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Effects of Velocity Loss Threshold Within Resistance Training During Concurrent Training on Endurance and Strength Performance

Miguel Sánchez-Moreno, David Rodríguez-Rosell, David Díaz-Cueli, Fernando Pareja-Blanco, and Juan José González-Badillo

Purpose: This study analyzed the effects of 3 training interventions: 1 isolated endurance training (ET) and 2 concurrent training (CT), which differed in the velocity loss (VL) magnitude allowed during the resistance training (RT) set: 15% (VL15) versus 45%, on strength and endurance running performance. ***Methods:*** A total of 33 resistance- and endurance-trained men were randomly allocated into 3 groups: VL15, VL 45%, and ET. ET was similar across all groups. The CT groups differed in the VL allowed during the RT set. Before and after the 8-week training program the following tests were performed: (1) running sprints, (2) vertical jump, (3) progressive loading test in the squat exercise, and (4) incremental treadmill running test up to maximal oxygen uptake. ***Results:*** Significant differences ($P < .001$) in RT volume (approximately 401 vs 177 total repetitions for VL 45% and VL15, respectively) were observed. Significant "group" × "time" interactions were observed for vertical jump and all strength-related variables: the CT groups attained significantly greater gains than ET. Moreover, a significant "group" × "time" interaction ($P = .03$) was noted for velocity at maximal oxygen uptake. Although all groups showed increases in velocity at maximal oxygen uptake, the VL15 group achieved greater gains than the ET group. ***Conclusions:*** CT interventions experienced greater strength gains than the ET group. Although all groups improved their endurance performance, the VL15 intervention resulted in greater gains than the ET approach. Therefore, moderate VL thresholds in RT performed during CT could be a good strategy for concurrently maximizing strength and endurance development.

Keywords: velocity-based training, training volume, aerobic training, maximal oxygen uptake, muscle fatigue, maximal aerobic speed

Concurrent strength and endurance training (ET) have been studied extensively due to its potential to simultaneously increase both aspects of performance.[1] This training modality is often used in sports disciplines requiring high levels of strength and endurance (eg, rowing and canoeing)[2] or team sports (eg, soccer and handball), which demand a complex nature of endurance performance and explosive strength manifestations such as maximal speed or jumps actions.[3] Likewise, the incorporation of resistance training (RT) in addition to habitual ET may improve endurance performance more than isolated ET,[4] which can be especially important for athletes who compete in endurance sports disciplines (eg, middle- and long-distance runners).[5,6] In this regard, it has been widely reported that maximal oxygen consumption (VO_2max) remains unaffected by strength training[4]; however, velocity at VO_2max (vVO_2max) has been established as a superior marker of success in elite endurance runners.[7] The term vVO_2max could be understood as a "functional" expression of VO_2max in velocity units (in kilometer per hour), and it is composite of both VO_2max and running economy.[8] In this regard, Beattie et al[8] reported that a concurrent training (CT) intervention improved strength performance, vVO_2max, and running economy in competitive distance runners, without changes for the isolated ET regime. However, the resulting adaptations evoked by CT on strength and endurance development may be explained by the manipulation of training variables (eg, training sequence, volume and intensity, and recovery time between sessions).[4,9,10] Hence, it is of interest to find combinations of both types of training regimes that concurrently maximize strength and endurance development.

Training volume is one of the variables that could be manipulated when configuring CT programs. With regard to RT volume, the actual number of repetitions performed in a set in relation to the maximum number of repetitions that could be completed (ie, "level of effort")[11] seems to be a factor that should be considered when designing an RT program.[11–13] In this regard, Izquierdo-Gabarren et al[14] observed that CT incorporating nonfailure RT (approximately 50% of the maximum number of repetitions that could be completed in a set) provided greater gains in strength, power, and rowing performance compared with RT to muscle failure in trained rowers. Indeed, these authors[14] reported that both muscle strength and rowing performance could be compromised if a given threshold volume was exceeded. However, the effects of different levels of effort during RT on the simultaneous development of lower body strength and running endurance performance remain unexplored.

Recently, the velocity loss (VL) induced within each set during RT has been proposed as a criterion to determine when the set should be ended.[11,15] This approach is based on the relationships ($R^2 \geq .83$) found between the VL incurred in the set and the level of fatigue,[11] together with the associations observed between the VL magnitude and the percentage of completed repetitions in each set

Sánchez-Moreno is with the Dept of Physical Education and Sports, Universidad de Sevilla, Seville, Spain. Rodríguez-Rosell and Pareja-Blanco are with the Dept of Sports and Computers Sciences, Universidad Pablo de Olavide, Seville, Spain. Díaz-Cueli is with the Medical Service, PFC CSKA Moscow, Moscow, Russia. González-Badillo is with the Physical Performance & Sports Research Center, Universidad Pablo de Olavide, Seville, Spain. Sánchez-Moreno (msmoreno@us.es) is corresponding author.

with respect to the maximum number of repetitions until failure ($R^2 = .96$).[16] With this approach, rather than performing a fixed number of repetitions, a training set stops as soon as a certain fatigue threshold is detected. For the full-squat (SQ) exercise, a VL threshold of 15% to 20% means that about 50% of maximal repetitions within the set have been completed, whereas a VL threshold about 40% to 50% within the set means that the set is conducted close to muscle failure.[16] This novel strategy would allow the application of more homogeneous stimuli across individuals, which would be useful in order to standardize the level of fatigue induced during strength training. Previous studies have reported that moderate VL thresholds (ie, 10%–20%) during a full SQ training program produce similar or even superior strength gains to higher values of VL (ie, 30%–40%).[15,17,18] As no previous study has analyzed the effect of different VL magnitudes during CT on strength and endurance performance, it is still unknown whether it is possible to extrapolate the findings from previous RT studies analyzing effects of different VL thresholds to a CT setting. Hence, in an attempt to gain further insight into the adaptations brought about by different VL thresholds during CT, the authors aimed to analyze the effects of 3 training interventions—1 ET alone and 2 CT protocols that differed in the VL magnitude allowed—on strength and endurance running performance. The authors hypothesized that given CT improves endurance performance more than ET alone, via improvements in running economy, musculoskeletal stiffness and muscle strength and power,[4] and moderate VL thresholds produce better neuromuscular adaptations[15,17,18] along with lower residual fatigue,[12] it would be expected superior enhancements in endurance performance following a CT program including moderate VL thresholds during RT.

Methods

Subjects

A total of 36 young resistance- and endurance-trained men (mean [SD]: age = 25.2 [4.9] y, body mass = 73.9 [7.2] kg, height = 1.76 [0.05] m) volunteered to take part in this study. Subjects had a training background ranging from 2 to 5 years (2–4 sessions per week; one-repetition maximum [1RM] = 87.0 [8.2] kg in SQ; and $VO_2max = 51.9$ [5.2] $mL \cdot kg^{-1} \cdot min^{-1}$). After an initial evaluation, the participants were matched according to their vVO_2max and then randomly assigned to 1 of 3 groups. Three participants withdrew from the study during the experimental period (1 due to exercise-induced knee joint soreness and 2 because of missed training sessions). Thus, of the 36 enrolled participants, 33 remained for statistical analysis (VL15, n = 11; VL45, n = 11; endurance group [EG], n = 11), whose training compliance was 100% of all sessions. All participants were fully informed about the procedures, potential risks, and benefits of the study, and they all signed written informed consents prior to the tests. The study was conducted in accordance with the Declaration of Helsinki II and approved by the Research Ethics Committee of Pablo de Olavide University.

Design

An experimental research design was used to compare the effects of 3 training programs for an 8-week period. There were 2 CT programs that differed in the magnitude of VL induced during the RT set: 15% (VL15) versus 45% (VL45), and 1 group that only performed ET. The ET was similar across all training groups and was performed twice a week. The CT groups (ie, VL15 and VL45) also engaged in strength training twice a week. Endurance and strength training sessions were not performed on the same day to minimize the potential residual fatigue induced by the previous exercise. All subjects were evaluated in 2 testing sessions separated by a 72-hour rest interval. During the first testing session, the participants performed the following battery of tests: running sprints, countermovements jump (CMJ), and a progressive loading test in the SQ exercises. During the second testing session, subjects undertook an incremental treadmill running test until VO_2max was attained. Testing sessions were performed at the same time of day for each participant under the same environmental conditions (~20°C and ~60% humidity). All participants were assessed the previous week (pretraining) and 3 days after (posttraining) the training intervention. Subjects were required not to engage in any other type of strenuous physical activity during the study period.

Testing Procedures

Sprint Testing. Participants performed two 20-m sprints on an indoor running track, with a 3-minute rest between sprints. Sprint times over 0 to 10, 0 to 20, and 10 to 20 m were measured using photocells (Witty; Microgate, Bolzano, Italy). The best time of the 2 trials was scored. Runs were performed from a static biped start position with the start line located 1 m behind the start photocell. The test–retest reliability measured by intraclass correlation coefficient (ICC) with 95% confidence interval (95% CI) and coefficient of variation (CV) was: ICC (95% CI) > .87 (.78–.94) and CV < 2.0%.

Countermovement Jump. Participants performed 5 maximal CMJs with both hands on the waist, separated by 45-second rests. The highest and lowest CMJ height values were discarded, and the resulting average kept for analysis. Jump height was determined using an infrared timing system (OptojumpNext; Microgate). Test–retest reliability was: ICC (95% CI): .99 (.98–.99) and CV: 1.7%.

Progressive loading test in the full SQ exercise. A Smith machine (Multipower Fitness Line; Peroga Fitness, Murcia, Spain) was used for this test. The initial load was set at 30 kg and progressively increased in 10-kg increments until the attained mean propulsive velocity (MPV) was <0.70 $m \cdot s^{-1}$. Thereafter, the load was individually adjusted in smaller increments (5 down to 2.5 kg) until the MPV was <0.50 $m \cdot s^{-1}$ (ie, ≥90%1RM). All velocity measures reported in this study refer to the MPV, which corresponds to the portion of the concentric action during which the measured acceleration is greater than the acceleration due to gravity (−9.81 $m \cdot s^{-2}$).[19] Three repetitions were executed for light (>1.00 $m \cdot s^{-1}$), 2 for medium (1.00–0.80 $m \cdot s^{-1}$), and only 1 for the heaviest loads (<0.80 $m \cdot s^{-1}$). Interset rests were 3 minutes for the light and medium loads and 5 minutes for the heaviest loads. Only the best repetition (ie, highest MPV) for each load was considered for subsequent analysis. Owing to the very close relationship ($R^2 = .95$) between percentage of 1RM (%1RM) and MPV in SQ exercise,[20] the 1RM was estimated from the MPV attained against the heaviest load of the test (ie, ≥90%1RM), as follows: $\%1RM = -5.961\ MPV^2 - 50.71\ MPV + 117.0$ (standard error of estimate = 4.0% 1RM).[20] In addition to 1RM, 3 other variables derived from this test were used to analyze how the different training interventions affected the load–velocity relationship: (1) average MPV attained against all absolute loads common to pretraining and posttraining (AV), (2) average MPV attained against absolute loads that were moved faster than 1 $m \cdot s^{-1}$ at pretraining (AV>1, "light" loads), and (3) average MPV attained against absolute loads that were moved slower than 1 $m \cdot s^{-1}$ at pretraining (AV<1, "heavy" loads). A linear velocity transducer (T-Force System; Ergotech, Murcia, Spain), whose reliability has been reported elsewhere,[12] was used to measure bar velocity.

Incremental Treadmill Test. A treadmill (Mercury-Med LE 300C; H/P/Cosmos, Nußdorf, Germany) was used for this test. The initial velocity of 7.0 $km \cdot h^{-1}$ was increased by 0.2 $km \cdot h^{-1}$ every 12 seconds until exhaustion, with a constant gradient of 1%. Oxygen consumption was measured breath-by-breath throughout the test using a gas analyzer (CPX Ultima GX; Medical Graphics Corporation, St Paul, MN) that was calibrated before each test day, using instructions provided by the manufacturer. Heart rate (HR) was recorded continuously using a 12-channel electrocardiogram machine (Universal ECG; QRS Diagnostic, Plymouth, MN). VO_2max was defined as the highest 30-second average VO_2 during the test and was considered to have been reached if there was no increase (<100 $mL \cdot min^{-1}$) in VO_2 with an increase in exercise intensity.[21] To ensure that VO_2max was reached, each subject had to meet the following criteria: respiratory exchange ratio >1.00; and HR within 5% of their age-predicted maximum. All tests were terminated by volitional exhaustion and all subjects achieved VO_2max according to these criteria. In addition to VO_2max, this test allows us to determine the vVO_2max, which was defined as the minimum velocity at which the VO_2max was reached.

Training Protocol

RT Program. The RT program used only the SQ exercise. The descriptive characteristics are presented in Table 1. Both VL15 and VL45 performed a total of 16 strength sessions (on Mondays and Thursdays). Relative intensity (from 60% to 80% 1RM), number of sets (3) and interset recovery periods (3 min) were identical for both groups in each training session. Relative intensities were determined from the load–velocity relationship for the SQ exercise.[20] Thus, a target MPV to be attained in the first (usually the fastest) repetition of the first exercise set in each session was used as an estimation of %1RM. The absolute load (in kilogram) was individually adjusted to match the velocity associated (±0.03 $m \cdot s^{-1}$) with the %1RM intended for each session. The groups differed in the magnitude of VL attained in each set (15% vs 45%) and, consequently, differed in the number of repetitions performed per set and the total number of repetitions completed during the training program (Table 1). All repetitions were recorded using a linear velocity transducer (T-Force System; Ergotech). Training sessions were performed in a research laboratory at the same time of day (±1 h) for each subject and under the direct supervision of a researcher.

ET Program. The descriptive characteristics of the ET program are presented in Table 2. All groups performed a total of 16 endurance running sessions (on Tuesdays and Fridays). The relative intensity (from 80% to 120% vVO_2max), number of sets, set duration, and recovery times were identical for all groups in each training session. The relative intensity was determined from the individual vVO_2max. The training distance was individually calculated according to the scheduled velocity and time for each session (Table 2). Each of these distances was adjusted with an odometer (MW1; UMAREX GmbH & Co. KG, Arnsberg, Germany) and marked by visual references. The HR was recorded during all sessions through a HR monitor (Polar V800; Polar Electro Oy, Kempele, Finland). Training sessions were performed on a 400-m outdoor running track, at the same time of day (±1 h) for each subject and under the direct supervision of a researcher.

Statistical Analyses

Values are reported as mean (SD). Test–retest absolute reliability was measured using the standard error of measurement, which was expressed in relative terms through CV. The standard error of measurement was calculated as the root mean square of the total intrasubject mean square. Relative reliability was assessed using ICC with 95% CI calculated with the 1-way random effects model. The normality of distribution of the variables at pretraining test and the homogeneity of variance across groups were verified using the Shapiro–Wilk test and Levene test, respectively. Data were analyzed using a 3×2 factorial analysis of covariance (with baseline values as covariate) analysis with Bonferroni's *post hoc* adjustments using one between factor (VL15 vs VL45 vs ET) and one within factor (pretraining vs posttraining). Statistical significance was established at the $P \leq .05$ level. The effect sizes (ES) were calculated using Hedge *g* on the pooled SD with 95% CI. The statistical analyses were performed using SPSS software (version 18.0; SPSS Inc, Chicago, IL).

Results

No significant differences between groups were found at pretraining for any of the variables analyzed. The total number of repetitions and the repetitions performed in different velocity ranges by VL15 and VL45 are shown in Figure 1. The VL15 group trained at a significantly faster mean velocity than VL45 (0.76 [0.03] vs 0.67 [0.02] $m \cdot s^{-1}$, respectively; $P < .001$), whereas VL45 performed more repetitions ($P < .001$) than VL15 (401.6 [121.1] vs 177.1 [38.5], Figure 1). The mean fastest repetition during each session (which indicates the %1RM being lifted) and magnitude of VL matched the expected target values for every training session (Table 1). With regard to ET, the relative intensity attained during training did not differ between groups, which matched the expected target intensities for every training session except for the last sessions (sessions 11–16), where there was a tendency to run at higher velocity (between 5% and 10%) than scheduled (Table 2). In addition, no significant differences between the different interventions were observed for the mean total time and percentage of maximum HR reached during the training program (Table 2).

Sprint and CMJ Tests

No "group" × "time" interactions were observed for any sprint variable, although an almost significant "group" × "time" interaction ($P = .06$) was observed for sprint time over 0 to 20 m. The VL15 group showed a significant improvement in sprint time over 10 to 20 m ($P = .02$) while the rest of the sprint variables remained unchanged for all groups (Table 3). A significant "group" × "time" interaction ($P < .001$) was noted for CMJ, where VL15 and VL45 attained significantly greater gains than ET ($P < .001$–.05, Table 3). Moreover, VL15 and VL45 showed significant increases in CMJ height ($P < .001$), whereas no significant changes were observed for ET (Table 3).

Isoinertial Progressive Loading Tests

Significant "group" × "time" interactions ($P < .001$) were found for all variables measured during the progressive loading test (1RM, AV, AV<1, and AV>1; Table 3). The VL15 and VL45 groups attained greater gains than ET for all strength parameters ($P <$ .001–.05; Table 3). The VL15 and VL45 groups showed significant

Table 1 Descriptive Characteristics of the Velocity-Based SQ Training Program Performed by VL15 and VL45 Experimental Groups

Actually performed	Session 1	Session 2	Session 3	Session 4	Session 5	Session 6	Session 7	Session 8	Session 9
Best MPV (% 1RM)									
VL15	0.99 (0.03) (~59% 1RM)	1.00 (0.04) (~58% 1RM)	0.98 (0.03) (~60% 1RM)	1.00 (0.04) (~58% 1RM)	0.82 (0.03) (~70% 1RM)	0.83 (0.03) (~70% 1RM)	0.84 (0.04) (~69% 1RM)	0.83 (0.04) (~70% 1RM)	0.76 (0.04) (~75% 1RM)
VL45	1.00 (0.04) (~58% 1RM)	0.98 (0.05) (~60% 1RM)	0.97 (0.03) (~61% 1RM)	0.98 (0.04) (~60% 1RM)	0.83 (0.03) (~70% 1RM)	0.82 (0.03) (~70% 1RM)	0.82 (0.03) (~70% 1RM)	0.83 (0.01) (~70% 1RM)	0.76 (0.03) (~75% 1RM)
VL (%)									
VL15	15.8 (3.1)	15.5 (2.3)	15.2 (2.4)	14.8 (2.6)	14.7 (2.4)	15.3 (2.9)	18.0 (6.4)	16.2 (3.7)	18.0 (5.4)
VL45	39.6 (2.1)	39.7 (3.9)	43.7 (2.0)	45.2 (4.0)	39.7 (4.0)	38.5 (2.8)	43.2 (3.0)	42.1 (3.5)	39.2 (4.3)
Rep per set									
VL15	5.8 (2.1)	5.7 (1.7)	5.7 (2.1)	5.7 (1.4)	4.0 (1.1)	4.2 (0.8)	4.3 (1.3)	4.1 (1.2)	3.6 (0.8)
VL45	15.5 (6.0)	12.8 (4.8)	14.2 (6.4)	15.1 (5.9)	9.7 (3.4)	8.8 (3.2)	9.1 (2.8)	9.3 (2.9)	8.2 (2.5)

Actually performed	Session 10	Session 11	Session 12	Session 13	Session 14	Session 15	Session 16	Overall
Best MPV (% 1RM)								MPV all reps
VL15	0.76 (0.02) (~75% 1RM)	0.77 (0.04) (~73% 1RM)	0.76 (0.02) (~75% 1RM)	0.69 (0.02) (~80% 1RM)	0.69 (0.04) (~80% 1RM)	0.68 (0.03) (~80% 1RM)	0.69 (0.02) (~80% 1RM)	0.82 (0.12) (~70% 1RM)
VL45	0.77 (0.04) (~73% 1RM)	0.78 (0.03) (~73% 1RM)	0.75 (0.02) (~75% 1RM)	0.69 (0.03) (~80% 1RM)	0.69 (0.02) (~80% 1RM)	0.68 (0.03) (~80% 1RM)	0.71 (0.03) (~78% 1RM)	0.82 (0.11) (~70% 1RM)
VL (%)								Mean VL
VL15	16.4 (3.7)	17.6 (3.6)	18.6 (4.8)	21.1 (10.0)	19.0 (5.3)	19.9 (4.4)	18.1 (6.4)	17.1 (4.9)
VL45	43.4 (3.9)	44.6 (3.8)	43.1 (2.5)	39.6 (2.6)	43.4 (3.1)	45.4 (4.7)	46.8 (6.3)	42.3 (4.3)
Rep per set								Mean reps
VL15	3.9 (0.6)	3.8 (0.9)	3.5 (0.6)	3.2 (1.1)	3.2 (0.6)	3.3 (0.8)	3.3 (0.9)	4.2 (1.5)
VL45	8.8 (2.9)	8.5 (2.7)	7.5 (2.3)	6.0 (2.3)	6.5 (2.2)	6.6 (2.3)	6.9 (2.5)	9.1 (2.8)

Abbreviations: Best MPV, the fastest mean propulsive velocity attained with the intended load (%1RM); mean reps, average number of repetitions performed in each set; mean VL, average velocity loss attained during the entire training program; MPV, mean propulsive velocity; MPV all reps, average mean propulsive veolcity attained during the entire training program; rep, repetition; Rep per set, actual number of mean repetitions performed in each set; SQ, squat; VL, magnitude of velocity loss expressed as percent loss in mean repetition velocity from the fastest (usually first) to the slowest (last one) repetition of each set; VL15, group that trained with a mean velocity loss of 15% in each set (n = 11); VL45, group that trained with a mean velocity loss of 45% in each set (n = 11). Note: Data are presented as mean (SD). Only one exercise (full SQ) was used in training.

Table 2 Descriptive Characteristics of the ET Program Performed by all Groups

Scheduled	Session 1	Session 2	Session 3	Session 4	Session 5	Session 6	Session 7	Session 8	Session 9
S×T	4×8	5×8	6×5	7×5	4×4	5×4	4×3	5×3	5×2
Rest, min	2	2	2	2	2	2	2	2	2
Intensity (%vVO$_2$max)	80	80	85	85	90	90	95	95	100
Actually performed									
Average intensity (%vVO$_2$max)									
VL15	80.1 (0.09)	79.7 (1.2)	84.3 (1.1)	83.8 (1.5)	89.5 (2.4)	89.4 (1.8)	94.3 (2.0)	93.5 (2.3)	99.9 (2.7)
VL45	79.9 (1.8)	79.4 (2.0)	83.0 (4.5)	85.1 (1.9)	89.5 (2.5)	89.6 (2.9)	96.1 (4.1)	94.0 (3.4)	100.0 (5.5)
ET	79.9 (1.8)	80.5 (1.1)	84.1 (2.8)	83.4 (3.3)	90.0 (2.9)	89.9 (1.9)	95.4 (2.5)	93.4 (2.6)	100.5 (2.4)

	Session 1 TT	Session 1 % HRmax	Session 2 TT	Session 2 % HRmax	Session 3 TT	Session 3 % HRmax	Session 4 TT	Session 4 % HRmax	Session 5 TT	Session 5 % HRmax	Session 6 TT	Session 6 % HRmax	Session 7 TT	Session 7 % HRmax	Session 8 TT	Session 8 % HRmax	Session 9 TT	Session 9 % HRmax
VL15	30.2 (4.0)	88.2 (2.7)	37.9 (3.9)	87.6 (2.9)	29.7 (1.4)	86.6 (2.9)	33.8 (4.0)	85.6 (2.3)	16.2 (0.5)	85.3 (3.9)	19.7 (1.2)	85.4 (3.2)	12.1 (1.2)	85.2 (2.2)	15.1 (0.3)	85.4 (2.7)	9.9 (0.2)	84.0 (2.5)
VL45	31.1 (2.3)	88.3 (3.6)	40.1 (0.9)	87.5 (2.9)	27.9 (4.3)	86.3 (2.6)	34.6 (2.1)	86.3 (2.3)	16.2 (0.8)	86.4 (1.9)	19.3 (2.5)	86.8 (2.4)	12.0 (0.3)	85.1 (1.9)	15.2 (0.6)	86.7 (2.5)	9.8 (0.7)	84.2 (2.0)
ET	30.2 (6.1)	87.7 (2.5)	39.9 (0.6)	87.5 (2.9)	30.3 (0.7)	86.0 (3.8)	35.2 (1.9)	84.3 (3.9)	16.0 (0.7)	85.4 (3.4)	19.9 (0.6)	86.1 (2.7)	11.9 (0.3)	84.9 (3.5)	15.0 (0.9)	84.9 (4.2)	10.0 (0.3)	84.7 (4.0)

Scheduled	Session 10	Session 11	Session 12	Session 13	Session 14	Session 15	Session 16	Overall
S× T	6×2	4×1	6×1	8×30″	12×30″	10×20″	14×20″	
Rest, min	2	2	2	2	1	1	1	
Intensity (%vVO$_2$max)	100	105	105	110	110	120	120	
Actually performed								
Average intensity (%vVO$_2$max)								
VL15	99.2 (2.4)	112.9 (5.0)	111.2 (3.8)	118.1 (4.6)	118.5 (4.9	132.7 (11.7)	130.6 (5.9)	101.1 (17.4)
VL45	99.7 (3.7)	114.9 (5.1)	112.3 (3.9)	118.9 (5.8)	119.0 (6.3)	130.9 (9.1)	128.6 (6.5)	101.3 (17.1)
ET	100.4 (2.4)	114.5 (4.3)	110.8 (4.2)	120.4 (6.6)	118.3 (4.6)	130.1 (5.7)	128.0 (4.3)	101.5 (16.8)

	Session 10 TT	Session 10 % HRmax	Session 11 TT	Session 11 % HRmax	Session 12 TT	Session 12 % HRmax	Session 13 TT	Session 13 % HRmax	Session 14 TT	Session 14 % HRmax	Session 15 TT	Session 15 % HRmax	Session 16 TT	Session 16 % HRmax	Overall TT	Overall %HRmax
VL15	12.0 (0.3)	83.8 (3.1)	3.8 (0.2)	79.0 (4.0)	5.7 (0.2)	78.5 (4.0)	3.7 (0.2)	82.2 (3.4)	5.5 (0.3)	82.3 (3.0)	5.5 (0.3)	82.3 (3.0)	3.1 (0.1)	82.3 (3.1)	15.1 (11.6)	84.1 (4.0)
VL45	11.7 (1.0)	84.8 (3.2)	3.7 (0.2)	80.1 (3.2)	5.6 (0.3)	80.2 (2.6)	3.7 (0.1)	84.4 (3.1)	5.5 (0.2)	84.9 (3.1)	5.5 (0.2)	84.9 (3.1)	3.1 (0.2)	83.2 (2.3)	15.1 (11.6)	84.9 (3.4)
ET	12.1 (0.3)	83.2 (3.6)	3.7 (0.1)	79.6 (3.1)	5.7 (0.3	78.4 (4.0)	3.6 (0.2)	81.3 (4.4)	5.3 (0.5)	80.1 (4.6)	5.3 (0.5)	80.1 (4.6)	3.1 (0.1)	81.6 (4.3)	15.0 (11.9)	83.6 (4.6)

Abbreviations: ET, group that performed endurance training alone (n = 11); Rest, rest between sets; S, number of series; vVO$_2$max, velocity associated withVO$_2$max; average intensity (%vVO$_2$max), average intensity reached during the session; VL15, group that trained with a mean velocity loss of 15% in each set (n = 11); VL45, group that trained with a mean velocity loss of 45% in each set (n = 11); TT, total running time (min); % HRmax, percentage of maximum heart rate reached during the session; T, running time series (minutes, except on sessions 13, 14, 15, and 16, which was second). Note: Data are presented as mean (SD).

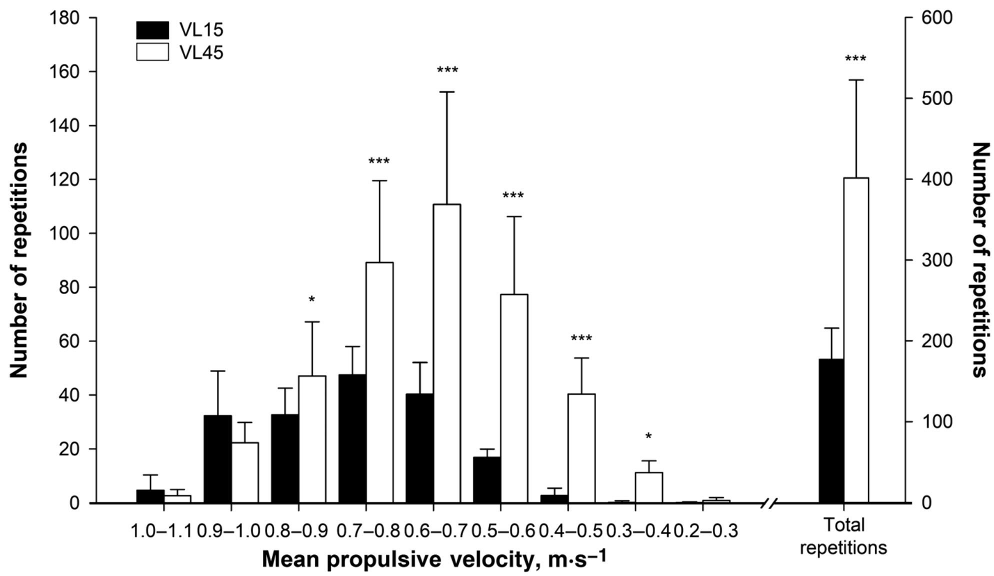

Figure 1 — Number of repetitions in the SQ exercise performed in each velocity range, and total number of repetitions completed by both CT groups. Data are presented as mean (SD). Statistically significant differences between groups: $^{*}P < .05$, $^{***}P < .001$. CT indicates concurrent training; MPV, mean propulsive velocity; SQ, squat; VL15, group that trained with a mean velocity loss of 15% in each set (n = 11); VL45, group that trained with a mean velocity loss of 45% in each set (n = 11).

improvements ($P < .001–.05$) in all these variables, whereas a significant decrease ($P < .05$) was observed for ET in all variables except for AV > 1 (Table 3).

Incremental Treadmill Test

A significant "group" × "time" interaction ($P = .03$) was noted for vVO_2max, where the VL15 group attained greater gains in vVO_2max than the ET group (Table 3). Moreover, all groups showed significant increases in vVO_2max ($P < .001–.05$, Table 3). No statistically significant changes in VO_2max were observed for any group (Table 3).

Discussion

The 2 main findings of this study were as follows. First, both of the combined resistance and ET programs experienced greater gains when compared with the group that performed ET alone, in terms of CMJ height and all strength-related variables. However, no significant differences were observed between the 2 CT programs despite the large differences in the total volume accumulated by each group over the training intervention. Second, although all experimental groups showed improvements in vVO_2max, the VL15 group improved vVO_2max to a greater extent than the ET group. Therefore, these findings indicate that moderate VL thresholds (ie, VL15) during RT combined with ET could be a good strategy for concurrently maximizing strength and endurance development.

From a strength perspective, both CT groups showed higher improvements in 1RM strength and the rest of the variables derived from the progressive loading SQ test (AV, AV > 1, and AV < 1) than the ET group. In addition, ET showed significant deterioration in almost all strength variables. This negative effect on strength gains when ET is carried out in isolation could be due to strength and endurance regimes eliciting divergent adaptive mechanisms, which often may conflict one another.[2,22] Thus, our results confirm the need to add strength training to ET to avoid impairments in strength performance. Moreover, the CT group that trained with lower levels of fatigue during the RT set (ie, VL15) showed a higher magnitude of change (ie, ES) than the CT including RT with repetitions close to muscle failure (ie, VL45) for all strength-related variables (Table 3). In agreement with our findings, Izquierdo-Gabarren et al[14] observed that 8 weeks of CT with a nonfailure RT provides similar or even greater gains in strength in the bench-pull exercise than CT with an RT to muscle failure in well-trained rowers. Coinciding with our findings, after an 8-week RT program in SQ exercise, similar or even higher strength gains have been observed for moderate VL thresholds (ie, 10%–20% VL) compared with RT programs attaining high levels of fatigue or even reaching muscle failure during the set in SQ exercise (ie, 30%–40% VL).[15,17,18] However, none of these studies analyzed the effects of different VL thresholds in CT programs. Likewise, both CT interventions showed greater gains in CMJ height than ET, and the VL15 group was the only one that obtained significant improvements in sprint performance (sprint time over 10 to 20 m). It has been reported that RT protocols consisting of low VL thresholds (ie, 10% VL) induce a decrease in muscle deformation in response to single-twitch stimulation using tensiomyography,[17] which has been interpreted as an increase in muscle stiffness.[23] Furthermore, after an 8-week RT program in SQ exercise with high VL thresholds (ie, 40% VL), a reduction in the IIX fiber type was observed,[15] together with an impairment in rate of force development in the first 50 millisecond,[17] which may not provide an optimal physiological environment for improving sprint performance.

From an endurance perspective, the 3 training protocols resulted in improvements in vVO_2max without significant changes in VO_2max (Table 3). Improvements in endurance performance after CT programs are often reported in the absence of any changes in VO_2max.[5,6,8,24–26] Therefore, enhancements in endurance running performance following CT programs may not be facilitated by

Table 3 Changes in Sprint, Jump, Strength, and Endurance Performance From Pretraining to Posttraining for Each Group (Mean [SD])

Performance variables	VL15 (n = 11) PRE	VL15 (n = 11) POST	VL15 (n = 11) ES (95% CI)	VL45 (n = 11) PRE	VL45 (n = 11) POST	VL45 (n = 11) ES (95% CI)	ET (n = 11) PRE	ET (n = 11) POST	ET (n = 11) ES (95% CI)	*P* value time effect	*P* value group × time
T10, s	1.78 (0.06)	1.77 (0.06)	0.10 (–0.26 to 0.46)	1.81 (0.07)	1.80 (0.06)	0.17 (–0.14 to 0.48)	1.80 (0.08)	1.82 (0.08)	–0.28 (–0.74 to 0.18)	0.05	0.15
T20, s	3.09 (0.11)	3.06 (0.11)	0.24 (–0.03 to 0.50)	3.12 (0.12)	3.10 (0.10)	0.22 (0.01 to 0.44)	3.11 (0.12)	3.14 (0.13)	–0.18 (–0.54 to 0.18)	0.16	0.06
T10–20, s	1.30 (0.04)	1.28 (0.06)*	0.39 (0.10 to 0.68)	1.30 (0.05)	1.29 (0.05)	0.29 (0.05 to 0.53)	1.30 (0.04)	1.30 (0.05)	–0.04 (–0.44 to 0.36)	0.84	0.14
CMJ, cm	35.4 (3.6)	39.4 (4.4)$^{***,\#\#\#}$	0.99 (0.47 to 1.51)	35.5 (3.4)	38.2 (2.7)$^{***,\#}$	0.91 (0.35 to 1.47)	34.9 (3.6)	35.3 (3.3)	0.13 (–0.13 to 0.39)	0.11	<0.001
1RM, kg	86.3 (7.3)	96.0 (7.0)$^{***,\#\#\#}$	1.35 (0.65 to 2.05)	86.1 (10.6)	97.1 (14.2)$^{***,\#\#\#}$	0.88 (0.34 to 1.42)	88.6 (6.7)	84.3 (6.1)*	–0.67 (–1.15 to –0.18)	0.55	<0.001
AV, $m \cdot s^{-1}$	0.88 (0.05)	1.00 (0.08)$^{***,\#\#\#}$	1.81 (0.91 to 2.70)	0.91 (0.08)	1.01 (0.09)$^{***,\#\#\#}$	1.10 (0.43 to 1.77)	0.94 (0.06)	0.90 (0.05)*	–0.77 (–1.34 to –0.20)	0.18	<0.001
AV>1, $m \cdot s^{-1}$	1.21 (0.06)	1.29 (0.07)$^{***,\#\#\#}$	1.05 (0.46 to 1.63)	1.23 (0.08)	1.27 (0.07)$^{*,\#}$	0.53 (–0.02 to 1.07)	1.22 (0.05)	1.20 (0.07)	–0.29 (–0.71 to 0.12)	0.13	<0.001
AV<1, $m \cdot s^{-1}$	0.65 (0.06)	0.80 (0.08)$^{***,\#\#\#}$	2.16 (0.99 to 3.32)	0.66 (0.04)	0.80 (0.11)$^{***,\#\#\#}$	1.72 (0.83 to 2.61)	0.71 (0.05)	0.65 (0.07)*	–1.07 (–1.78 to –0.36)	0.70	<0.001
VO_2max, $mL \cdot min^{-1}$	3825.5 (436.8)	3787.3 (421.9)	–0.09 (–0.37 to 0.20)	3804.9 (385.3)	3782.0 (359.4)	–0.06 (–0.28 to 0.16)	3825.1 (521.6)	3791.5 (442.1)	–0.07 (–0.38 to 0.24)	0.39	0.99
vVO_2max, $km \cdot h^{-1}$	16.4 (1.5)	17.3 (1.5)$^{***,\#}$	0.62 (0.31 to 0.92)	16.5 (1.2)	17.0 (1.2)**	0.40 (0.16 to 0.64)	16.5 (1.1)	16.9 (0.9)*	0.35 (–0.07 to 0.77)	0.04	0.03

Abbreviations: 1RM, one-repetition maximum; AV, average mean propulsive velocity with the common load in squat; AV<1, average MPV attained against absolute loads that were moved slower than 1 $m \cdot s^{-1}$ at pretraining; AV>1, average MPV attained against absolute loads that were moved faster than 1 $m \cdot s^{-1}$ at pretraining; CI, confidence interval; CMJ, countermovement jump height; ES, intragroups effects size; ET, group that performed endurance training alone; POST, posttraining evaluation; PRE, pretraining evaluation; T10, 10-m sprint time; T10–20, 10- to 20-m sprint time; T20, 20-m sprint time; VL15, group that trained with a mean velocity loss of 15% in each set; VL45, group that trained with a mean velocity loss of 45% in each set; VO_2max, maximal oxygen uptake; vVO_2max, velocity associated withVO_2max.
Significant differences respect to ET: $^{\#}P < .05$, $^{\#\#\#}P < .001$. Significant differences intragroups: $^{*}P < .05$, $^{**}P < .01$, $^{***}P < .001$.

changes in cardiorespiratory fitness. Likewise, the CT group with the lower VL threshold (ie, VL15) showed greater gains in vVO_2max than the ET group (Table 3). In agreement with our findings, it has been reported that CT improves endurance running performance more than ET alone, as shown by greater 400-m to 10-km time-trial results.[26–29] Moreover, Izquierdo-Gabarren et al[14] reported greater improvements in 20-minute rowing time-trial performance following an 8-week CT performing RT without reaching muscle failure compared with CT performing RT to failure, and to isolated ET. The mechanisms underpinning the superior gains in endurance performance (vVO_2max) observed in one of the CT interventions, specifically the VL15 group, compared with ET may be related to increments in muscle strength and power,[25,30] neuromuscular control,[24,29] and musculoskeletal stiffness.[27,29] Increased muscle strength would allow athletes to generate lower relative strength values during sustained endurance running.[31] As a consequence, recruitment of higher threshold motor units would be reduced, producing a more economical behavior.[31] The fact that the CT intervention including RT close to muscle failure (ie, VL45) did not obtain higher endurance adaptations compared with the isolated ET may be related to hypertrophic adaptations induced by this type of RT, as it has been shown that higher VL thresholds within the RT set (ie, 40%) maximize the hypertrophic response.[15,17] Muscle hypertrophy could have a negative impact on weight-bearing endurance events.[6] Furthermore, an increase in muscle fiber cross-sectional area would decrease the capillary to cross-sectional area ratio, which would increase diffusion distance.[6] It should be noted that CT and ET groups conducted a different weekly structure and density, since CT groups performed 4 training sessions per week (2 strength and 2 endurance sessions, 24- to 48-h rest between sessions, and 32 sessions in total) while ET trained twice a week (2 endurance sessions, 72-h rest, and 16 sessions in total). In this regard, higher VL thresholds during RT promote higher fatigue levels and slower rates of recovery than lower VL thresholds.[12] This fact should be considered given that the residual fatigue evoked by these RT sessions may compromise the quality of ET sessions (24-h rest between sessions), and, likely, induce suboptimal endurance development.[32] Finally, previous reports have suggested no differences between CT approaches with different intensity distributions but with work-matched training regimens.[33,34] Whether the moderate VL training intervention (ie, VL15) performed a higher number of sets in order to equalize total training volume with higher VL thresholds (ie, VL45) would result in additional strength and endurance improvements should be assessed in future studies.

Practical Applications

As already suggested in isolated RT programs,[15,17,18] during RT programs concurrently performed with ET, once a given "optimal" VL during the RT set is reached, further repetitions do not elicit additional strength gains. Furthermore, these further repetitions do not elicit additional endurance gains and could even blunt the improvement in endurance performance. Those coaches and practitioners cannot measure repetition velocity could use the level of effort approach (ie, relationship between repetitions actually performed and maximum number of repetitions until failure[12]) to prescribe the optimal training volume within each set. This approach using moderate levels of effort (~4[10]) or VL thresholds (VL15) in RT performed during CT induces greater gains in strength and endurance performance accumulating lower training volume, which results in lower residual fatigue by RT and higher training efficiency than efforts close to muscle failure (9–10[10] or VL45).

Conclusions

Both CT interventions (VL15 and VL45) showed greater strength gains when compared with the ET alone. Moreover, although all groups showed improvements in vVO_2max, the VL15 group improved vVO_2max to a greater extent than the ET alone group. Therefore, moderate VL thresholds (ie, VL15) during RT combined with ET could be a good strategy for concurrently maximizing strength and endurance development. Further studies should confirm or refute these findings and examine the long-term adaptations of different VL thresholds during CT settings in highly trained subjects.

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