failure

EQ(s) = Equation(s)

Leg Ext = Leg Extension

CE = Constant Error

SEE = Standard Error of the Estimate

TE = Total Error

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