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Acute Effect of Velocity-Based Resistance Training on Subsequent Endurance Running Performance: Volume and Intensity Relevance

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Abstract: This study aimed to compare the acute effect of four back squat velocity-based training (VBT) protocols in terms of intensity (60% vs. 80% of the one repetition maximum [1RM]) and volume (10% vs. 30% threshold for velocity loss in the set) on the maximal aerobic speed (MAS) estimated from a running track test (RTT) in recreationally trained young adult men and women. Twenty participants (eleven men and nine women) undertook five randomized protocols in separate occasions: (i) RTT alone (control condition); (ii) VBT with 60% 1RM and a 10% velocity loss followed by RTT ($VBT_{60–10}$ + RTT); (iii) VBT with 60% 1RM and a 30% velocity loss followed by RTT ($VBT_{60–30}$ + RTT); (iv) VBT with 80% 1RM and 10% velocity loss followed by RTT ($VBT_{80–10}$ + RTT); (v) VBT with 80% 1RM and 30% velocity loss followed by RTT ($VBT_{80–30}$ + RTT). All VBT protocols involved three sets with three minutes of rest. The MAS was higher for RTT (control) than $VBT_{60–30}$ + RTT ($p < 0.001$; $\Delta = 3.8\%$), $VBT_{60–10}$ + RTT ($p = 0.006$; $\Delta = 2.8\%$), $VBT_{80–10}$ + RTT ($p = 0.008$; $\Delta = 2.7\%$), and $VBT_{80–30}$ + RTT ($p = 0.019$; $\Delta = 1.9\%$). No protocol × sex interaction was noted ($p = 0.422$). Therefore, regardless of sex, MAS is acutely impaired after VBT, especially if the training sets are performed with a low relative load and a high velocity loss threshold.

Keywords: endurance training; human physical conditioning; musculoskeletal and neural physiological phenomena; resistance training

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1. Introduction

Running performance depends on the complex interaction of several factors, particularly physiological, as well as biomechanical and psychological [1,2]. From a physiological point of view, it is well documented that the ventilatory/lactate threshold, maximal oxygen uptake (VO_2max), and running economy are strong performance indicators, especially when the latter are combined, and these indicators determine the maximal aerobic speed (MAS) [2–4]. Therefore, running performance could be improved through central adaptations, but also through the ability of athletes to produce more mechanical work for a given energy cost [2,5]. It is therefore not surprising that increased running performance has been reported when resistance and endurance training are incorporated simultaneously within the same program (e.g., "*concurrent training*") [1,3,6,7]. However, if exercise variables such as intensity and volume are not adequately prescribed in a concurrent training session, resistance training-induced fatigue may acutely impair the quality of subsequent endurance training sessions and induce an interference effect on long-term cardiorespiratory adaptations in a phenomenon referred to as "*resistance training-induced suboptimization on endurance performance*" (RT-SEP) [8,9]. For example, Doma et al. [10] reported impaired running time-to-exhaustion at 110% of the second ventilatory threshold six hours after a resistance training session with heavy loads (six repetitions at ~80% of the one-repetition maximum [1RM]) compared to light loads (total work equated with 20 repetitions) in trained male runners. Relatedly, it has been suggested that heavy loads (≥80% 1RM) may increase susceptibility to RT-SEP [9].

Velocity-based training (VBT) may help to assess optimization (e.g., auto-regulation) and individualization of resistance training intensity and volume according to the training readiness of athletes [11,12], thus reducing chances of RT-SEP [9]. For example, using VBT, Nájera-Ferrer et al. [13] found that compared to a moderate (20%) magnitude of velocity loss during resistance training (three full-squat sets at 60% 1RM), a high (40%) velocity loss resulted in higher metabolic (e.g., greater blood lactate, higher ventilatory equivalents) and mechanical stress (e.g., impaired vertical jump and squat velocity), as well as impaired running performance (e.g., unable to run 10 min at 90% MAS). Sánchez-Moreno et al. [14] observed higher running performance (i.e., MAS) following an eight-week concurrent training program with a moderate rather than high velocity loss (15% > 30%) in the resistance training bouts. Further, 2000 m rowing ergometer time-trial performance was compromised by greater velocity loss in the set (30% vs. 10%), but not by the loading magnitude (60% = 80% of 1RM) [15]. However, further research is needed to gain a deeper understanding of the acute effects of different concurrent VBT protocols, in terms of loading magnitude (60% vs. 80% of 1RM) and velocity loss in the set (10% vs. 30%), on running performance.

It has been shown that men reported higher velocities than women for the same %1RM during a variety of resistance training exercises and, consequently, the load-velocity relationship should be sex-specific for a better adjustment of the training intensity [16]. Similarly, it has been reported that recreationally trained men and women can achieve similar increases in strength and power performance following an eight-week VBT program with either 20% or 40% velocity loss, although some results (1RM strength and velocity attained to low/moderate loads) have indicated that strength and power gains favor using 40% rather than 20% velocity loss in women [17]. Therefore, it seems that women require a greater within-set fatigue than men to maximize strength and power development. These authors also observed that men were more susceptible to acute neuromuscular fatigue than women, but these differences in fatigability were reduced after the VBT program [18]. Likewise, Taipale et al. [19] generally observed greater fatigue in terms of decreased maximal and explosive strength in men than in women after a concurrent training session composed of multiple sets of different maximal and explosive strength exercises focused primarily on the leg extensors muscles, along with 10 min of running at ~80% of VO_2max. However, although these results are encouraging in addressing the sex gap observed in the scientific literature, there is scarce evidence on how sex could mediate the RT-SEP phenomenon, particularly for the VBT prescription variables (loading magnitude and velocity loss in the set), and its effect on MAS while running.

Therefore, this study aimed to examine the acute effect of four different VBT protocols, in terms of loading magnitude (60% vs. 80% 1RM) and velocity loss in the set (10% vs. 30%), on MAS performance estimated from a running track test (RTT) in recreationally trained men and women. We hypothesized that MAS performance would be compromised when the RTT is preceded by the different VBT protocols [9]. Specifically, greater impairment in MAS performance would be expected with (i) a high relative load along with a high velocity loss threshold in the set [10,15] and (ii) men [18,19].

2. Materials and Methods

2.1. Subjects

Twenty recreationally trained young adults, 11 men (age = 28.4 ± 6.4 years [range: 19–38]; body mass = 78.9 ± 11.2 kg; body height = 176.4 ± 6.0 cm; back squat 1RM relative to body mass = 1.8 ± 0.4 kg·kg^{-1}; VO_2max = 46.0 ± 7.8 mL·kg^{-1}·min^{-1}) and nine women (age = 23.6 ± 2.2 years [range: 21–28]; body mass = 56.1 ± 6.6 kg; body height = 161.7 ± 8.1 cm; back squat 1RM relative to body mass = 1.6 ± 0.3 kg·kg^{-1}; VO_2max = 37.2 ± 5.1 mL·kg^{-1}·min^{-1}), volunteered to participate in this study. All subjects had at least one year of resistance and endurance training experience (7.3 ± 5.9 and 10.3 ± 5.9 years for men, and 2.2 ± 1.2 and 9.3 ± 3.4 years for women, respectively) and were familiar with the back-squat and running exercises. No physical limitations, health problems, or musculoskeletal injuries that could compromise testing were reported. In addition, none of the subjects were taking drugs, medications, or dietary supplements to influence physical performance. All subjects were informed about the research purpose and procedures of the study before signing a written informed consent form. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board.

2.2. Design

A randomized-controlled crossover design was used to compare the acute effect between control condition (i.e., RTT) and four different VBT protocols followed by the RTT ($VBT_{60–10}$ + RTT, $VBT_{60–30}$ + RTT, $VBT_{80–10}$ + RTT, and $VBT_{80–30}$ + RTT) on MAS performance between recreationally trained men and women. Subjects completed the five randomized protocols in sessions separated by 48–72 h (Figure 1). The *Test VAM-HPSS* application (version 3.3, University of Murcia, Murcia, Spain) was installed on a Samsung Galaxy A71 smartphone (Samsung, Suwon, South Korean) to estimate VO_2max and MAS during each RTT (see below for further details). Both VO_2max and MAS estimated from the RTT protocol were very similar to those observed during the laboratory test and gas exchange methods (bias = 0.2 mL·kg^{-1}·min^{-1} and <0.1 km·h$^{-1,}$ respectively [20]. Subjects were required to avoid any strenuous exercise throughout the study. All sessions were conducted at the university's running track, at the same time of the day for each subject (±3 h), and under similar environmental conditions (temperature: 6–15 °C; wind: <8 km·h^{-1}).

2.3. Procedures

Body mass and body height were measured at the beginning of the first session using a contact electrode foot-to-foot body fat analyzer system (TBF-300A; Tanita Corp of America Inc., Arlington Heights, IL, USA) and a wall-mounted stadiometer (Seca 202; Seca Ltd., Hamburg, Germany), respectively. Each protocol began with the same general warm-up, which consisted of five minutes of running at a self-selected pace, dynamic stretching, and joint mobility exercises. The specific warm-up consisted of two sets of ten air squats and five sub-maximal countermovement jumps, followed by one set of six, four, and two repetitions at 40%, 60%, and 80% of the subjects' self-perceived back squat 1RM with 3 min of inter-set rest, respectively. After warming up, subjects rested passively for three minutes before beginning each protocol (see Figure 1).

2.3.1. VBT Protocols

Two different relative loads (60% vs. 80% 1RM) and two different magnitudes of velocity loss during the set (10% vs. 30%) were used. Specifically, the configuration of the four VBT protocols was as follows: (i) 60% 1RM with a velocity loss in the set of 10% ($VBT_{60–10}$), (ii) 60% 1RM with a velocity loss in the set of 30% ($VBT_{60–30}$), (iii) 80% 1RM with a velocity loss in the set of 10% ($VBT_{80–10}$), and (iv) 80% 1RM with a velocity loss in the set of 30% ($VBT_{80–30}$). The relative load of each testing session was determined from the individualized load-velocity relationship using the specific warm-up sets and a minimal velocity threshold of 0.33 m·s^{-1} [21]. Sets were terminated when the subjects were unable to complete two consecutive repetitions above the velocity loss limit or with the full range of motion. The fastest repetition from the first set was used to define the target velocity loss limit (e.g., if the fastest velocity is 0.75 m·s^{-1}, the target velocity used to finish a set would be 0.68 m·s^{-1} for the 10% velocity loss). The same exercise (back squat), number of sets (three), and inter-set rest (three minutes) were used in all VBT protocols. A validated linear velocity transducer (T-Force system; Ergotech, Murcia, Spain) was used to automatically calculate the mean velocity and provide auditory mean velocity feedback after each repetition [22]. The VBT performance indicators were: (i) the number of repetitions completed in the set, (ii) the fastest velocity of the set, and (iii) the average velocity of the set.

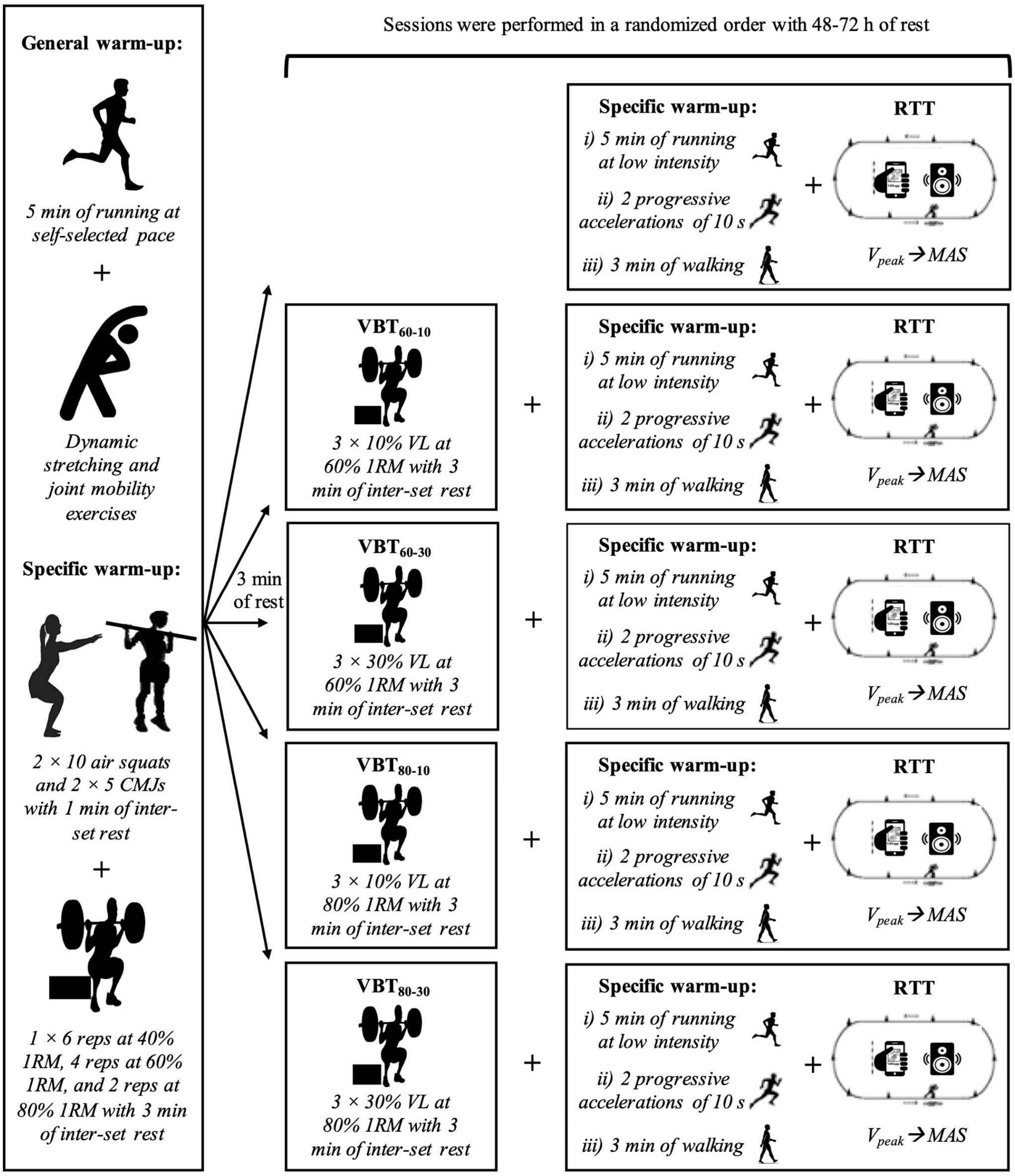

Figure 1. Overview of the experimental design. MAS, maximal aerobic speed; CMJ, countermovement jump; 1RM, one-repetition maximum; RTT, running track test; V_{peak}, peak velocity; $VBT_{60–10}$, velocity-based training (VBT) with 60% of 1RM and a velocity loss (VL) in the set of 10%; $VBT_{60–30}$, VBT with 60% of 1RM and a VL in the set of 30%; $VBT_{80–10}$, VBT with 80% of 1RM and a VL in the set of 10%; $VBT_{80–30}$, VBT with 80% of 1RM and a VL in the set of 30%.

The back-squat technique involved subjects standing with the knees and hips fully extended, feet approximately shoulder-width apart, and the barbell held across the top of the shoulders and upper back. From this position, they were required to descend in a continuous motion until their buttocks made contact with a wooden box and, immediately after, return to the initial position as fast as possible. The height of the wooden box was individually set at 90° of knee flexion with a manual goniometer (Goniómetro Rulong, Fisaude, Spain).

2.3.2. RTT Protocol

The *Test VAM-HPSS* application was used to determine running performance (MAS and VO_2max) following the manufacturer's instructions. First, the RTT protocol was selected based on the subjects' self-reported peak velocity: (i) <17.0 km·h^{-1} (>41.0 min in a 10-km race), 17.0–19.0 km·h^{-1} (36.5–41.0 min in a 10-km race), and >19.0 km·h^{-1} (<36.0 min in a 10-km race). Second, subjects completed five minutes of running at low intensity, two ten-second progressive runs, and three minutes of walking as part of the specific warm-up. Third, subjects received an auditory "*ready, set*" cue before beginning the RTT protocol with a beep signal. After pressing the start button, the stopwatch, distance, and velocity fields were launched in the *Test VAM-HPSS* application. Subjects were previously instructed to reach each cone located every 25 m around a running track while they regulated their running pace according to the beep signals. The frequency of the beep signal was automatically set according to the peak velocity selected for each RTT protocol. All auditory cues and beep signals were provided by the *Test VAM-HPSS* application connected to a loudspeaker. The RTT protocol ended when the subjects were unable to reach the cone at the time of the beep signal on two consecutive occasions, or they voluntarily decided to stop running after perceiving maximal exertion. The peak heart rate (HR) was recorded with a Polar H10 chest strap (Polar Electro Oy, Kempele, Finland) during the RTT, and the Borg's category-ratio 10 scale (CR-10) was reported after the test. The HR and CR-10 were used as maximal effort criteria [23]. The *Test VAM-HPSS* application automatically estimated the MAS and VO2max from the peak velocity achieved in each RTT [20].

2.4. Statistical Analyses

Descriptive data are presented as mean ± SDs. The Shapiro-Wilk test confirmed the normal distribution of all variables ($p > 0.05$), except for CR-10. A one-way repeated-measures analysis of variance (ANOVA) and Friedman test were used to compare peak HR and CR-10 between protocols, respectively. A mixed model ANOVA was conducted on each VBT performance indicator (numbers of repetitions, fastest velocity, and average velocity) with the protocol and set as within-subject factor and sex as between-subject factor. A mixed model ANOVA was applied to the MAS, with the protocol as a within-subject factor and sex as a between-subject factor. The Greenhouse-Geisser correction was used when Mauchly's sphericity test was violated and pairwise comparisons were identified using Bonferroni post hoc corrections. The magnitude of the differences was quantified through the standardized mean differences (Cohen's *d* effect size [ES]). The following scale was used to interpret the magnitude of the ES: *trivial* (<0.20), *small* (0.20–0.59), *moderate* (0.60–1.19), *large* (1.20–2.00), and *extremely large* (>2.00) [24]. All statistical analyses were performed using the software package SPSS (IBM SPSS version 25.0, Chicago, IL, USA) and statistical significance was set at an alpha level of 0.05. *Post hoc* statistical power was conducted using G*Power (Version 3.1) with an ES of 0.30 and α of 0.05, and this revealed a 0.93 statistic power.

3. Results

3.1. Descriptive Characteristics of the VBT Protocols

The main effect of protocol was significant for the number of repetitions, fastest velocity, and average velocity ($F_{(3,54)} \geq 46.9$; $p < 0.001$). A significant main effect of set was only reported for the fastest velocity ($F_{(2,36)} = 4.3$; $p = 0.021$). Finally, the protocol × sex interaction for the fastest and average velocity ($F_{(3,54)} = 5.8$ and 4.9; $p = 0.002$ and 0.005, respectively) and protocol × set interaction for the average velocity ($F_{(6,108)} = 3.9$; $p = 0.002$) also reached statistical significance (Table 1).

Table 1. Comparison of the number of repetitions, fastest velocity, and average velocity between protocols (Pr), set numbers, and sexes.

Variable	Set Number	Sex	$VBT_{60–10}$	$VBT_{60–30}$	$VBT_{80–10}$	$VBT_{80–30}$	ANOVA Main Effects	ANOVA Interactions
Number of repetitions	1	Men	9.5 ± 4.0	18.6 ± 5.4	5.9 ± 1.2	9.4 ± 3.6	Pr: $F_{(3,54)}$ = 49.6; p < 0.001 Set: $F_{(2,36)}$ = 0.9; p = 0.426 Sex: $F_{(1,19)}$ = 0.1; p = 0.755	Pr × Set: $F_{(6,108)}$ = 3.2; p = 0.028 Pr × Sex: $F_{(3,54)}$ = 0.2; p = 0.906 Set × Sex: $F_{(2,36)}$ = 1.8; p = 0.181 Pr × Set × Sex: $F_{(6,108)}$ = 1.8; p = 0.116
		Women	7.4 ± 2.6	17.1 ± 2.6	7.3 ± 3.1	9.6 ± 3.6		
	2	Men	9.8 ± 3.2	17.3 ± 4.9	5.9 ± 2.3	8.9 ± 3.5		
		Women	10.0 ± 6.3	19.7 ± 7.2	5.1 ± 2.7	7.7 ± 2.2		
	3	Men	10.1 ± 3.9	15.4 ± 4.8	4.5 ± 1.8	7.8 ± 3.2		
		Women	12.0 ± 8.2	18.0 ± 8.2	5.1 ± 2.8	8.0 ± 3.3		
Fastest velocity ($m \cdot s^{-1}$)	1	Men	0.76 ± 0.07	0.73 ± 0.07	0.54 ± 0.06	0.55 ± 0.07	Pr: $F_{(3,54)}$ = 80.9; p < 0.001 Set: $F_{(2,36)}$ = 4.3; p = 0.021 Sex: $F_{(1,19)}$ = 4.4; p = 0.051	Pr × Set: $F_{(6,108)}$ = 1.7; p = 0.129 Pr × Sex: $F_{(3,54)}$ = 5.8; p = 0.002 Set × Sex: $F_{(2,36)}$ = 0.9; p = 0.432 Pr × Set × Sex: $F_{(6,108)}$ = 0.8; p = 0.584
		Women	0.67 ± 0.03	0.67 ± 0.05	0.57 ± 0.07	0.52 ± 0.05		
	2	Men	0.77 ± 0.07	0.70 ± 0.06	0.55 ± 0.04	0.53 ± 0.07		
		Women	0.67 ± 0.07	0.66 ± 0.05	0.56 ± 0.07	0.50 ± 0.05		
	3	Men	0.76 ± 0.06	0.69 ± 0.06	0.53 ± 0.06	0.53 ± 0.05		
		Women	0.67 ± 0.06	0.64 ± 0.04	0.57 ± 0.05	0.52 ± 0.04		
Average velocity ($m \cdot s^{-1}$)	1	Men	0.70 ± 0.06	0.63 ± 0.06	0.48 ± 0.05	0.47 ± 0.06	Pr: $F_{(3,54)}$ = 84.5; p < 0.001 Set: $F_{(2,36)}$ = 1.4; p = 0.260 Sex: $F_{(1,19)}$ = 2.5; p = 0.132	Pr × Set: $F_{(6,108)}$ = 3.9; p = 0.002 Pr × Sex: $F_{(3,54)}$ = 4.9; p = 0.005 Set × Sex: $F_{(2,36)}$ = 0.2; p = 0.791 Pr × Set × Sex: $F_{(6,108)}$ = 1.1; p = 0.348
		Women	0.62 ± 0.02	0.59 ± 0.05	0.52 ± 0.07	0.45 ± 0.04		
	2	Men	0.71 ± 0.06	0.62 ± 0.06	0.49 ± 0.04	0.45 ± 0.05		
		Women	0.63 ± 0.05	0.58 ± 0.05	0.51 ± 0.07	0.45 ± 0.04		
	3	Men	0.71 ± 0.06	0.61 ± 0.06	0.48 ± 0.05	0.45 ± 0.04		
		Women	0.64 ± 0.05	0.56 ± 0.06	0.51 ± 0.06	0.46 ± 0.05		

Data are presented as means ± standard deviations. $VBT_{60–10}$, velocity-based training (VBT) protocol with 60% of one-repetition maximum (1RM) and a velocity loss in the set of 10%; $VBT_{60–30}$, VBT protocol with 60% 1RM and a velocity loss in the set of 30%; $VBT_{80–10}$, VBT protocol with 80% 1RM and a velocity loss in the set of 10%; $VBT_{80–30}$, VBT protocol with 80% 1RM and a velocity loss in the set of 30%; ANOVA, analysis of variance; F = Snedecor's F.

The pairwise comparisons revealed that (i) the number of repetitions grew higher as the relative load was reduced and the velocity loss threshold was increased ($p \leq 0.008$; ES ≥ 0.75), although no differences were reported between $VBT_{60–10}$ and $VBT_{80–30}$ ($p = 0.100$; ES = 0.23), (ii) the fastest velocity was higher for $VBT_{60–10}$ and $VBT_{60–30}$ than for $VBT_{80–10}$ and $VBT_{80–30}$ ($p < 0.001$; ES ≥ 1.49), with no significant difference for the same relative loads ($p \leq 0.096$; ES ≤ 0.58), (iii) the average velocity was higher for $VBT_{60–10}$, followed by $VBT_{60–30}$, $VBT_{80–10}$, and $VBT_{80–30}$ ($p \leq 0.001$; ES ≥ 1.04), although no differences were reported between $VBT_{80–10}$ and $VBT_{80–30}$ ($p = 0.081$; ES = 0.56), (iv) the fastest velocity was higher for the first set than the third set ($p = 0.031$; ES = 0.34), with no significant differences with respect to the second set ($p \geq 0.233$; ES ≤ 0.20), (v) the fastest velocity was significantly higher for $VBT_{60–10}$, followed by $VBT_{60–30}$, $VBT_{80–10}$, and $VBT_{80–30}$ ($p \leq 0.009$; ES ≥ 0.68), although no differences were reported between $VBT_{80–10}$ and $VBT_{80–30}$ for men ($p = 0.081$; ES = 0.02) and $VBT_{60–10}$ and $VBT_{60–30}$ for women ($p = 0.772$; ES = 0.30), (vi) the average velocity was significantly higher for $VBT_{60–10}$, followed by $VBT_{60–30}$, $VBT_{80–10}$, and $VBT_{80–30}$ ($p \leq 0.013$; ES ≥ 0.66), although no differences were reported between $VBT_{80–10}$ and $VBT_{80–30}$ for men ($p = 0.329$; ES = 0.35), and (vii) the average velocity was comparable between sets for each protocol ($p \geq 0.135$; ES ≤ 0.48), except for $VBT_{60–10}$ where it was significantly lower for the third set than the first and second sets ($p = 0.007$; ES = 0.79).

3.2. MAS Performance

No significant differences were reported for peak HR ($F_{(4,76)} = 1.7$; $p = 0.164$) and CR-10 ($\chi^2_{(4,N=20)} = 4.2$; $p = 0.378$) between protocols (RTT = 188 ± 13 bpm and 8.9 ± 0.5; $VBT_{60–10}$ + RTT = 188 ± 14 bpm and 8.7 ± 0.5; $VBT_{60–30}$ + RTT = 186 ± 10 bpm and 8.8 ± 0.6; $VBT_{80–10}$ + RTT = 190 ± 10 bpm and 8.7 ± 0.4; $VBT_{80–30}$ + RTT = 187 ± 11 bpm and 8.9 ± 0.6, respectively). A significant main effect of protocol ($F_{(4,72)} = 7.3$; $p < 0.001$) and sex ($F_{(1,18)} = 8.3$; $p = 0.010$) was observed for MAS performance. The protocol × sex interaction did not reach statistical significance ($F_{(4,72)} = 1.0$; $p = 0.422$). The main effects revealed that the MAS was significantly higher (i) for RTT than $VBT_{60–30}$ + RTT ($p < 0.001$; ES = 1.71; Δ = 3.8%), $VBT_{60–10}$ + RTT ($p = 0.006$; ES = 0.93; Δ = 2.8%), $VBT_{80–10}$ + RTT ($p = 0.008$; ES = 0.93; Δ = 2.7%), and $VBT_{80–30}$ + RTT ($p = 0.019$; ES = 0.77; Δ = 1.9%) (Figure 2), and (ii) for men than women ($p = 0.010$; ES = 1.34; Δ = 13.0%).

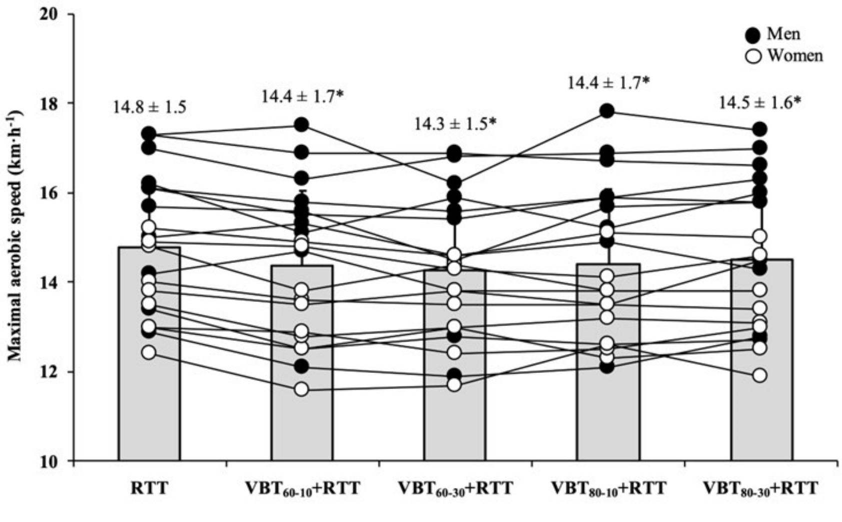

Figure 2. Comparison of the maximal aerobic speed between protocols. Data are depicted as means and standard deviation, whereas each point represents the individual data of each man (black circles) and woman (white circles). RTT, running track test; $VBT_{60–10}$ + RTT, velocity-based training (VBT) with 60% of one-repetition maximum (1RM) and a velocity loss in the set of 10% followed by RTT; $VBT_{60–30}$ + RTT, VBT with 60% of 1RM and a velocity loss in the set of 30% followed by RTT; $VBT_{80–10}$ + RTT, VBT with 80% of 1RM and a velocity loss in the set of 10% followed by RTT; $VBT_{80–30}$ + RTT VBT with 80% of 1RM and a velocity loss in the set of 30% followed by RTT. *, significantly lower than RTT ($p < 0.05$; analysis of variance with Bonferroni correction).

4. Discussion

This study was designed to examine the acute effect of four different VBT protocols ($VBT_{60–10}$ + RTT, $VBT_{60–30}$ + RTT, $VBT_{80–10}$ + RTT, and $VBT_{80–30}$ + RTT) on the MAS estimated from an RTT in recreationally trained men and women. Results revealed that, when compared to the control condition (RTT alone), the MAS was acutely compromised after the four different VBT protocols. Regardless of sex, the $VBT_{60–30}$ + RTT impaired the MAS to a greater extent than the $VBT_{60–10}$ + RTT, $VBT_{80–10}$ + RTT, and $VBT_{80–30}$ + RTT protocols. These results suggest that, regardless of sex, running performance (MAS) is impaired when preceded by VBT, especially if the training sets are performed with a low relative load (60% 1RM) and a high velocity loss threshold (30%).

The main strength of this study has been the implementation of the VBT methodology during resistance training sessions. First, the subjects received velocity performance feedback immediately after each repetition. This is of paramount importance, since the provision of velocity performance feedback has been proposed as an effective strategy to increase the quality (i.e., movement velocity) of the strength-oriented resistance training sessions [25]. Second, the individualized load-velocity relationships were used to match the intensity of load to individuals' daily readiness to train. In line with previous research [15], the fastest velocity significantly differed between relative loads, but not for the same relative load. Note that, while the accuracy of traditional methods may be affected by normal daily fluctuations in strength levels [26], the individualized load-velocity profiles provided high stability to prescribe resistance training intensity [27]. Third, velocity loss thresholds have been proposed as a more objective and homogeneous alternative to control proximity to failure during non-failure resistance training sets (e.g., subjects can complete ~60% of the maximum possible number of repetitions when reaching 30% velocity loss during the back-squat sets performed against 60% 1RM) [28]. Of note, while the target velocity loss is commonly determined from the fastest velocity achieved in each training set [13,14], the fastest repetition from the first set was used in the present study to guide set termination. Like Pérez-Castilla et al. [15], we have observed that the fastest velocity was higher for the first set than the third set. Therefore, if the fastest velocity of each set had been taken as the criterion, the subjects would have been closer and closer to muscular failure in the successive sets. Practitioners must keep this methodological aspect in mind when comparing different VBT studies.

The RT-SEP phenomenon suggests that neural and metabolic fatigue derived from previous resistance training sessions may compromise the quality of subsequent endurance training sessions and, consequently, induce sub-optimal endurance adaptations [8]. In line with previous research [10,29,30], our results provide further evidence that running performance (i.e., MAS) is compromised when preceded by a resistance training bout. This phenomenon may be related to various mechanisms, including (but not limited to) (i) impaired neural recruitment patterns, (ii) attenuated movement efficiency, (iii) increased muscle damage and soreness, and (iv) reduced muscle glycogen [8,9]. However, RT-SEP is a complex phenomenon conditioned by multiple training variables, including resistance training intensity and volume as acute interference modulators [9]. Indeed, supporting our hypothesis, the MAS was compromised to a greater extent when a low relative load (60% 1RM) along with a high velocity loss threshold (30%) was used in the set. This finding partially concurs with the results of Pérez-Castilla et al. [15] who reported, regardless of intensity (60% = 80% 1RM), a greater impairment in rowing ergometer performance when preceded by VBT protocols with high velocity loss in the set (30% > 10%). Such discrepancies regarding the effect of the relative load with the Pérez-Castilla's study [15] could be partly explained by the endurance performance indicator (MAS estimated from RTT vs. 2000 m rowing ergometer time trial), or the level of the study sample (recreationally trained adults vs. competitive rowers). More specifically, the muscles groups involved (back squat in our study vs. prone bench pull in Pérez-Castilla's study [15]) may explain potential differences between studies. Indeed, our results are in line with Nájera-Ferrer et al. [13] who reported a higher detriment to running performance when subjects completed three full-squat sets at 60% 1RM with a magnitude of 40% but not 20% velocity loss. It is therefore not surprising that, due to the higher fatigue levels and slower rates of recovery, a higher MAS has been reported following a concurrent running and VBT program with a lower velocity loss threshold in the set (15% vs. 45%) [14].

It has been shown that men have a higher muscle mass and proportion of type I fibbers than women [31]. Such sex differences might explain the greater muscle fatigability in women compared to men [31]. Rissanen et al. [17] recently observed that women require a greater velocity loss (40%) than men to maximize strength and power gains after an eight-week resistance training program. More specifically, Taipale et al. [19] reported a greater amount of fatigue, in terms of decreased maximal and explosive strength, in men than in women after a concurrent training session. In disagreement with those studies [17,19], our hypothesis was rejected since men not only reported a comparable number of repetitions during VBT protocols, but also a comparable MAS performance deterioration after VBT protocols than women. It is possible to speculate that the greater muscular fatigability in the women may be offset by the greater muscular strength (back squat 1RM relative to body mass = 1.8 vs. 1.6) and VO_2max (46 vs. 37 mL·kg^{-1}·min^{-1}) reported in the men. Of note, research has reported that resistance-untrained individuals present a greater magnitude of muscle damage and attenuation in muscle function than resistance-trained individuals [32]. Taken together, our results suggest that there is a comparable impairment of running performance (MAS) immediately after VBT between recreationally trained men and women.

Several issues need to be acknowledged when interpreting the findings from the present study. First, it should be taken into account the training status and history of our sample before generalizing the results of this crossover study. For example, Walker et al. [18] revealed that men were more susceptible to acute loss in force production capacity after different VBT protocols, but there were no signs of females being less fatigable after the eight-week velocity-based intervention. Second, we have examined the impact of resistance training-induced fatigue on endurance performance following a single bout of resistance training. In this regard, Doma et al. [33] reported that the magnitude of the increase in muscle damage markers was attenuated following a second resistance training bout in resistance-untrained runners and, therefore, it has been speculated that repeated resistance training bouts during concurrent training could minimize RT-SEP [8]. Finally, it is important to highlight that the subjects performed both training modalities (VBT and RTT) in the same session. Note that previous research [34] has reported that the magnitude of increase in peak oxygen consumption was greater when resistance and endurance training was performed on alternate days with 24 h of recovery compared to both training modalities performed in the same session with and without six hours of recovery, suggesting that the interference effect depends on the recovery period, although the influence of training variables must be also kept in mind [8].

5. Conclusions

Resistance training can improve running performance. However, several prescription variables should be considered to minimize the RT-SEP phenomenon during concurrent training programs. Our results revealed impaired running performance (MAS estimated from RTT) when preceded by different VBT protocols in loading magnitude (60% vs. 80% 1RM) and velocity loss in the set (10% vs. 30%). This acute interference effect was comparable between recreationally trained men and women. Additionally, the greatest MAS detriment was reported after VBT performed with a low relative load (60% 1RM) together with a high velocity loss threshold (30%). Therefore, practitioners who wish to optimize running performance while simultaneously incorporating resistance training into endurance athletes' training programs should avoid high repetition volumes to reduce susceptibility to RT-SEP. Indeed, a recent systematic review with meta-analysis [35] indicated that high-repetition strength training may not result in improved performance in competitive endurance athletes over a four- to twelve-week period, although a high-repetition strength training session induces high physiological (blood lactate concentration > 8.8 mmol·L^{-1})

and perceptual (rating of perceived exertion $\geq$ 17) demands. Hence, regardless of sex, running endurance athletes may consider a cautious approach when implementing resistance training sessions of low load (e.g., 60% 1RM) and high volume (e.g., 30% threshold for velocity loss in the set), as running endurance performance can be acutely reduced, which might affect long-term adaptations. Instead, VBT sessions involving greater load (e.g., 80% 1RM) and controlled volume (e.g., 10% threshold for velocity loss in the set), might offer better results in male and female endurance runners' performance.

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