UPPER-BODY WORK CAPACITY AND 1RM PREDICTION ARE UNALTERED BY INCREASING MUSCULAR STRENGTH IN COLLEGE FOOTBALL PLAYERS

WILLIAM F. BRECHUE[1] AND **JERRY L. MAYHEW**[2,3]

[1]Center for Physical Development Excellence, Department of Physical Education, United States Military Academy, West Point, New York; [2]Human Performance Laboratory, Truman State University, Kirksville, Missouri; and [3]Department of Physiology, A. T. Still University of Health Sciences, Kirksville, Missouri

ABSTRACT

Brechue, WF and Mayhew, JL. Upper-body work capacity and 1RM prediction are unaltered by increasing muscular strength in college football players. *J Strength Cond Res* 23(9): 2477–2486, 2009—The purpose of this study was to assess changes in upper-body muscular strength and work capacity following off-season resistance training and the resultant effect on prediction of muscular strength (1 repetition maximum, or 1RM). National Collegiate Athletic Association (NCAA) Division II football players ($n = 58$) were divided into low-strength (LS, 1RM <275 lb, $n = 23$) and high-strength (HS, 1RM ≥275 lb, $n = 35$) groups based on initial 1RM bench press. Maximal repetitions to failure (RTF) were performed with a relative (60, 70, 80, and 90% of 1RM) and absolute load (185 lb for players with 1RM <275 lb; 225 lb for players with 1RM ≥275 lb) at pre- and post-training. Following training ($n = 58$), there was a significant increase in 1RM bench press (22.8 ± 12.0 lb) and body mass (3.7 ± 10 lb). There was no change in the number of repetitions performed (RTF) during relative load testing following training. However, RTF during absolute load testing was increased. Relative and absolute load work capacity (reps × load) increased with training, but there was no relationship between the change in work capacity and the changes in muscular strength. Predicted 1RMs were better at lower repetitions (3–5 RM, >85% 1RM) than at higher repetitions (>6RM, ≤80% 1RM) at both pre-and post-training. In conclusion, changes in muscular strength associated with the off-season training program used herein appear to have little effect on work capacity or prediction of 1RM using submaximal loads. For repetition predictions to accurately track changes following resistance training, the test load must be relatively high (>85% 1RM) and the repetitions low (≤5 reps).

KEY WORDS off-season conditioning, performance evaluation, bench press

INTRODUCTION

Maximal improvement in physical ability among football players is usually achieved during the off-season conditioning period. The most concentrated period of off-season conditioning typically occurs during the winter months when training is focused on improvement of muscular strength and speed. Although the primary objective of off-season training may be the increase in muscular strength, the ability to perform multiple repetitions with a given submaximal load (work capacity) may also be important. The increase in muscular work capacity might indicate improved ability of a player to perform at high intensities over the short span of a single football play (6). Although muscular strength and work capacity are generally accepted to be related, the relationship is questionable and is defined by training state (11,15,22) and/or set and repetition pattern utilized in the training program (9,23).

Training program design is based on various combinations of sets and repetitions, with the training load typically based on percentages of the 1-repetition maximum (%1RM), especially for foundational exercises such as the bench press and squat. Assessment of progress and accurate progression of training load require the frequent measurement of the 1RM, which could prove to be a distraction with limited training time available during the off-season period. In addition, and perhaps more important, many coaches are reluctant to perform 1RM testing because of injury/safety issues relative to the information received. Some studies have shown that using repetition to fatigue (RTF) with submaximal loads to predict 1RM may offer an acceptable alternative to actual measurement of the 1RM when assessing strength during a training cycle (8). Paramount in the use of these prediction techniques is their ability to accurately and reliably

Address correspondence to William F. Brechue, bill.brechue@usma.edu.

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assess changes in actual strength during and following training. Recent studies have shown that predicted strength values can accurately reflect actual 1RM strength in both trained and untrained individuals (18,19) and provide sufficient accuracy in tracking changes in actual 1RM (1). However, these studies have typically been limited to nonathlete populations or previously untrained individuals with little information on the accuracy of prediction models to track changes within the training cycle of athletes. It would be beneficial for strength and conditioning specialists to know the impact of training state on prediction of 1RM and how well prediction methods parallel actual changes in 1RM with training in high-level athletes. Therefore, the purpose of this study was to assess work capacity following an off-season training program designed to increase muscular strength and to assess the effect of changing muscular strength on the predictive potential of various relative load (%1RM) RTF tests, in contrast to absolute load RTF tests, to estimate 1RM bench press of trained football players.

METHODS

Experimental Approach to the Problem

To assess the changes in work capacity resulting from off-season resistance training and the effect of training state on predictive potential for estimating 1RM strength in the bench press, National Collegiate Athletic Association (NCAA) Division II college football players ($n = 58$) were assessed for maximal muscular strength and absolute and relative load RTF; work capacity was calculated from the product of load and repetitions (RTF). The capability of various load and repetition prediction equations from the literature to accurately estimate the 1RM bench press performance was assessed prior to and following training. All testing procedures were reviewed and approved by the University Human Subjects Review Board. The physical characteristics of the players by strength group are presented in Table 1.

Performance Testing

Players were evaluated for 1RM and absolute and relative muscular work capacity in the bench press at the beginning and end of 12 weeks of a winter conditioning program (December–March, prior to spring ball). All testing was performed in the competitive environment of the weight room. The 1RM was performed on the first day of each testing session. Relative-load RTF was performed on different days in random order using loads of 60, 70, 80, and 90% of 1RM. To perform the absolute-load RTF task, players were initially divided into 2 groups based on 1RM performance. However, following training and changes in muscular strength, a third group emerged and groups were as follows: low-strength (LS), change-strength (CG), and high-strength (HS) groups. The low-strength group (1RM <275 lb, $n = 11$) utilized an absolute load of 185 lb at both the pre- and post-training because their 1RM remained <275 lb following training. The change-strength group (CS, $n = 12$) utilized an absolute load of 185 lb at the pre-training test and 225 lb at the post-training test because their 1RM increased to higher than 275 lb following training. The high-strength group (HS, $n = 35$) utilized an absolute load of 225 lb at both the pre- and post-training because their 1RM was ≥275 lb throughout. These loads were selected because they represent loads typically used in college and professional football testing combines and they represented approximately the same percentages of 1RM for each group (Table 2). Work capacity was calculated as repetitions (RTF) times the load.

Training Program

Following the pre-tests, players participated in a 12-week winter training program designed in a linear periodization fashion prior to the spring practice schedule. The training program consisted of three 4-week training microcycles. The make-up of the microcycles was 3 weeks of training followed by 1 week of testing/recovery. Microcycles consisted of

TABLE 1. Physical characteristics of college football players by strength group.

	Low-strength group (LS, $n = 11$)		Change-strength group (CS, $n = 12$)		High-strength group (HS, $n = 35$)	
Variable	Pre-training	Post-training	Pre-training	Post-training	Pre-training	Post-training
Age (y)	18.9 ± 0.5		19.5 ± 1.2		19.7 ± 1.3	
Height (inches)	70.8 ± 2.2		72.7 ± 1.9		73.0 ± 2.9	
Body mass (lb)	184.1 ± 18.0	190.6 ± 17.3†	214.2 ± 33.7	218.0 ± 33.2†	249.5 ± 43.3*	252.1 ± 43.4*
BMI (kg/m^2)	25.9 ± 2.5	26.8 ± 2.4†	28.5 ± 3.6	29.0 ± 3.5†	32.8 ± 4.7*	33.2 ± 4.7*
1RM bench press (lb)	230 ± 10*	247 ± 9†	256 ± 12*	287 ± 11†	303 ± 32*	325 ± 37*†
1RM/lb BM	1.26 ± 0.13	1.31 ± 0.14	1.22 ± 0.17	1.34 ± 0.19	1.25 ± 0.21	1.32 ± 0.23

*Group significantly different than other groups ($p < 0.001$).
†Significantly different than pre-test ($p < 0.01$).

Table 2. Performance characteristics by strength group in college football players ($n = 58$).

Variable	Team ($n = 58$)		Low-strength group (LS, $n = 11$)		Change-strength group (CS, $n = 12$)		High-strength group (HS, $n = 35$)	
	Pre-training	Post-training	Pre-training	Post-training	Pre-training	Post-training	Pre-training	Post-training
Relative-load tests								
Reps @ 60% 1RM	20.0 ± 2.9	19.9 ± 3.4	22.0 ± 3.4	22.1 ± 3.6	19.5 ± 1.9	20.2 ± 2.7	19.6 ± 2.8*	19.1 ± 3.3*
Work capacity@60%	3,341 ± 566	3,581 ± 659†	3,026 ± 422	3,270 ± 538	3,000 ± 351	3,468 ± 487†	3,556 ± 569*	3,717 ± 715
Reps @ 70% 1RM	12.6 ± 2.2	12.8 ± 2.4	14.2 ± 1.8	13.8 ± 3.0	12.9 ± 1.5	13.3 ± 2.3	12.0 ± 2.3*	12.4 ± 2.1
Work capacity@70%	2,442 ± 440	2,689 ± 481†	2,280 ± 282	2,383 ± 511	2,323 ± 333	2,677 ± 481†	2,534 ± 493	2,789 ± 444*†
Reps @ 80% 1RM	9.0 ± 1.8	8.7 ± 1.9	9.9 ± 1.8	9.8 ± 2.0	8.4 ± 1.8	8.8 ± 2.0	8.9 ± 1.8	8.3 ± 1.7†
Work capacity@80%	1,992 ± 429	2,073 ± 410	1,819 ± 317	1,934 ± 375	1,721 ± 369*	2,022 ± 452†	2,140 ± 420*	2,134 ± 404
Reps @ 90% 1RM	3.8 ± 1.0	3.5 ± 1.4	4.1 ± 1.2	4.5 ± 1.8	4.4 ± 0.9	3.7 ± 1.6	3.6 ± 0.9*	3.2 ± 1.1*
Work capacity @90%	960 ± 252	934 ± 337	846 ± 251	983 ± 375	1,016 ± 203	946 ± 416	976 ± 262	914 ± 303
Absolute-load tests								
Repetitions	11.9 ± 3.6	12.9 ± 3.5†	9.2 ± 2.8	12.4 ± 2.2†	13.4 ± 3.3*	10.0 ± 2.7*†	12.3 ± 3.6*	14.0 ± 3.6†
Work capacity	2,388 ± 739	2,804 ± 822†	2,066 ± 627	2,287 ± 408	3,018 ± 746*	2,250 ± 599†	2,272 ± 657*	3,156 ± 803*†
%1RM	75.4 ± 6.0	72.7 ± 6.4†	80.6 ± 3.5	75.0 ± 2.7†	72.4 ± 3.8	78.6 ± 3.0†	74.9 ± 6.4	69.9 ± 6.5†
RepWt/lb BM	0.84 ± 0.16	0.95 ± 0.16†	1.01 ± 0.09	0.98 ± 0.09	0.88 ± 0.14	1.05 ± 0.16†	0.76 ± 0.14*	0.91 ± 0.16†

*Significantly different than the other groups ($p < 0.01$).
†Significantly different than pre-test ($p < 0.01$).

4 training days per week, of which 2 days focused on leg power/strength and 2 days focused on upper-body power/strength. The lifts utilized were the squat, power clean, power snatch, and jerk (leg power/strength) and push press, bench press, and incline press (upper-body power/strength). Training intensity increased from week 1 to week 3. Individual lifts were performed for 4 to 8 sets with 1 to 5 repetitions per set, with a decreasing intensity and an increasing repetition pattern as follows: week 1, intensity 85/80% for 4/5 repetitions; week 2, intensity 90/85/80% for 2/4/5 repetitions; and week 3, intensity 95/90/85/80% for 1/2/4/5 repetitions. The testing/recovery week consisted of 1RM testing on the first 2 days of the week and active recovery consisting of 4 sets per lift at 70% for 4 reps (first microcycle) and 80% for 2 reps (second and third microcycles) on the other 2 training days.

Auxiliary lifts were performed on each upper-body power/strength training day for 4 sets of 8 repetitions. Three to 4 exercises were performed in various combinations. The exercises included close-grip bench press, dumbbell press, bent-over rows, triceps extensions, biceps curls, parallel dips, pull-ups (pronated grip), and chin-ups (supine grip). Torso stability work was performed 2 times per week.

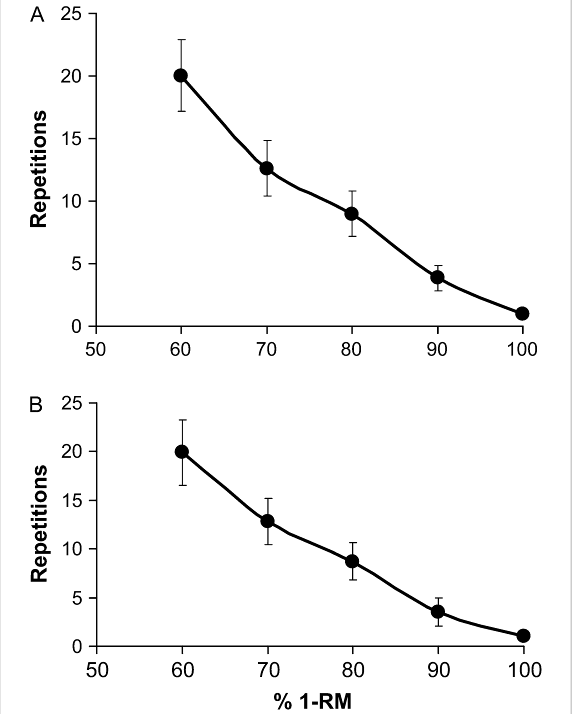

Figure 1. Relationship between load (%1-RM) and repetitions in the bench press. A, Curvilinear relationship between repetitions and %1-RM at pre-training. B, Curvilinear relationship between repetitions and %1-RM at post-training.

Running drills were performed 3 days per week in 30-minute sessions with the following emphasis: day 1, agility and speed development drills; day 2, speed development drills and conditioning; and day 3, speed, agility and jump testing.

Post-training performance testing was administered following completion of the third microcycle. Players performed 2 days of low-volume/intensity training followed by 3 days of complete rest prior to post-training 1RM testing. There were 3 days of complete rest between the 1RM test and relative- and absolute-load RTF testing. Otherwise, testing procedures were that same as pre-training testing.

Statistical Analyses

Differences among the strength groups were assessed using 1-way analysis of variance. Changes in performance were assessed using a paired *t*-test. Comparisons between predicted and actual 1RM performances were made using paired *t*-test with Bonferroni correction and interclass correlation coefficients (ICC). Reliability for testing with subjects of this level has previously been established at ICC >0.97 (13).

RESULTS

Pre-Training Performance

The 1RM for the team was 279 ± 40 lb ($n = 58$), whereas the different strength groups were similar in 1RM/body mass (BM; Table 1). The number of repetitions (RTF) performed at each relative load was greatest at 60% 1RM and decreased with each successive load (Table 2). RTF was significantly greater in LS at 60 and 70% of 1RM than HS but not more than CS (Table 2). RTF at 80% of 1RM was similar among the groups (Table 2). At 90% of 1RM, RTF was significantly greater in CS than HS but equivalent to LS. The relationship between RTF and muscular strength (1RM) at 60% ($r = -0.28$), 70% ($r = -0.39$), and 80% ($r = -0.28$) was statistically significant but poor; the relationship at 90% of 1RM ($r = -0.22$) was not significant. The coefficients of determination (r^2) were low (0.05 to 0.15), indicating very little shared variance between muscular strength (1RM) and RTF.

For absolute load tests, RTF was significantly lower in LS than CS and HS, which were similar (Table 2). The absolute loads represented a significantly higher %1RM for each of the strength groups (LS>HS>CS; Table 2). If the difference in %1RM was held constant by analysis of covariance, there was no significant difference in absolute-load RTF among the groups.

Work capacity was greatest at 60% 1RM and decreased at each incremental load thereafter (%1RM; Table 2). The relationship between submaximal work capacity and 1RM was statistically significant, but the correlation coefficients were poor (0.04–0.60) and the coefficients of determination indicated little shared variance. Of note, the relationships among the various work capacities (relative and absolute loads) were not very strong, although significant; the correlation coefficients ranged from $r = 0.32$ to 0.71, indicating very little commonality among them. This was more evident

Table 3. Strength prediction before and after training using repetitions at selected %1RM loads in college football players ($n = 58$).

Variable	Team ($n = 58$)		Low-strength group (LS, $n = 11$)		Change-strength group (CS, $n = 12$)		High-strength group (HS, $n = 35$)	
	Pre-training	Post-training	Pre-training	Post-training	Pre-training	Post-training	Pre-training	Post-training
Reps @ 60% 1RM								
Brzycki equation	365 ± 73*	402 ± 139*	345 ± 68*	386 ± 135*	321 ± 46*	379 ± 74	386 ± 75*	416 ± 158*
Lander equation	358 ± 68*	393 ± 122*	335 ± 62*	373 ± 118*	316 ± 43*	371 ± 68*	380 ± 70*	407 ± 137*
Mayhew et al. equation	253 ± 34*	273 ± 36*	213 ± 8*	229 ± 12*	231 ± 13*	260 ± 13*	273 ± 28*	291 ± 32*
Wathen equation	275 ± 37*	296 ± 38*	232 ± 10	250 ± 14*	251 ± 15*	283 ± 15	296 ± 31*	315 ± 35*
Welday equation	279 ± 38	301 ± 40	239 ± 14	257 ± 20	254 ± 17	288 ± 19	300 ± 33	319 ± 38
Reps @ 70% 1RM								
Brzycki equation	290 ± 40*	317 ± 41*	255 ± 20*	272 ± 34*	270 ± 25*	308 ± 35	308 ± 39	334 ± 34
Lander equation	290 ± 40*	317 ± 41*	255 ± 20*	372 ± 33*	270 ± 25*	308 ± 34*	308 ± 38	334 ± 33
Mayhew et al. equation	267 ± 35*	289 ± 36*	225 ± 10*	240 ± 13	246 ± 15	277 ± 15*	287 ± 29*	309 ± 29*
Wathen equation	279 ± 36	304 ± 37	239 ± 12*	254 ± 17	259 ± 18	292 ± 19	299 ± 30	323 ± 29
Welday equation	277 ± 36	301 ± 37	237 ± 12*	252 ± 18	257 ± 18	290 ± 20	296 ± 31*	320 ± 29
Reps @ 80% 1RM								
Brzycki equation	288 ± 40*	308 ± 36	245 ± 17*	263 ± 20*	259 ± 19	294 ± 23	311 ± 31*	326 ± 29
Lander equation	290 ± 40*	310 ± 37*	247 ± 19*	264 ± 19*	261 ± 19	296 ± 22	313 ± 31*	329 ± 29
Mayhew et al. equation	287 ± 38*	308 ± 38*	240 ± 11*	257 ± 11*	261 ± 14	294 ± 14*	311 ± 29*	329 ± 30*
Wathen equation	292 ± 39*	313 ± 37*	247 ± 13*	264 ± 14*	264 ± 16	299 ± 18*	316 ± 30*	334 ± 29*
Welday equation	290 ± 39*	311 ± 37*	245 ± 13*	262 ± 14*	262 ± 16	297 ± 17*	314 ± 30*	331 ± 29*
Reps @ 90% 1RM								
Brzycki equation	273 ± 38	292 ± 37*	227 ± 12	246 ± 12	255 ± 13	279 ± 17	294 ± 32*	311 ± 32*
Lander equation	276 ± 38	296 ± 37*	229 ± 12	249 ± 12	258 ± 13	283 ± 17	297 ± 32*	315 ± 32*
Mayhew et al. equation	292 ± 40*	313 ± 40*	242 ± 11*	261 ± 10*	271 ± 13	298 ± 15*	315 ± 34*	334 ± 34*
Wathen equation	282 ± 39	301 ± 37	234 ± 13	254 ± 13	264 ± 13*	288 ± 19	303 ± 33	320 ± 32*
Welday equation	283 ± 39	303 ± 42	235 ± 12	246 ± 9	264 ± 13*	289 ± 16	305 ± 33	323 ± 33
Actual 1RM (lb)	279 ± 40	302 ± 42	230 ± 10	247 ± 9	256 ± 12	287 ± 11	303 ± 32	325 ± 37

*Predicted 1RM significantly different from actual 1RM ($p < 0.01$).

TABLE 4. Comparison of predicted vs. actual strength changes following resistance training in college football players ($n = 58$).

	Diff ± *SD* (Predicted − Actual)	95% Confidence interval on mean difference	*t*-ratio	ICC
Reps @ 60% 1RM				
Brzycki equation	38 ± 126	−48 to 18	0.92	0.07
Lander equation	35 ± 109	−41 to 16	0.88	0.09
Mayhew et al. equation	20 ± 14	1 to 5	2.54*	0.87†
Wathen equation	21 ± 17	−2 to 5	0.97	0.80†
Welday equation	22 ± 21	−3 to 6	0.88	0.67†
Reps @ 70% 1RM				
Brzycki equation	27 ± 31	−11 to 3	1.18	0.50†
Lander equation	27 ± 30	−11 to 3	1.19	0.52†
Mayhew et al. equation	23 ± 16	−3 to 3	0.04	0.86†
Wathen equation	24 ± 20	−5 to 2	0.77	0.75†
Welday equation	24 ± 20	−5 to 3	0.72	0.74†
Reps @ 80% 1RM				
Brzycki equation	20 ± 19	−2 to 7	1.31	0.63†
Lander equation	20 ± 19	−2 to 7	1.24	0.64†
Mayhew et al. equation	21 ± 14	−1 to 4	1.09	0.86†
Wathen equation	21 ± 17	−2 to 6	1.02	0.72†
Welday equation	21 ± 16	−2 to 5	1.10	0.75†
Reps @ 90% 1RM				
Brzycki equation	19 ± 14	0 to 7	2.30*	0.74†
Lander equation	19 ± 14	0 to 6	2.15*	0.75†
Mayhew et al. equation	21 ± 13	−1 to 4	1.40	0.86†
Wathen equation	19 ± 16	0 to 7	2.10*	0.67†
Welday equation	20 ± 14	0 to 6	1.98*	0.74†
Actual difference (kg)	23 ± 12	–	–	

*Predicted difference significantly different from actual difference in 1RM ($p < 0.01$).
†Intraclass correlation coefficient is significant at $p < 0.05$.

in those with 1RM values <275 lb ($r = 0.14$ to 0.62) than in those with 1RM values >275 lb ($r = 0.37$ to 0.70).

Post-Training Performance

The post-training 1RM bench press showed a significant ($p < 0.001$) gain of 22.8 ± 12.0 lb (8.3 ± 4.5%) for the entire team ($n = 58$). Likewise, body mass increased 3.7 ± 10.1 lb (1.9 ± 4.8%, $n = 58$). The gain in bench press 1RM (Table 2) was significantly greater in CS (12 ± 5%) than in LS (7 ± 3%) and HS (7 ± 4%). The increase in body mass was not significantly different among the strength groups (Table 2). The change in 1RM relative to body mass (1RM/BM) was similar among the groups (Table 2). The gain in muscular strength (1RM) was not related ($r = 0.07$) to the gain in body mass; however, the gain in relative strength (lb/lb BM) was negatively related ($r = -0.73$, $p < 0.01$) to the change in body mass.

When considering all players ($n = 58$), there were no changes in RTF at 60% (−0.1 ± 2.8), 70% (0.2 ± 2.1), 80% (−0.3 ± 1.6), or 90% (−0.3 ± 1.3) of 1RM following training. RTF was significantly greater in LS than in HS but not CS at 60% and 90% of 1RM. There were no differences in RTF at 70% or 80% of 1RM among the groups (Table 2). Work capacity increased at 60 and 70% of 1RM loads but not at 80 and 90% 1RM loads (Table 2) following training. The relationship between work capacity and muscular strength was poor ($r = -0.16$ to 0.43) with only the work capacity at 60% of 1RM being statistically significant. Because the relationship between work capacity and muscular strength (1RM) accounted for only 18% of the common variance, it is not considered to be of much practical significance, as observed in the pre-training data. There were moderate but significant negative relationships ($p < 0.05$) between RTF and muscular strength at 60% ($r = -0.32$), 70% ($r = -0.41$), 80% ($r = -0.51$), and 90% ($r = -0.43$) of 1RM. However, these relationships accounted for no more than 26% of the shared variance between the variables.

For absolute load tests, RTF increased significantly in LS (25 ± 21%; $n = 11$) and HS (12 ± 14%; $n = 35$) following training (Table 2). There was no significant difference ($p = 0.07$) in the magnitude of the gain in repetitions between LS (3.2 ± 2.8) and HS (1.7 ± 2.1), but the percent gain by LS was significantly greater ($p = 0.02$). In both LS and HS the respective load (%1RM) represented by 185 lb or 225 lb decreased significantly following training with the increase in

1RM (Table 2). In CS the absolute load increased from 185 lb to 225 lb as a result of the increase in 1RM (>275 lb), and RTF decreased from 13 to 10 repetitions (Table 2). The load represented by the absolute test load in CS increased from 72 to 78% of the 1RM. If the change in %1RM was removed by analysis of covariance, there was no significant difference in the number of repetitions performed by CS before and after training. As with the pre-training data, the relationships among the various post-training work capacities were weak to moderate ($r = 0.32$ to 0.73) and again accounted for a minimal amount of the common variance among them ($r^2 = 0.10$ to 0.53).

Prediction Equations

The relationship between RTF and relative load was curvilinear at both pre- and post-training testing intervals (Figure 1). Although the standard deviations for each %1RM interval decreased with increasing intensity (%1RM), the coefficients of variation (CV = SD/mean × 100) increased from 14% at 60% 1RM to 26% at 90% 1RM at pre-training and from 12% at 60% 1RM to 41% 1RM at 90% 1RM post-training.

Five previously published prediction equations were selected and used here to estimate 1RM bench press from the 4 relative load RTF. In general, the equations of Welday (27) and Wathen (23) produced the best estimates of 1RM across the range of %1RM (Table 3) with ICCs ranging from 0.96 to 0.99. The equations of Lander (17) and Brzycki (5) produced poor overpredictions of 1RM at 60% 1RM (ICC = 0.59 and 0.54, respectively) and 70% 1RM (ICC = 0.85 and 0.86). At 80% 1RM, all predictions of 1RM were significantly different from the actual 1RM, but ICCs were high for all equations (0.93–0.96). At 90% 1RM, only the equation of Mayhew et al. (18) produced estimates that were significantly different from the actual 1RM, whereas all ICCs were high (0.95–0.99). However, when comparing actual-predicted values for 1RM, the equation of Mayhew et al. had the smallest range of differences (95% confidence interval) and the highest ICCs across all % 1RM (Table 4).

The equations for estimating 1RM using the absolute load RTF tended to overpredict muscular strength by 1 to 11% (Table 5). The best equation appeared to be the Mayhew et al. (18) equation, which overpredicted by 1 ± 5% (range = −21 to 10%).

Following training, the equations of Wathen and Welday were again superior in predicting 1RM. With the other equations the relative-load RTF prediction again significantly overestimated the 1RM in all 3 groups (Table 3). The overestimation tended to be greater at the lower %1RM loads. It was not until the relative load reached 90% 1RM that the predictions become statistically accurate. The difference between the actual changes in 1RM bench press (22.8 ± 12.0 lb) and the predicted changes were similar for all equations using repetitions at 70% 1RM or higher (Table 4). The application of these prediction equations to the absolute load condition revealed similar findings to those at pre-training. Again, the Mayhew et al. equation appeared to provide the

Table 5. Strength prediction before and after training using absolute loads and repetitions in college football players ($n = 58$).

Equation	Team ($n = 58$)		Low-strength group (LS, $n = 11$)		Change-strength group (CS, $n = 12$)		High-strength group (HS, $n = 35$)	
	Pre-training	Post-training	Pre-training	Post-training	Pre-training	Post-training	Pre-training	Post-training
Brzycki equation	309 ± 66*	333 ± 68*	242 ± 24*	273 ± 26*	288 ± 45*	303 ± 32*	337 ± 65*	363 ± 70*
Lander equation	309 ± 64*	333 ± 65*	243 ± 23*	273 ± 25*	288 ± 43*	304 ± 31*	336 ± 61*	362 ± 66*
Mayhew et al. equation	282 ± 33	298 ± 28	238 ± 12*	252 ± 9	256 ± 13	294 ± 13*	305 ± 17	314 ± 16*
Wathen equation	294 ± 39*	313 ± 34*	244 ± 18*	264 ± 13*	269 ± 19*	303 ± 20*	319 ± 24*	331 ± 23
Welday equation	293 ± 39*	311 ± 36*	242 ± 17*	261 ± 14*	258 ± 20*	300 ± 20*	317 ± 27*	330 ± 27
Actual 1RM (lb)	279 ± 39	302 ± 42	230 ± 10	247 ± 9	256 ± 12	287 ± 11	303 ± 32	325 ± 37

*Predicted 1RM significantly different from actual 1RM ($p < 0.01$).

best estimates with a nonsignificant underprediction of -4 ± 23 lb ($n = 58$; $-1 \pm 6\%$; ICC $= 0.89$) and 60% of the players within ±10 lb of their actual 1RM.

DISCUSSION

Although numerous studies have assessed the effect of simultaneously training to improve both muscular strength and aerobic capacity, few studies have evaluated the effect of changing muscular strength on local muscular work capacity. Further, this is one of the first studies to evaluate the accuracy of prediction equations for assessing changes in 1RM in athletes during training. Two things were evident in the current study: (a) Changes in submaximal work capacity are minimal following a high-load, low-repetition training program and are unrelated to changes in muscular strength; (b) predicting 1RM from submaximal work capacity and the accuracy of these predictions in tracking changes with training was best when using low RTF tests (load $>85\%$ of 1RM). In essence, the prediction repetition range must be matched with the training repetition range.

Typically, muscle work capacity (muscle endurance) is inferred from the number of repetitions (RTF) performed at a given load. The pre-training RTF were in relative agreement with previous studies across various loads in the bench press (17,20,21). Of note, RTF at each workload were significantly, negatively correlated with 1RM, albeit with low correlation coefficients (-0.39 through -0.28) suggesting in this population of football players that strength and work capacity are poorly related. The lack of relationship between RTF and muscular strength has been observed in other populations (21,22). Indeed, work capacity at the various submaximal loads was poorly related to muscular strength with little common variance (coefficients of determination <0.15).

Work capacity at 60 and 70% of 1RM increased following training, whereas there were no changes at 80 and 90% 1RM. However, as noted at pre-training, submaximal work capacity was poorly associated with muscular strength; thus the changes in each are somewhat independent (minimal shared variance). The basis for the minimal impact of the strength training program on submaximal work capacity is related to absence of change in RTF following training. This too is in agreement with previous studies reporting no change in RTF at loads ranging from 55 to 95% of 1RM following bench press training in previously untrained individuals (17,21).

When comparing trained versus untrained individuals, a slightly different picture emerges. Trained individuals generally produced more repetitions in various exercises than untrained individuals (11). Specific to the bench press, however, only trained females had a greater RTF (11), whereas there are no differences between trained and untrained males (11,22). When an increase in RTF has been reported in trained versus untrained (11) or following training in previously untrained (3) individuals, the changes have been ascribed to the training program; in both cases the increased RTF was attributed to the higher repetition training program. This is consistent with the observation that muscle "endurance" (knee extension work volume) was reduced following a low-repetition strength training program in generally active physical education students (9). In the present case, the lack of relationship between muscular strength and work capacity, the poor negative relationships between RTF and 1RM, and the fact that these relationships did not change with training would reflect the strength emphasis of the periodized, low-repetition training program administered here. Additionally, this supports the conclusion that the relationship between submaximal work capacity and muscular strength and possible changes following training are dictated by the training program repetition range.

In the present study the lower strength groups (LS and CS) generally performed a greater number of repetitions at 90, 70, and 60% of 1RM, a relationship not altered by training. Untrained individuals have been shown to perform more repetitions at 90% of 1RM than trained individuals (22). The lower RTF observed in trained individuals at 90% 1RM was in contrast to the higher mean power output. Despite working at the same relative load, the trained individuals would have a greater mass on the bar, requiring higher force generation and therefore higher power (22). A greater force generation may alter the fatigue mechanism and thus limit repetitions in the trained individuals (see later). As with the previous study (22), neither contraction/rest duty cycle nor velocity of shortening were controlled in the present study and thus remain issues to be resolved.

Thus, it appears that training status would dictate the submaximal load RTF and the relationship with muscular strength. However, taken together these observations (present data, 22) would appear to indicate that training status is the magnitude of muscular strength expressed and the terms trained vs. untrained would be relative to maximal muscular strength rather than training history (i.e., participation in resistance exercise). The impact of training history on this relationship would be based on the training program, repetition ranges utilized and the emphasis of the training, muscular strength vs. work capacity, or resistance exercise vs. general physical activity unless there was no prior resistance training experience (present data, 3,9,11).

At a given muscle mass, the expression of muscular strength is typically determined, and limited, by neural factors. The expression of submaximal work capacity (2RM or greater) is determined by an interaction between neural factors and energy supply (4). As muscle contraction intensity increases, muscle force generation becomes sufficient to occlude circulation within the exercising muscle (2,12,14), thus potentially hastening the onset of fatigue by limiting energy supply/waste removal and intracontractile metabolic recovery (4). At 70% of 1RM, RTF appears to be more related to metabolic factors (energy supply) as indicated by its relationship to capillary density rather than slow-twitch fiber characteristics (23). Although metabolic changes could explain the increased work capacity at 60 and 70% 1RM, it is unlikely that capillary density increased significantly in 12 weeks. Alternatively, a neural component to the increased work capacity could be motor unit desynchronization (19). Following strength training, desynchronization of motor units would require fewer motor units to complete a given task and use less muscle to lift the same load. Fatigue would be delayed by having a greater motor unit reserve pool, resulting in a greater RTF, as was observed in the absolute load testing (Table 3). This same mechanism may explain the observations with relative load testing. In this case the test load would increase in proportion to the strength gain, and the delay in fatigue would be observed as an increase in work capacity (load × RTF) without a change in RTF. However, this effect appears to be limited because increases in muscular strength may have more of a positive effect on lower-intensity work capacity rather than higher intensities. This and the negative correlations between RTF and 1RM (before and after training) lead to the conclusion that muscle fatigue may occur more rapidly at higher intensities. Increases in intensity (%1RM) are associated with greater force generation requiring an increased recruitment (10) and synchronization (7) of motor units forming the neural basis for increased force generation and adaptation to strength training. This increasing neural component would limit the effects of desynchronization and shift away from global energy supply issues. The latter is supported in part by the lack of relationship between capillary density and RTF at 85% of 1RM (23). Thus, the decrease in work capacity with increasing intensity (%1RM) and lower RTF at 90% 1RM in lower strength (present study) or untrained individuals (22) could be motor integration fatigue and/or insufficient fatigue recovery time for each motor unit subsequent to the higher force generation.

This study is one of the first to evaluate the accuracy of prediction methods for tracking the changes in 1RM strength in athletes during training. The major concern with using any prediction technique to estimate muscular strength (1RM) is the degree to which such predictions are able to accurately capture the actual change in strength.

In addition to prediction statistics, it is valuable to discuss effect size (ES) in the present context to determine the practical application of a statistical analysis. ES is a means of emphasizing the practical value of the data. In the current study, this would amount to the difference between predicted and actual means divided by the standard deviation for the actual 1RM, with the most desirable ES being the smallest possible value indicating no practical difference between the actual and predicted 1RM.

Pre- and post-training prediction statistics and ES values were similar in magnitude and pattern. ES essentially increased with decreasing load with 60% load having the poorest prediction (Lander [16], ES = 1.98; Brzycki [5], ES = 2.15; Mayhew [17], ES = 0.65). The pre- and post-training predictions of 1RM were best when using the 90% 1RM load across all equations, as indicated by prediction statistics (Tables 3 and 5) and ES (range 0.02–0.23). However, the Wathen (24) and Welday (25) equations produced the most consistent predictions and lowest ES (<0.30) across all testing loads. With absolute load testing, the Mayhew equation (17) appears to be the best with effect size of 0.08 (pre-training) and 0.09 (post-training).

The basis for prediction of 1RM is the relationship between submaximal work capacity and 1RM, and the nature of that relationship is assumed to be linear. There was a weak relationship between submaximal work capacity (at the various loads) and RTF with 1RM (as described earlier), and the relationship between RTF and submaximal load was curvilinear (Figure 1). Training had no impact on either. The poorest predictions occurred at 60 and 70% 1RM at both pre- and post-training. It appears that the equations of Wathen (24) and Welday (25) account for the curvilinear relationship, whereas the linear nature of the Brzycki (5) and Lander (16) equations likely caused them to substantially overestimate 1RM with RTF at lower %1RMs (Table 3).

Because muscular strength increased following training, each of the post-training %1RM loads was increased. Greater loads with the same repetitions may result in changed work capacity and, of importance, a change in the relationship with 1RM. In the present study, work capacity at 60 and 70% 1RM was increased following training, which exacerbated the overestimation error with the Lander (16) and Brzycki (5) equations (Table 3). This is consistent with previous work (3). In contrast, predicting and tracking changes in 1RM following training were acceptable utilizing 80% and 90% 1RM loads where work capacity did not change with the best prediction being with 90% 1RM (Table 4).

The ability of a prediction equation to accurately track a change in muscular strength following training appears to be related to accounting for changes in submaximal work capacity, which would alter the relationship with muscular strength. It would appear that matching the equation to the training goals and repetition range used in the training program may control for changes in work capacity. From the present data it appears that RTF <6 (load >85% 1RM) would approximate the linear portion of the RTF-load curve (Figure 1) in the present study and likely across all referenced studies given the prediction statistics and high ICCs (Table 3). This repetition range and load holds for bench press; other repetition ranges need to be determined for other exercises to control for influence of muscle mass and motor unit recruitment patterns associated with different exercises (11,22).

PRACTICAL APPLICATIONS

There is little disagreement that the 1RM is the accepted technique for gauging maximal dynamic muscular strength, and it is widely used at various stages of a training program. However, some strength and conditioning specialists are hesitant to subject players to a 1RM test at specific times in the yearly training cycle as a result of apprehension about injury and disruption of the training schedule. At these times, an accurate prediction technique would be useful to gauge strength levels or assess the progress made during a training program. The best prediction (i.e., minimal error) will be achieved when the equation used is matched to the training status (level of muscular strength), training goal of the cycle, and the general training base of the athletes. In the present context, the best predictions were realized when repetitions are maintained in the 2 to 5RM range, thus loads greater than 85% of the 1RM. This will assure that predictions are based on the linear portion of the curve and specifically matched to strength training emphasis. This approach may save valuable training time, provide a gauge of training progress, and allow adjustments in periodized training loads across a mesocycle.

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