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Velocity Loss During Resistance Training: Implications for Concurrent Training Adaptations

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ABSTRACT

This study examined the effects of different velocity loss (VL) thresholds during resistance training (RT) on adaptations to concurrent training (CT), with particular focus on strength, endurance, neuromuscular, and hypertrophic outcomes. Forty-one moderately trained men were randomly assigned to one of four groups: CT with RT at 0% (VL0; $n=10$), 15% (VL15; $n=10$), or 40% (VL40; $n=11$) VL, or endurance training (ET; $n=10$) alone. Over 8 weeks, CT groups performed squat-based RT at 70%–85% of one-repetition maximum followed by ET (separated by 10 min), consisting of running at 90%–105% (from 18 to 8 min) of maximal aerobic speed (MAS) two times per week. Assessments included cross-sectional area of the vastus lateralis, maximal isometric squat, progressive loading squat, countermovement jump, sprinting, MAS, fatigue resistance, and electromyography (EMG) during squat tests. All CT groups significantly increased muscle mass, with VL40 achieving the greatest gains (group × time interaction, $p<0.05$), while ET showed no changes. MAS improved in all groups ($p<0.001$), with ET achieving the greatest gains; within CT, the lower the VL, the higher the effect size (group × time interaction, $p=0.04$). VL15 and VL40 obtained greater 1RM gains than ET (group × time interaction, $p=0.009$). VL15 and VL40 significantly improved strength-related variables. ET showed no strength gains and significantly reduced the rate of force development at 400 ms ($p=0.01$). VL0 increased EMG amplitude across loads, while ET reduced it (group × time interactions, $p<0.05$). CT improved strength and endurance performance. However, fatigue induced during RT may attenuate endurance adaptations. ET enhanced aerobic performance but impaired neuromuscular function and failed to improve strength.

1 | Introduction

Concurrent training (CT) is recommended to enhance both strength and endurance simultaneously [1]. There is strong evidence that endurance performance in activities such as running or cycling can be enhanced through resistance training (RT). Among multiple factors, key adaptations such as running economy [2, 3], an increased proportion of type IIA fibers, and improvements in the rate of force development (RFD) [4] are commonly reported. Nevertheless, since 1980, when Hickson [5] first described the "interference effect", a potential decrease in training-induced adaptations when RT and endurance training (ET) are performed simultaneously, it has become a hot topic in sports science. More than three decades later, this topic remains a subject of debate, and even the most recent reviews do not reach consensus on the optimal combination of RT and ET [1, 6].

Several factors influencing the interference effect include the RT variables (e.g., volume, intensity, frequency, and others) [7]. In this context, velocity-based training (VBT) has been recognized as a valid and reliable method to control RT intensity [8] and the level of effort (i.e., the relationship between the number of repetitions completed by a given subject and the maximum number of repetitions they can perform with a certain load) [9]. This method enables researchers and coaches to determine the level of effort achieved by measuring velocity loss (VL) in each set [10]. Using VL to prescribe training volume enables real-time fatigue management and ensures consistent effort among athletes. It also allows targeted adaptations by adjusting the VL threshold and provides individualized training [11]. It has been demonstrated that lower VL thresholds within sets during RT sessions can be more efficient (i.e., yielding similar or greater gains with less work) than higher VL thresholds [11–13]. For example, Pareja-Blanco et al. [12] reported similar or even greater increases in strength capacity in a group that trained with a 20% VL compared to another that trained with 40% VL, meaning the 20% VL group performed approximately 66% of the total repetitions completed by the 40% VL group. Similarly, Pareja-Blanco et al. [11] compared four different VL thresholds (i.e., 0%, 10%, 20%, and 40% VL) and demonstrated that 10%–20% VL maximized strength gains, and even performing only one repetition per set (0% VL) can lead to improvements in certain strength-related variables, such as early RFD.

While in isolated RT, there is substantial evidence demonstrating that moderate VL thresholds are more efficient than higher VLs for increasing strength performance [11–13], the same does not hold for CT, with only one study addressing this topic [14]. Sánchez-Moreno et al. [14] compared two CT protocols: one in which strength- and endurance-trained men performed RT with a high level of fatigue (45% VL), and the other in which the subjects performed a similar RT protocol but with a moderate level of fatigue (15% VL). Both CT groups conducted ET on separate days from RT, and a third group performed only ET sessions (ET group). After the 8-week intervention, both CT groups showed improvements in all strength-related variables; however, the 15% VL group showed greater strength gains and greater improvements in maximal aerobic speed (MAS) than the ET group. Therefore, the authors concluded that moderate VL thresholds during RT combined with ET can be an effective and efficient way to optimize adaptations in both strength- and endurance-related qualities. These findings align with research conducted by other authors, who have demonstrated that higher volumes of RT (and, consequently, higher levels of fatigue) can be detrimental to performance in endurance sports [15, 16].

Since fatigue induced by RT is one of the main modulators of the interference phenomenon, and because this factor can significantly influence training-induced adaptations [16, 17], it is relevant to examine its effects on strength and endurance performance, neuromuscular adaptations [e.g., muscle activation patterns assessed through electromyography (EMG)], and muscle hypertrophy across different CT protocols involving varying levels of fatigue resulting from RT sessions performed under different %VL. Therefore, the aim of this study was to analyze the adaptations elicited by three CT protocols, each involving distinct levels of fatigue induced during RT (as determined by specific %VL), on neuromuscular and hypertrophic adaptations, as well as a range of strength- and endurance-related capacities in moderately trained subjects. For consistency and control, an additional group that performed only ET sessions was included in the intervention. We hypothesized that the CT groups training with lower %VL would achieve not only similar but potentially superior improvements in physical performance compared to the group that trained with higher %VL.

2 | Materials and Methods

2.1 | Study Design

A randomized controlled trial was conducted to examine the effects of four training programs over an 8-week period. Three of these programs combined RT and ET (i.e., CT) but varied in their VL thresholds attained during RT: 0% (VL0), 15% (VL15), and 40% (VL40). The fourth group performed only ET, which was identical across all groups. Strength and endurance sessions were conducted on the same day, with RT always before ET, separated by a 10-min rest interval. Testing was conducted during the week preceding the training program and during the week following its completion. Testing included two evaluation sessions, spaced 72 h apart. The first session included ultrasound measurements of the vastus lateralis' cross-sectional area (CSA), sprinting, and MAS tests. The second session consisted of countermovement jump (CMJ) and different types of squat tests, including maximal voluntary isometric contraction, a progressive loading test, and a fatigue test. EMG was also measured during squat tests. Both pre- and post-training evaluations were conducted under the same conditions and at the same time of day for each participant. Subjects received velocity feedback and verbal cues from researchers after every repetition during testing and training sessions. Two familiarization sessions were conducted during the week prior to the pre-intervention assessments. They focused on standardizing squat depth and emphasized performing repetitions at the intended maximum velocity. Anthropometric parameters (height and body mass) were assessed during these sessions. Throughout the intervention, participants were instructed to refrain from any additional training or competitive activities.

2.2 | Subjects

The sample size was calculated using G*Power (Version 3.1.9.2, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) with the following parameters: statistical test: repeated measures ANOVA, within-between interaction; effect size (ES) = 0.35, based on ES observed for MAS in previous literature using a similar approach [14]; and α error probability (0.05) and power (0.95), four groups and two measurements, which resulted in a sample size of 10 subjects per group. Considering potential dropouts, 48 men were recruited for this study. Participants were allocated to the four training conditions using a stratified blocked randomization procedure based on baseline 1RM values. Specifically, subjects were first ranked from highest to lowest according to their pre-intervention 1RM. This ordered list was then used to sequentially assign participants to the four groups using a balanced forward–reverse block sequence (ABCDDCBA), repeated until all participants were allocated. Seven subjects did not complete the intervention, dropping out due to schedule incompatibility. Thus, the final sample comprised forty-one moderately trained men (mean ± standard deviation [SD]: age = 25.0 ± 4.3 years, height = 1.78 ± 0.07 m, body mass = 74.4 ± 13.2 kg; one-repetition maximum [1RM] = 108.9 ± 18.3 kg; MAS = 15.7 ± 1.7 km·h^{-1}). The inclusion criteria were that the subjects should be resistance-trained men with at least 1 year of RT experience in the squat exercise and that the level of performance of the participants fell under tiers 1 and 2 based on the framework outlined by McKay et al. [18], which defines this population as physically active individuals who engage in training at least three times per week. The exclusion criteria were that subjects could not have physical limitations, health problems, or musculoskeletal injuries during the experiments that could affect the physical tests and evaluation protocols. Additionally, they were not allowed to take any medications or drugs before the test. They were informed of the potential risks associated with the testing and training process and signed a written informed consent form. The study followed the Declaration of Helsinki and was approved by the Local Research Ethics Committee (Ref: 1547-N-19). After the initial evaluation, the subjects were randomly assigned to one of four groups.

2.3 | Testing Procedures

Before the fitness tests, participants completed a standardized 10-min warm-up that included 5 min of jogging, joint mobility exercises, and a test-specific warm-up. Throughout all testing sessions, participants were verbally encouraged to exert their maximum effort. The testing procedures are described below.

2.3.1 | Ultrasonography

The CSA of the vastus lateralis was measured using B-mode ultrasonography (MyLab 25, Esaote Biomedica, Italy) with a 50-mm linear probe at 5–12 MHz. Participants lay supine with their knees slightly flexed to 150° (full extension = 180°) on a foam roll for imaging. After 15 min in this position, the length of the vastus lateralis was measured from the lateral femoral condyle to the greater trochanter of the right leg [19]. CSA images were captured at three sites: 40%, 57.5%, and 75%, designated CSA40, CSA57.5, and CSA75, respectively. Muscle volume (cm^3) was estimated from five CSA slices [20]. An extended field-of-view mode was used to capture the CSA of the muscle. Adhesive tape secured the probe to the skin, with ultrasound gel applied at the proximal and distal boundaries to ensure a straight path for the tracing. A panoramic image was taken from medial to lateral, at a constant speed and with the probe perpendicular to the surface, using minimal pressure to prevent tissue compression. An experienced researcher recorded and analyzed these images using ImageJ 1.51j8 (NIH) to outline the muscle boundaries. Each measurement was based on two images; a third was used if the coefficient of variation (CV) exceeded 5%. The mean of all images was used for analysis. To ensure consistent probe placement both before and after training, positions were recorded on transparent acetate sheets with anatomical landmarks.

2.3.2 | Sprint Testing

Participants performed two maximal 20-m sprints on an indoor running track, with a 3-min rest period between attempts. Before the test, they performed four submaximal sprints as a warm-up. Times over 0–10, 0–20, and 10–20 m (T10, T20, and T10–20, respectively) were recorded using photocells (Witty, Microgate, Bolzano, Italy). The best time (i.e., fastest sprint) was used for analysis. Sprints were initiated from a static bipedal stance positioned 1 m behind the first timing gate.

2.3.3 | Maximal Aerobic Speed

A treadmill (Valiant 2 Sport/XL, Lode, Netherlands) was used for this test. The initial speed of 8.0 km·h^{-1} was increased automatically by 0.1 km·h^{-1} every 12 s until exhaustion, with a constant gradient of 1%. The highest speed attained, minus 0.5 km·h^{-1}, was identified as MAS. This protocol was originally proposed by Léger and Boucher (1980) to estimate MAS [21]. All subjects were encouraged throughout the test to push themselves to the point of exhaustion.

2.3.4 | Countermovement Jump Test

Participants performed five maximal CMJs with hands on the hips, with a 45-s rest interval between attempts. Jump height was estimated from flight time using an infrared timing system (Optojump Next, Microgate, Bolzano, Italy). The lowest and highest values were excluded, and the average of the remaining values was retained for analysis. As a warm-up, participants performed two sets of 10 bodyweight squats, followed by one set of three CMJs with progressively increasing height.

2.3.5 | Maximal Voluntary Isometric Squat Test (MVIST)

The test was conducted using a Smith machine equipped with height-adjustable movable supports to standardize the test position for each participant, set at 90° of knee flexion in the squat position. Participants were instructed to apply force as quickly as possible for 5 s following the cue, "Ready, set, go!". Each subject performed two trials, separated by a 1-min rest interval. Kinetic data were captured at a sampling frequency of 1000 Hz using a dynamometric platform (80 × 80 cm; FP-500, Ergotech, Murcia, Spain). The raw force-time signals were processed automatically using custom software (T-Force System, Ergotech, Murcia, Spain) with a fourth-order low-pass Butterworth filter (zero-phase shift, 200 Hz cut-off frequency). From these data, maximal isometric force (MIF), maximal RFD (RFDmax) using a moving window of 20 ms with an overlap of 19 ms, and the average tangential slope of the force-time curve over various time windows (100, 200, and 400 ms from force onset) were computed, yielding $RFD_{0–100}$, $RFD_{0–200}$, and $RFD_{0–400}$ values, respectively. The onset of force production was defined manually by the same researcher as the point at which the signal rose above baseline.

2.3.6 | Progressive Loading Squat Test

Participants performed the exercise on a Smith machine (Multipower Fitness Line; Peroga Fitness, Murcia, Spain) following standardized technique: (a) starting from an upright position with knees and hips fully extended, feet parallel and shoulder-width apart; (b) the barbell placed across the upper back at the acromion level; (c) descending in a continuous motion to ~35°–40° of knee flexion (180° = full extension), and immediately ascending to the upright position. The concentric phase was executed at maximal intended velocity, without jumping or detaching the bar from the shoulders. A linear velocity transducer (T-Force System; Ergotech, Murcia, Spain), whose reliability has been previously demonstrated [22], was used to measure bar velocity. The participants performed six squat repetitions with a 20-kg barbell as a warm-up. The first load measured was 20 kg and was progressively increased by 10 kg increments until the mean propulsive velocity (MPV) was lower than $0.6\,m{\cdot}s^{-1}$. Then, the load was increased in increments of 2.5–5 kg until the MPV was less than $0.5\,m{\cdot}s^{-1}$. Three repetitions were executed for light loads ($>1.00\,m{\cdot}s^{-1}$), two for medium loads ($1.00–0.80\,m{\cdot}s^{-1}$), and one for the heaviest load ($<0.80\,m{\cdot}s^{-1}$), with a 3-min rest interval between trials. Only the highest MPV for each load was retained for further analyses. The same absolute load progression was performed during the post-training test. The 1RM value was calculated from the participants' linear load-velocity relationship, specifically the load that could be lifted at $\sim 0.32\,m{\cdot}s^{-1}$ [23]. In addition to the 1RM and the load–velocity relationship, the following variables were also measured and computed: (a) the average MPV across all absolute loads common to both pre- and post-training (AV), (b) the average MPV for loads moved faster than $1\,m{\cdot}s^{-1}$ at pre-training (AV > 1), and (c) the average MPV for loads moved slower than $1\,m{\cdot}s^{-1}$ at pre-training (AV < 1). These parameters were evaluated to analyze the effects on different parts of the load-velocity relationship (i.e., velocity attained against light and heavy loads). The propulsive phase refers to the portion of the concentric movement where the barbell's acceleration exceeds gravity ($-9.81\,m{\cdot}s^{-2}$) [24].

2.3.7 | Fatigue Test

Five minutes after the progressive loading test, participants were instructed to perform as many squat repetitions as possible using a load equivalent to 70% of their 1RM, continuing until their MPV dropped below $0.50\,m{\cdot}s^{-1}$, using the same absolute load for pre- and post-training tests. The execution technique and equipment employed were identical to those used during the progressive loading test. Participants were verbally encouraged to complete each repetition at the maximal intended velocity. The maximal number of repetitions (MNR) completed was recorded for subsequent analysis.

2.3.8 | EMG Signal Acquisition

After preparing the skin and in accordance with SENIAM guidelines [25], surface EMG electrodes were positioned on the vastus medialis and vastus lateralis muscles of the right leg. A Trigno wireless EMG system (Delsys Inc., Natick, MA, USA) with a parallel-bar bipolar sensor was used for signal acquisition. The system featured an inter-electrode distance of 10 mm, a common-mode rejection ratio greater than 80 dB, and a bandwidth filter ranging from 20 to 450 Hz, with a tolerance of ±10%. Baseline noise was below 5 μV peak-to-peak, and the sampling rate was set at 2000 Hz. Raw EMG data were digitally recorded using EMGworks Acquisition Software. For each repetition, the highest root mean square (RMS) and median frequency (MDF) values were identified using 100-ms sliding windows with 99-ms overlap. RMS and MDF values from both muscles were averaged for each repetition for subsequent analysis. Since EMG was measured in all squat tests, the following variables were obtained: RMS_{iso} and MDF_{iso} (RMS and MDF values recorded during the isometric test); RMS_{AV} and MDF_{AV} (RMS and MDF attained against all absolute loads common to pre- and post-training); $RMS_{AV<1}$ and $MDF_{AV<1}$ (RMS and MDF attained against absolute loads that were moved slower than $1\,m{\cdot}s^{-1}$ at pre-training); $RMS_{AV>1}$ and $MDF_{AV>1}$ (RMS and MDF attained against absolute loads that were moved faster than $1\,m{\cdot}s^{-1}$ at pre-training); RMS_{MNR} and MDF_{MNR} (RMS and MDF recorded during the MNR completed at pre-training).

2.4 | Training Protocol

2.4.1 | Resistance Training Sessions

The only exercise performed during the RT sessions was the squat. The technical execution and settings were identical to those described in the progressive loading test. Descriptive characteristics are provided in Table 1. All groups (VL0, VL15, and VL40) completed 16 sessions, with at least 48 h of rest between each session. Relative intensity progressively increased from 70% to 85% 1RM, in 5% increments every 4 sessions. Three sets with a 3-min inter-set recovery were performed in every training session. The absolute intensity in each session was selected based on the load-velocity relationship from the progressive loading test ($R^2 = 0.986 \pm 0.017$). Therefore, a target MPV ($\pm 0.03\,m{\cdot}s^{-1}$) was used to adjust the absolute load to the scheduled %1RM. Previous research has shown that $0.03\,m{\cdot}s^{-1}$ is the smallest detectable change in MPV for the squat exercise when using the settings of this study [22]. Before each training session, the participants carried out a standardized warm-up: (a) 5 min of jogging at a self-selected leisurely pace, (b) 6-6-4-3 repetitions with 20 kg, 40%, 50%, and 60% 1RM, respectively, (c) 2 repetitions with 70% 1RM (only in sessions 5–16); and (d) 1 repetition with 80% 1RM (only in sessions 13–16). A 3-min rest was always allowed between sets. All training sessions were performed under the supervision of an experienced researcher.

TABLE 1 | Descriptive characteristics of the 8-week velocity-based squat training program performed by the three concurrent training groups.

	Session 1	Session 2	Session 3	Session 4	Session 5	Session 6	Session 7	Session 8	Session 9
Best MPV (% 1RM)									
VL0	0.72 (0.06)	0.72 (0.07)	0.73 (0.05)	0.73 (0.07)	0.64 (0.07)	0.66 (0.05)	0.66 (0.06)	0.66 (0.04)	0.59 (0.05)
VL15	0.72 (0.05)	0.73 (0.05)	0.72 (0.04)	0.72 (0.05)	0.65 (0.04)	0.66 (0.04)	0.66 (0.04)	0.66 (0.04)	0.61 (0.02)
VL40	0.75 (0.05)	0.75 (0.06)	0.76 (0.06)	0.76 (0.05)	0.68 (0.03)	0.68 (0.05)	0.69 (0.05)	0.67 (0.05)	0.61 (0.05)
VL (%)									
VL0	0	0	0	0	0	0	0	0	0
VL15	16.9 (3.0)	17.2 (4.3)	16.9 (3.7)	17.7 (2.1)	16.2 (2.3)	19.4 (4.1)	17.9 (2.5)	17.1 (1.6)	18.5 (2.9)
VL40	40.6 (1.7)	41.6 (2.6)	42.4 (3.7)	41.0 (1.9)	42.7 (4.3)	43.0 (4.9)	43.0 (4.4)	39.7 (3.7)	42.4 (2.9)
Rep/Set									
VL0	1	1	1	1	1	1	1	1	1
VL15	4.6 (1.3)	3.9 (1.1)	4.2 (1.5)	4.4 (1.6)	3.4 (0.9)	3.3 (1.0)	3.7 (1.7)	3.4 (1.0)	2.9 (0.8)
VL40	9.7 (3.8)	9.8 (4.2)	9.2 (2.5)	10.0 (5.1)	7.9 (2.6)	7.2 (2.4)	7.4 (1.9)	7.3 (2.0)	5.7 (1.4)

	Session 10	Session 11	Session 12	Session 13	Session 14	Session 15	Session 16	Overall
Best MPV (% 1RM)								MPV all reps
VL0	0.58 (0.04)	0.57 (0.04)	0.60 (0.05)	0.50 (0.03)	0.50 (0.03)	0.50 (0.04)	0.50 (0.04)	0.62 (0.09)
VL15	0.60 (0.04)	0.58 (0.04)	0.59 (0.05)	0.52 (0.04)	0.52 (0.03)	0.53 (0.02)	0.53 (0.05)	0.63 (0.08)
VL40	0.59 (0.02)	0.61 (0.03)	0.63 (0.03)	0.54 (0.04)	0.54 (0.03)	0.53 (0.04)	0.48 (0.04)	0.64 (0.09)
VL (%)								Mean VL
VL0	0	0	0	0	0	0	0	0
VL15	18.2 (5.8)	17.4 (3.5)	19.9 (4.7)	16.5 (3.6)	17.4 (3.6)	18.1 (3.6)	15.9 (2.0)	17.6 (1.7)
VL40	41.2 (4.0)	41.9 (2.3)	42.2 (3.5)	40.4 (2.5)	43.4 (5.4)	38.7 (8.8)	37.1 (2.8)	41.3 (1.7)
Rep/set								Mean rep/sets
VL0	1		1	1	1	1	1	1
VL15	2.9 (0.8)	2.8 (0.9)	3.2 (1.2)	2.3 (0.6)	2.27 (0.6)	2.6 (0.7)	2.4 (0.8)	3.3 (0.8)
VL40	4.9 (1.5)	5.1 (1.3)	5.3 (1.9)	3.79 (1.2)	4.06 (1.2)	3.9 (1.7)	3.6 (1.6)	6.5 (2.3)

Note: Data are expressed as mean (standard deviation).
Abbreviations: MPV, mean propulsive velocity; Rep/Set, number of repetitions performed for set; VL, velocity loss; VL0, concurrent group that trained with a velocity loss (VL) of 0% in each set; VL15, concurrent group that trained with a 15% VL in each set; VL40, concurrent group that trained with a 40% VL in each set.

2.4.2 | Endurance Training

The descriptive characteristics of the ET are presented in Table 2, and they were similar across the four groups. The relative intensity, ranging from 90% to 105% MAS, was individualized relative to baseline MAS. The training distance was calculated individually for each session based on the selected velocity and time. Training sessions were conducted on a 400-m outdoor running track, except on rainy days with heavy precipitation, when they were held on a treadmill (Valiant 2 Sport/XL, Lode, Netherlands), under the supervision of an experienced researcher.

3 | Statistical Analyses

Values are reported as means ± SD. Absolute test–retest reliability was examined using the standard error of measurement (SEM), expressed in relative terms through the CV. The SEM was calculated as the square root of the mean total within-subject variance. Relative reliability was calculated using the intraclass correlation coefficient (ICC) with a 95% confidence interval (CI), applying a one-way random-effects model. Repeated measurements obtained in the pre-training assessment were used to calculate reliability indices. Normality and homoscedasticity were tested with the Shapiro–Wilk and Levene tests. Data were analyzed using a 4×2 repeated-measures analysis of covariance (ANCOVA) with one between-groups factor (VL0, VL15, VL40, and ET) and one within-groups factor (pre-training and post-training), taking the baseline measures of each variable as covariates. Bonferroni adjustments were applied for post hoc comparisons. Statistical significance was established at $p \leq 0.05$. The ES was calculated using Hedges' g on the pooled SD [26]. The analysis was conducted using SPSS software, in addition to Microsoft Excel (Microsoft Corp., Redmond, WA, USA) for calculating the ES and CV.

TABLE 2 | Descriptive characteristics of the 8-week endurance training program performed by the four experimental groups.

	Session 1	Session 2	Session 3	Session 4	Session 5	Session 6	Session 7	Session 8
S×T	3×6	3×6	4×6	4×6	3×4	3×4	4×4	4×4
Rest, min	4	4	4	4	2	2	2	2
Intensity (% MAS)	90	90	90	90	95	95	95	95
Actually performed								
Average distance performed (% total distance)								
ET	98.0 (3.8)	98.7 (2.1)	94.2 (11.9)	96.21 (11.8)	99.8 (0.1)	99.7 (0.9)	100	98.7 (3.4)
VL0	97.7 (4.4)	97.9 (3.8)	97.0 (3.9)	94.8 (8.2)	99.5 (1.4)	99.0 (2.2)	99.1 (3.0)	98.9 (2.1)
VL15	98.2 (3.0)	96.7 (6.2)	95.0 (5.1)	96.7 (5.2)	96.8 (5.9)	97.2 (5.6)	98.2 (4.9)	97.1 (7.5)
VL40	92.5 (28.6)	93.5 (6.6)	86.4 (15.3)	92.4 (7.4)	93.7 (10.5)	97.5 (3.0)	95.4 (4.9)	96.0 (5.3)
	Session 9	**Session 10**	**Session 11**	**Session 12**	**Session 13**	**Session 14**	**Session 15**	**Session 16**
S×T	4×2	4×2	5×2	5×2	6×1	6×1	8×1	8×1
Rest, min	1	1	1	1	1	1	1	1
Intensity (% MAS)	100	100	100	100	105	105	105	105
Actually performed								
Average distance performed (% total distance)								
ET	100	100	99.4 (1.9)	100	100	100	100	100
VL0	99.8 (0.4)	99.9 (0.3)	100	100	100	100	100	100
VL15	99.5 (1.1)	100	98.0 (6.1)	98.6 (4.0)	100	100	100	100
VL40	99.0 (2.7)	99.9 (0.3)	99.9 (0.5)	99.9 (0.1)	100	100	100	100

Note: Data are expressed as mean (standard deviation).
Abbreviations: ET, group that only performed the endurance training; MAS, maximal aerobic speed; Rest, rest time between sets; S×T, number of sets and the time of each set; VL0, concurrent group that trained with a velocity loss (VL) of 0% in each set; VL15, concurrent group that trained with a 15% VL in each set; VL40, concurrent group that trained with a 40% VL in each set.

4 | Results

The reliability values of different tests conducted are shown below. *MVIST*: CV values = MIF: 6.2%, RFDmax: 23.0%, RFD_{0-100}: 30.9%, RFD_{0-200}: 23.9%, and RFD_{0-400}: 7.9%; and ICC (95% CI) values = MIF: 0.96 (0.93–0.98), RFDmax: 0.83 (0.66–0.91), RFD_{0-100}: 0.83 (0.66–0.91), RFD_{0-200}: 0.81 (0.63–0.90), and RFD_{0-400}: 0.88 (0.76–0.94). *EMG*: CV values = RMS: 8.8% and MDF: 6.0%; ICC (95% CI) values = RMS: 0.99 (0.97–0.99) and MDF: 0.96 (0.93–0.98).

The total repetitions, as well as the repetitions completed within different velocity intervals by the CT groups, are shown in Figure 1. The VL0 group exhibited a significantly higher mean velocity compared to the VL40 group (0.62 ± 0.09 vs. $0.51 \pm 0.09\,m\cdot s^{-1}$; $p = 0.001$), but not in comparison to VL15 ($0.57 \pm 0.07\,m\cdot s^{-1}$; $p = 0.26$). No significant difference in velocity was observed between VL15 and VL40 (0.57 ± 0.07 vs. $0.51 \pm 0.09\,m\cdot s^{-1}$; $p = 0.06$). However, the total repetitions completed differed significantly across the CT groups (VL0 = 48 ± 0; VL15 = 152 ± 37; VL40 = 297 ± 77; $p < 0.001$). The mean fastest repetition and the VL levels achieved during each session corresponded closely with the intended targets (see Table 1).

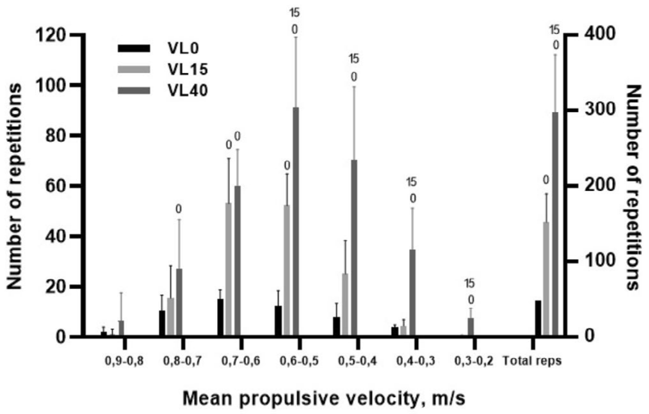

FIGURE 1 | Squat repetitions performed at different velocity ranges by each concurrent group. Between-groups significant differences ($p < 0.05$) with respect to: VL0, 0; VL15, 15, and VL40, 40. VL0, group that trained with a velocity loss (VL) of 0% in each set; VL15, group that trained with a 15% VL in each set; VL40, group that trained with a 40% VL in each set.

Regarding the ET (Table 2), significant differences were found in the total distance covered at 90% and 95% of MAS ($p < 0.05$), with the VL40 group covering a significantly smaller proportion of the distance (from 86.4% to 96%) than the other groups. No significant differences were observed among groups at 100% or 105% of MAS.

4.1 | Muscle Mass

The changes induced by the different protocols are presented in Table 3. A significant main effect of time ($p < 0.05$) was observed for all variables except CSA40 ($p = 0.21$). A significant group × time interaction was found for CSA75 ($p = 0.04$, respectively). The three CT groups presented significant increases in muscle mass ($p < 0.001$–0.05), with VL40 achieving the greatest gains. ET did not obtain significant changes in any muscle mass variable.

4.2 | Sprint and CMJ

There was no main time effect or group × time interaction for any of the sprint and jump variables (Table 4). No significant changes were observed in these performance measures.

4.3 | Incremental Treadmill Test

A group × time interaction was observed for MAS ($p = 0.04$). All groups improved their performance in the incremental test ($p < 0.001$ for all groups), with ET showing greater improvements than VL40 ($p < 0.05$). Within CT groups, the lower the VL, the higher the ES (Figure 2).

4.4 | Maximal Voluntary Isometric Squat Test

A significant group × time interaction was observed for RFD400 ($p = 0.01$). VL40 obtained greater gains in RFD400 than ET ($p < 0.05$). ET significantly reduced RFD400, and VL40 significantly increased RFD100, RFD200, and RFD400. There were no significant changes in the other variables (Table 5).

4.5 | Progressive Loading Test

There was a significant group × time interaction for 1RM ($p = 0.009$, Table 4). VL15 and VL40 obtained greater 1RM gains than ET ($p < 0.05$). VL15 ($p = 0.004$) and VL40 ($p = 0.008$) improved 1RM significantly, but not VL0 ($p = 0.09$). All CT groups improved their performance in AV, AV <1, and AV >1, except for VL0 in AV. The ET group showed no changes in strength-related variables.

4.6 | Fatigue Test

There was a significant main time effect ($p < 0.001$) but no group × time interaction for MNR ($p = 0.27$, Table 4). VL0

TABLE 3 | Pretraining and posttraining measures of muscle mass variables.

	ET ($n = 10$)			VL0 ($n = 7$)			VL15 ($n = 10$)			VL40 ($n = 8$)				
	Pre	Post	ES	Pre	Post	ES	Pre	Post	ES	Pre	Post	ES	p time effect	p group × time
CSA40, cm^2	20.1 (4.3)	19.0 (3.5)	−0.27	17.8 (5.0)	19.2 (6.1)	0.23	17.9 (2.4)	19.4 (3.1)	0.52	17.8 (3.50)	18.3 (2.22)	0.16	0.21	0.27
CSA57.5, cm^2	28.8 (3.9)	28.1 (4.2)	−0.17	25.6 (5.6)	27.6 (6.4)	0.31	25.1 (3.8)	27.3* (4.5)	0.51	25.2 (4.1)	26.7 (3.4)	0.38	**0.01**	0.26
CSA75, cm^2	29.3 (4.3)	29.7 (4.3)	0.09	24.9 (5.6)	27.0* (4.6)	0.38	24.4 (4.4)	25.6 (4.7)	0.25	25.0 (4.8)	29.3*** (6.0)	0.75	**<0.001**	**0.04**
Muscle volume, cm^3	678 (100)	667 (103)	−0.10	612 (140)	670* (133)	0.40	565 (70)	602* (81)	0.47	591 (100)	654** (107)	0.58	**<0.001**	0.13

Note: Data are expressed as mean (standard deviation). Significant intragroup differences: *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.
Abbreviations: CSA40, cross sectional area at 40% of femur length; CSA57.5, cross sectional area at 57.5% of femur length; CSA75, cross sectional area at 75% of femur length; ET, group that only performed the endurance training; Muscle volume, estimation of the vastus lateralis volume; VL0, concurrent group that trained with a velocity loss (VL) of 0% in each set; VL15, concurrent group that trained with a 15% VL in each set; VL40, concurrent group that trained with a 40% VL in each set.

TABLE 4 | Pretraining and posttraining measures of performance variables.

Performance variables	ET ($n = 10$)			VL0 ($n = 10$)			VL15 ($n = 10$)			VL40 ($n = 11$)			*p* value time effect	*p* group × time
	Pre	Post	ES	Pre	Post	ES	Pre	Post	ES	Pre	Post	ES		
T10, s	1.81 (0.06)	1.81 (0.07)	0.00	1.87 (0.11)	1.90 (0.10)	0.27	1.82 (0.10)	1.82 (0.07)	0.00	1.79 (0.09)	1.78 (0.09)	−0.11	0.42	0.13
T10–20, s	1.29 (0.07)	1.30 (0.06)	0.15	1.37 (0.08)	1.37 (0.09)	0.00	1.32 (0.08)	1.32 (0.08)	0.00	1.29 (0.07)	1.30 (0.06)	0.15	0.43	0.63
T20, s	3.10 (0.14)	3.11 (0.11)	0.08	3.24 (0.18)	3.27 (0.19)	0.16	3.14 (0.16)	3.14 (0.14)	0.00	3.10 (0.15)	3.10 (0.15)	0.00	0.48	0.32
CMJ, cm	40.1 (6.2)	40.0 (4.7)	−0.02	35.1 (6.8)	35.6 (7.4)	0.07	37.7 (5.2)	38.7 (6.4)	0.16	41.4 (6.7)	41.5 (6.1)	0.02	0.40	0.90
MAS, $km \cdot h^{-1}$	15.8 (1.5)	17.2*** (1.4)	0.92	15.1 (1.7)	16.5*** (1.7)	0.79	16.0 (1.6)	17.1*** (1.8)	0.62	15.9 (1.4)	16.6***# (1.5)	0.46	**< 0.001**	**0.04**
1RM, kg	115.4 (19.9)	109.4 (16.5)	−0.31	105.1 (15.0)	110.7 (11.7)	0.40	106.0 (23.2)	115.8**# (21.8)	0.42	110.5 (16.2)	119.0**# (13.6)	0.55	**0.008**	**0.009**
AV, $m \cdot s^{-1}$	1.03 (0.03)	1.02 (0.03)	−0.32	0.95 (0.03)	1.02 (0.03)	2.23	0.95 (0.03)	1.06** (0.03)	3.51	1.02 (0.03)	1.12*** (0.03)	3.21	**< 0.001**	0.08
AV > 1, $m \cdot s^{-1}$	1.27 (0.08)	1.30 (0.10)	0.32	1.28 (0.07)	1.36* (0.08)	1.02	1.26 (0.09)	1.36** (0.09)	1.06	1.32 (0.08)	1.39** (0.13)	0.62	**< 0.001**	0.43
AV < 1, $m \cdot s^{-1}$	0.76 (0.04)	0.72 (0.11)	−0.46	0.70 (0.04)	0.78* (0.06)	1.50	0.68 (0.05)	0.79** (0.09)	1.45	0.70 (0.06)	0.80** (0.10)	1.17	**< 0.001**	0.41
MNR, rep	9.8 (1.0)	10.8 (1.9)	0.63	8.7 (1.0)	14.0* (1.8)	3.49	9.2 (1.0)	16.0*** (1.8)	4.47	9.8 (2.9)	12.9 (1.8)	3.21	**< 0.001**	0.27

Note: Data are expressed as mean (standard deviation). Significant intragroup differences: $^{*}p \leq 0.05$, $^{**}p \leq 0.01$, $^{***}p \leq 0.001$. Significant differences with ET: $^{\#}p \leq 0.05$.
Abbreviations: 1RM, one-repetition maximum; AV, average mean propulsive velocity (MPV) with the common loads at pre and posttraining testing 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; CMJ, countermovement jump; ES: intragroup effect size; ET: group that performed endurance training alone; MAS: maximal aerobic speed; MNR: maximal number of repetitions in the fatigue test; POST, posttraining evaluation; PRE: pretraining evaluation; T10, 10-m sprint time; T10–20, 10- to 20-m split sprint time; T20, 20-m sprint time; VL0: group that trained with a velocity loss (VL) of 0% in each set; VL15: group that trained with a 15% VL in each set; VL40: group that trained with a 40% VL in each set training.

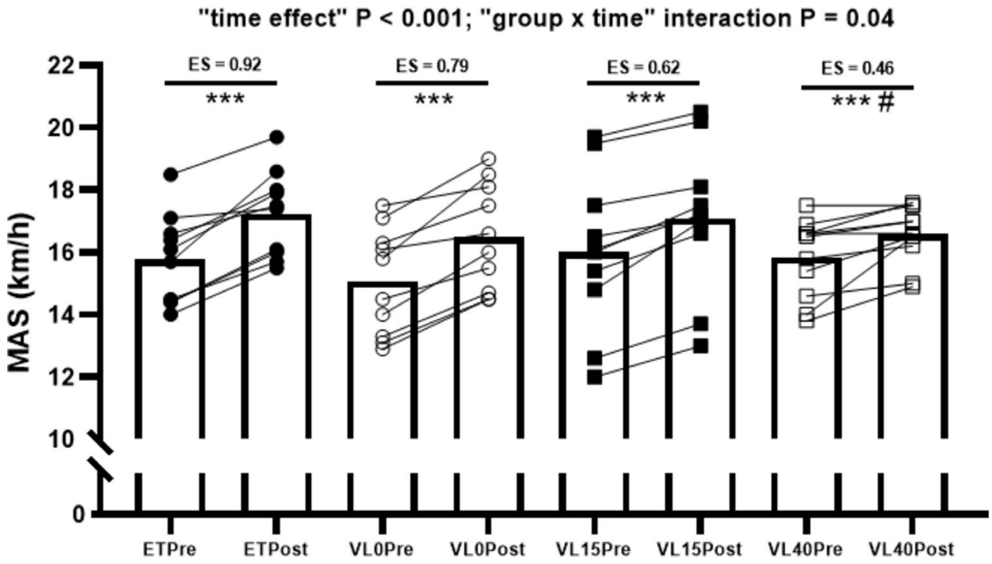

FIGURE 2 | Changes in maximal aerobic speed (MAS) for each training group. Each point represents a subject. re, pretraining evaluation; Post, posttraining evaluation; VL0, group that trained with a mean velocity loss (VL) of 0% in each set; VL15, group that trained with a 15% VL in each set; VL40, group that trained with a 40% VL in each set; ET, group that performed only endurance training; ES, effects size. Significant intragroup differences: ***$p \leq 0.001$. Significant differences with ET: $^{\#}p \leq 0.05$.

($p < 0.05$) and VL15 ($p < 0.001$) improved performance significantly, whereas VL40 and ET did not.

4.7 | EMG Variables

There were significant group × time interactions for RMS_{AV} and $RMS_{AV<1}$ (Table 6). VL0 obtained greater RMS_{AV} and $RMS_{AV<1}$ increases than ET ($p < 0.05$). The VL0 group significantly increased RMS_{AV} and $RMS_{AV<1}$ ($p < 0.01$). The ET group showed significant reductions in RMS_{AV} and RMS_{MNR} ($p < 0.05$). There were no significant changes in MDF variables.

5 | Discussion

The main findings of the present study were: (1) moderate levels of fatigue during RT are more efficient for optimizing strength performance during a CT protocol; (2) high levels of fatigue during RT maximize muscle hypertrophy during a CT protocol; (3) the ET-only intervention failed to increase strength and resulted in reduced late RFD and decreased neuromuscular activity during squat testing; and (4) although all groups improved endurance performance, gains diminished as fatigue levels during RT increased, following the pattern ET > VL0 > VL15 > VL40. Therefore, the present study suggests that VL15 is the most efficient strategy for improving strength. However, despite the use of moderate fatigue in CT, endurance performance gains may be attenuated by the proximity of the two training modalities.

The three groups that performed CT significantly improved all strength-related variables, except for 1RM and AV in the VL0 group (changes in 1RM, VL0: 5.3%; VL15: 9.2%; VL40: 7.7%). This indicates that performing only one repetition per set can still elicit meaningful strength adaptations but may be insufficient to maximize strength gains. These results agree with previous VL research, reinforcing the existence of an inverted-U relationship between VL and strength gains [11]. In that study, for example, Pareja-Blanco et al. [11] reported improvements of 13.7%, 18.1%, 14.9%, and 12.3% in 1RM for VL0, VL10, VL20, and VL40, respectively, using the same RT protocol. However, in that case, only RT was performed. A direct comparison between studies suggests that adding ET interferes with strength gains.

By contrast, Feuerbacher et al. [27] implemented a protocol comparable to the present study, with only 10–15 min of rest between strength and endurance sessions. In their case, ET was conducted on a cycle ergometer at 70%–80% of peak power output. They observed no impairment in strength gains compared to the group that performed only RT, except at lighter loads (i.e., 30%–50% of 1RM). This suggests that performance at heavier loads is not affected by CT when ET is conducted on a cycle ergometer at lower intensities than those used in the present study (i.e., 70%–80% peak power output vs. 90%–105% MAS). The use of cycling instead of running efforts, combined with reduced ET intensity, may have minimized neuromuscular fatigue and mechanical strain, thereby attenuating the interference effect typically observed in CT protocols [16]. Taken together, these findings suggest that, to optimize strength adaptations during a CT protocol on the same day, fatigue levels during RT sessions should be kept moderate (e.g., VL15) or even lower, as higher-fatigue protocols do not provide additional benefits and increase residual fatigue.

One of the most studied adaptations to CT protocols is hypertrophy [7, 28]. The present findings highlight that CT can elicit hypertrophic adaptations when RT is performed with varying VL thresholds, with VL40 producing the greatest muscle volume gains (group × time interaction: $p = 0.04$). These results are consistent with those of a previous study using similar RT protocols [11], suggesting that higher VL thresholds provide a stronger hypertrophic stimulus due to greater training volume and accumulated fatigue [12, 29]. However, it is worth noting

TABLE 5 | Pretraining and posttraining measures of force-time variables.

Force time variables	ET ($n=9$)			VL0 ($n=9$)			VL15 ($n=8$)			VL40 ($n=11$)			p time effect	p group×time
	Pre	Post	ES	Pre	Post	ES	Pre	Post	ES	Pre	Post	ES		
MIF, N	1217 (387)	1176 (186)	−0.13	1198 (237)	1196 (256)	−0.01	1192 (291)	1203 (251)	0.04	1178 (226)	1218 (260)	0.37	0.62	0.39
RFDmax, $N·s^{-1}$	5771 (2908)	5138 (1668)	−0.25	6188 (2043)	5925 (2731)	−0.10	5825 (1956)	4917 (1263)	−0.52	6192 (2902)	6659 (2394)	0.17	0.35	0.52
RFD100, $N·s^{-1}$	2937 (1366)	3434 (1191)	0.37	3347 (1171)	3277 (1724)	−0.05	3347 (1171)	2752 (1365)	−0.36	3742 (2277)	4720* (2777)	0.37	0.38	0.09
RFD200, $N·s^{-1}$	3284 (1421)	3295 (887)	0.01	3380 (1026)	3502 (1183)	0.11	3034 (1340)	2733 (1185)	−0.23	3593 (1550)	4084* (1395)	0.32	0.63	0.12
RFD400, $N·s^{-1}$	2481 (1157)	1957* (1957)	−0.50	2454 (674)	2501 (621)	0.07	2302 (651)	2332 (598)	−0.05	2375 (727)	2690*# (710)	0.42	0.62	**0.01**

Note: Data are expressed as mean (standard deviation). Significant intragroup differences: $*p<0.05$, $**p<0.01$, $***p<0.001$. Significant differences with ET: $^{\#}p \le 0.05$.
Abbreviations: MIF, maximal isometric force; RFD100, RFD from the onset production to 100 ms; RFD200, RFD from the onset production to 200 ms; RFD400, RFD from the onset production to 400 ms; RFDmax, maximal rate of force development (RFD); VL0, concurrent group that trained with a velocity loss (VL) of 0% in each set; VL15, concurrent group that trained with a 15% VL in each set; VL40, concurrent group that trained with a 40% VL in each set; ET, group that only performed the endurance training.

that both VL0 and VL15 also showed significant increases in muscle volume, indicating that hypertrophy can be achieved even under lower fatigue levels. On the other hand, ET failed to induce hypertrophy, reinforcing the need for RT to promote structural muscle adaptations. These findings suggest that while higher VL thresholds maximize hypertrophic responses, lower VL approaches may offer a more efficient balance between muscle growth and fatigue management in CT contexts.

In the EMG-related variables, VL0 showed increases in RMS across submaximal loads, while ET decreased. Pareja-Blanco et al. [11] also reported that the VL0 group exhibited the largest increases in RMS. Additionally, Hakkinen et al. [30] reported no differences in EMG between the CT and RT groups; however, they identified improvements within the first 500 ms, exclusively in the RT group. Notably, the RT group was also the only one to enhance RFDmax and mean force within this time frame. Likewise, in the present study, ET showed a significant reduction in RFD at 400 ms. This aligns with previous studies that attribute such decreases to the specific adaptations induced by ET, which are counterproductive to rapid force generation [31]. This supports the notion, as highlighted in recent reviews, that neuromuscular variables and the capacity to rapidly produce force are highly sensitive and responsive to the interference phenomenon [1]. This may be due to residual fatigue affecting motoneuron input prior to force generation, ultimately compromising the rate and efficiency of force application [30]. Further studies are needed to investigate the mechanisms underlying the effects of CT on RFD and clarify these differences.

No changes were observed in sprint and jump performance across any of the variables analyzed. In the work of Sánchez-Moreno [14], both groups significantly improved jump height, even in the high-fatigue group (45% of VL), a finding also reported in other interventions that performed only RT [12]. In contrast, in the present study, none of the groups improved jump height. The explanation may again lie in the proximity of the training sessions, since in Sánchez-Moreno et al. [14], in which similar fatigue levels during RT were induced, significant improvements were achieved. A recent review [1] analyzing 43 studies on CT concluded that strength (mostly evaluated with 1RM or MNR performed with submaximal loads) is not affected in a CT program, but variables related to the capacity to produce force rapidly (e.g., jumping ability) are negatively affected, especially when RT and ET are performed in the same training session. In other similar studies [32, 33], where there was a significant separation between sessions (i.e., recovery intervals ≥ 6 h), significant improvements in CMJ height were observed. Further studies should investigate the effects of different recovery intervals between RT and ET, while matching fatigue levels within RT sessions through VL.

Regarding endurance adaptations, there appears to be a relationship between fatigue levels in RT and MAS gains, with the greatest MAS improvements observed in ET, followed by VL0, VL15, and VL40 (group × time interaction: $p=0.04$). These results differ from those of Sánchez-Moreno et al. [14], in which the CT group with moderate fatigue (VL15%) obtained greater gains than the ET group. Such findings contradict numerous reviews that have reported the benefits of RT for endurance performance [34, 35]. Although in our study RT was performed before ET to optimize

TABLE 6 | Pretraining and posttraining measures of EMG variables.

	ET ($n = 9$)			VL0 ($n = 9$)			VL15 ($n = 9$)			VL40 ($n = 10$)				
EMG variables	**Pre**	**Post**	**ES**	**Pre**	**Post**	**ES**	**Pre**	**Post**	**ES**	**Pre**	**Post**	**ES**	***p* time effect**	***p* group × time**
RMS ISO, mV	0.34 (0.20)	0.30 (0.13)	−0.22	0.25 (0.14)	0.27 (0.16)	0.13	0.23 (0.10)	0.22 (0.08)	−0.11	0.22 (0.07)	0.27 (0.16)	0.39	0.74	0.49
RMS AV, mV	0.36 (0.20)	0.27* (0.13)	−0.50	0.23 (0.13)	0.35**# (0.31)	0.48	0.23 (0.07)	0.25 (0.11)	0.21	0.27 (0.09)	0.32 (0.12)	0.45	0.26	**0.01**
RMS AV > 1, mV	0.35 (0.20)	0.24 (0.10)	−0.66	0.21 (0.08)	0.30 (0.24)	0.48	0.23 (0.07)	0.25 (0.10)	0.22	0.26 (0.08)	0.31 (0.12)	0.47	0.43	0.06
RMS AV < 1, mV	0.38 (0.20)	0.30 (0.16)	−0.42	0.26 (0.19)	0.39**# (0.37)	0.42	0.24 (0.08)	0.26 (0.12)	0.19	0.27 (0.19)	0.32 (0.13)	0.29	0.18	**0.02**
RMS MNR, mV	0.34 (0.12)	0.25* (0.16)	−0.60	0.24 (0.17)	0.30 (0.16)	0.35	0.26 (0.08)	0.26 (0.09)	0.00	0.25 (0.12)	0.29 (0.16)	0.47	0.87	0.07
MDF ISO, Hz	89.6 (21.9)	100.9 (29.9)	0.41	101.9 (22.1)	97.5 (22.5)	−0.19	100.9 (28.7)	99.2 (33.3)	−0.06	101.9 (22.1)	97.5 (22.5)	−0.19	0.67	0.57
MDF AV. Hz	88.9 (22.4)	95.0 (25.7)	0.24	95.6 (21.8)	86.8 (25.2)	−0.35	91.7 (21.4)	94.1 (25.7)	0.11	94.1 (11.3)	91.4 (14.6)	−0.20	0.80	0.45
MDF AV > 1, Hz	87.7 (26.5)	93.9 (28.2)	0.25	92.7 (21.7)	83.1 (27.6)	−0.52	88.9 (23.6)	92.4 (33.4)	0.14	92.3 (11.0)	90.3 (12.5)	−0.16	0.90	0.42
MDF AV < 1, Hz	90.8 (19.3)	97.3 (23.9)	0.28	94.5 (24.2)	91.6 (23.7)	−0.12	94.2 (20.0)	94.7 (20.3)	0.02	93.2 (11.3)	95.6 (17.8)	0.14	0.82	0.59
MDF MNR, Hz	90.0 (18.2)	86.2 (12.5)	−0.23	91.4 (20.2)	86.1 (16.9)	−0.27	86.5 (18.3)	93.5 (31.1)	0.37	87.3 (10.2)	89.6 (11.8)	0.19	0.99	0.43

Note: Data are expressed as mean (standard deviation). Significant intragroup differences: $^{*}p < 0.05$, $^{**}p < 0.01$. Significant differences with ET: $^{\#}p \leq 0.05$.
Abbreviations: ET, group that only performed the endurance training; MDF AV <1, MDF against all absolute loads that were lifted slower than 1 m·s^{-1} at pretraining; MDF AV, MDF against all absolute loads common to pre and posttraining; MDF ISO, median frequency (MDF) measured during the isometric squat test; MDF MNR, MDF measured during the fatigue test; MDFAV > 1, MDF against all absolute loads that were lifted faster than 1 m·s^{-1} at pretraining; RMS AV < 1, RMS against absolute loads that were lifted slower than 1 m·s^{-1} at pretraining; RMS AV > 1, RMS against all absolute loads that were lifted faster than 1 m·s^{-1} at pretraining; RMS AV, RMS attained against all absolute loads common to pre and posttraining; RMS ISO, root mean square (RMS) measured during the isometric squat test; RMS MNR, RMS measured during the fatigue test; VL0, concurrent group that trained with a velocity loss (VL) of 0% in each set; VL15, concurrent group that trained with a 15% VL in each set; VL40, concurrent group that trained with a 40% VL in each set.

performance and adaptations [36, 37], the proximity between the training sessions (i.e., 10 min) may have been the reason for these differences, since in the study of Sánchez-Moreno's [14], RT and ET, performed under similar conditions but on alternate days, showed major improvements than ET alone.

Other investigations with small but relevant differences in methodological designs have found some promising and interesting results. For example, in the study conducted by Balabinis et al. [32], the effects of a CT protocol were compared with those of ET, with CT showing a slight advantage in the positive adaptations related to maximal oxygen uptake (i.e., VO2max). Nevertheless, the training sessions were separated by a 7-h interval. Similarly, Robineau et al. [37] examined the impact of different recovery times between RT and ET sessions during a CT intervention, reporting greater improvements in VO2max when the sessions were separated by 24 h compared with when they were performed within the same session, as in the present study. In this context, the recovery interval between RT and ET appears to be a critical factor modulating physical and physiological adaptations in CT protocols. Supported by previous findings [14, 32, 33] and our data, we propose that the short interval applied here (i.e., 10 min) may have intensified the interference phenomenon.

This study has some limitations that should be acknowledged. Total endurance volume was relatively low (12–30 min·session^{-1}, two sessions·week^{-1}), which may limit generalizability to higher-performance athletes (tiers 3–5) who typically perform substantially greater weekly volumes. Moreover, the short recovery interval between resistance and endurance sessions (10 min) does not reflect typical real-world practice, in which endurance volumes often range from ~8 to 15 h·wk.$^{-1}$ and inter-session separations can extend to 6–24 h; therefore, interference effects may differ under applied conditions. Furthermore, the resistance intervention consisted of a single exercise (squat), which, although it allowed strict experimental control, provided a limited stimulus and may not elicit the broader metabolic and hormonal responses associated with multi-exercise training programs. Finally, the RFD variables showed high CVs (all > 23%), suggesting caution when interpreting these results.

Taken together, CT enhanced strength and hypertrophy regardless of VL threshold, with VL40 producing the greatest muscle hypertrophy and VL15 emerging as the most efficient strategy for maximum strength improvements. ET alone maximized endurance performance but failed to enhance strength-related qualities or muscle mass, and even reduced force-time characteristics. Neuromuscular responses differed across protocols: VL0 was associated with increased EMG activity, whereas ET was associated with decreased EMG activity. Overall, moderate fatigue (VL15) appears to yield the most balanced adaptations, whereas higher VL levels promote greater hypertrophic development, and ET primarily promotes endurance-oriented adaptations.

6 | Practical Applications

When coaches' goal is to improve maximum strength effectively, prescribing sets targeting moderate magnitudes of VL (e.g., ~15%) seems to be an optimal strategy: it produces meaningful strength gains without excessive training volume, thereby inducing lower levels of fatigue. When hypertrophy is the training priority, prescribing sets with higher VL magnitudes (e.g., ~40% VL) can maximize muscle growth but may compromise endurance adaptations. It is also important to note that stopping sets very early (i.e., 0% VL, only 1 repetition per set) still produces some strength-related gains but may not be sufficient to improve 1RM strength, although it minimizes interference with endurance adaptations. As expected, ET alone improves aerobic performance but reduces explosive strength, reinforcing the need to include RT sessions in training programs for youth or senior athletes in any sport discipline that requires high levels of force application in short and very short time periods (as assessed by RFD across diverse time intervals).

7 | Perspectives

Future research should systematically manipulate inter-session recovery intervals (e.g., 0, 6, 24 h) to clarify the time-dependent nature of interference and to establish evidence-based scheduling guidelines. Mechanistic investigations integrating neuromuscular, metabolic, and molecular assessments (e.g., motor unit behavior and mTOR–AMPK signaling interactions) would further elucidate how different VL magnitudes influence the balance between strength, hypertrophy, and endurance adaptations. Additionally, alternative endurance configurations—including polarized models and varied intensity distributions—should be explored to determine whether specific endurance strategies mitigate interference while preserving aerobic development. Collectively, such research will help refine fatigue management strategies and optimize concurrent training prescription across performance levels and populations.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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