Effect of Movement Velocity during Resistance Training on Neuromuscular Performance

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Key words
- full squat
- velocity specificity
- athletic performance
- strength training
- lactate
- ammonia

Abstract

This study aimed to compare the effect on neuromuscular performance of 2 isoinertial resistance training programs that differed only in actual repetition velocity: maximal intended (MaxV) vs. half-maximal (HalfV) concentric velocity. 21 resistance-trained young men were randomly assigned to a MaxV (n=10) or HalfV (n=11) group and trained for 6 weeks using the full squat exercise. A complementary study (n=8) described the acute metabolic and mechanical response to the protocols used. MaxV training resulted in a likely more beneficial effect than HalfV on squat performance: maximum strength (ES: 0.94 vs. 0.54), velocity developed against all (ES: 1.76 vs. 0.88), light (ES: 1.76 vs. 0.75) and heavy (ES: 2.03 vs. 1.64) loads common to pre- and post-tests, and CMJ height (ES: 0.63 vs. 0.15). The effect on 20-m sprint was unclear, however. Both groups attained the greatest improvements in squat performance at their training velocities. Movement velocity seemed to be of greater importance than time under tension for inducing strength adaptations. Slightly higher metabolic stress (blood lactate and ammonia) and CMJ height loss were found for MaxV vs. HalfV, while metabolite levels were low to moderate for both conditions. MaxV may provide a superior stimulus for inducing adaptations directed towards improving athletic performance.

Introduction

Resistance training (RT) is recognized as an effective method for increasing or maintaining strength, power and muscle hypertrophy. The neuromuscular system specifically adapts to the stimuli it is faced with, resulting in increases in muscle strength and functional performance [31]. Since mechanical stress has been suggested to be of critical importance for inducing adaptation [8], a better understanding of the kinematics and kinetics associated with RT is required to advance our knowledge of the underlying mechanisms of the training adaptation process. Among the main acute resistance exercise variables that can be manipulated to configure the mechanical stimulus [31,37], movement velocity is possibly the least studied and understood. It is believed that movement velocity, which is dependent on both the magnitude of the load to overcome and the voluntary intent of the subject to move that load [17,31], is a relevant variable when it comes to improving sports performance [8,29]. Yet, very few studies have analysed the effect of training with distinct movement velocities on selected measures of dynamic athletic performance [5,19,20,24,25].

Research on movement velocity during RT is scarce and the results controversial [29]. Most of the studies examining the effect of movement velocity on neuromuscular performance were conducted on isokinetic equipment [4,21], but surprisingly only a few have used isoinertial exercise as the training modality. Isoinertial (constant external load) weight training is the most commonly available type of RT and generally considered to be the most specific to enhance sports performance [17,29]. Among the isoinertial studies that have compared the effects of fast-vs. slow-velocity training on strength, some found greater strength gains when performing the repetitions at fast velocities [17,20,25–27], while others did not find differences between the 'fast' and 'slow' training groups [10,30,35,40]. In order to differentiate between fast- and slow-velocity groups, some researchers chose to manipulate the magnitude of the relative loads to be lifted (low loads for fast-velocity and high loads for unintentional slow-velocity) [2,5,9, 17,20,22,24], while others opted for intention-

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ally reducing repetition velocity by imposing a certain lifting cadence by means of a metronome [10, 25, 26, 28, 30, 35, 40]. Several methodological inconsistencies may have contributed to the current lack of consensus as to whether resistance training should emphasize maximal or submaximal velocities. Thus, few studies have equated work volume between the different training groups [10, 17, 19, 25, 26, 40] and many of them have manipulated several training variables simultaneously [2, 9, 27, 28, 35] rather than only focusing on movement velocity as the independent variable, thus making it difficult to interpret research findings. Other noteworthy shortcomings affecting several of these studies were: i) very small sample sizes [5, 22, 30]; ii) samples consisting of subjects with no previous RT experience [2, 9, 22, 25, 26, 28, 30, 40]; iii) samples including both males and females [26, 30, 35]; iv) very short duration training interventions [17]; and v) choice of exercises or muscle actions with limited relation to actual sports performance [17, 22, 26].

The present investigation was designed in an attempt to shed some light on the influence of repetition velocity on the gains in strength consequent to isoinertial RT. 2 separate studies were undertaken. The main purpose of *Study I* was to compare the effect of 2 distinct RT interventions on strength gains and selected neuromuscular performance measures using movement velocity as the independent variable. 2 groups that differed only in the actual concentric velocity at which loads were lifted in each repetition –maximal intended velocity (MaxV) versus half-maximal velocity (HalfV)– trained for 6 weeks using the full squat exercise, while the remaining training variables were kept identical. *Study II* was a complementary study that aimed to describe the acute metabolic and mechanical response to the type of resistance exercise protocols used in *Study I*. We hypothesized that MaxV training would result in greater strength gains and improvements in vertical jump and sprint ability and it would be characterized by a higher metabolic stress when compared to HalfV.

Materials and Methods

▼

Subjects

21 men (mean ± SD: age 23.3 ± 3.2 years, height 1.77 ± 0.07 m, body mass 73.6 ± 9.2 kg, body fat 13.2 ± 3.8 %) volunteered to participate in *Study I*. Their 1RM strength for the full squat exercise was 92.1 ± 10.4 kg (1.25 ± 0.23 normalized per kg of body mass). An additional sample of 8 subjects (24.6 ± 3.0 years, 1.78 ± 0.09 m, body mass 74.6 ± 8.2 kg, body fat 12.0 ± 3.1 %) participated in *Study II*. All subjects were physically active sports science students with RT experience ranging from 1.5 to 4 years (1–3 sessions per wk) and were already accustomed to performing the full (deep) squat exercise. After being informed about the purpose, testing procedures and potential risks of the investigation, subjects gave their voluntary written consent to participate. No physical limitations, health problems or musculoskeletal injuries that could affect testing or training were found following a medical examination. None of the subjects were taking drugs, medications or dietary supplements known to influence physical performance. Height and body mass were determined using a medical stadiometer and scale (Seca 710, Seca Ltd., Hamburg, Germany) with the subjects in a morning fasting state and wearing only underclothes. Percent body fat was estimated using a skinfold calliper (Holtain Ltd., Dyfed, Wales) and the Jackson & Pollock formula [18]. The present investigation met the ethical standards of this journal [13] and was approved by the Research Ethics Committee of Pablo de Olavide University.

Familiarization

In the preceding 3 weeks of each study (*I* and *II*), 5 preliminary familiarization sessions were undertaken with the purpose of emphasizing proper execution technique in the full squat exercise as well as getting the subjects accustomed to both types of maximal and half-maximal velocity lifts which were performed in the present investigation. Several practice sets at different target velocities were performed while receiving immediate velocity feedback from the measuring system and verbal cues from a trained researcher. Anthropometric assessments and medical examinations were conducted during these sessions.

Study I (Experimental study)

Following preliminary familiarization and pre-testing, subjects were randomly assigned to one of 2 groups: MaxV (n = 10) or HalfV (n = 11). The only difference in the RT program between the two groups was the actual velocity at which loads were lifted: maximal intended velocity in the concentric phase of each repetition for MaxV vs. an intentional half-maximal concentric lifting velocity for HalfV. Both groups trained three times per week on non-consecutive days for a period of 6 weeks using only the squat exercise.

Study II (Descriptive study)

Following familiarization and an initial progressive loading test identical to the one used in *Study I*, subjects (n = 8) undertook a total of six RT sessions separated by 48–72 h during a 3-wk period in the following order: 3 × 8 repetitions (rep) with ~60 % 1RM at MaxV (0.98 $m \cdot s^{-1}$), 3 × 8 rep with ~60 % 1RM at HalfV (0.49 $m \cdot s^{-1}$), 3 × 6 rep with ~70 % 1RM at MaxV (0.82 $m \cdot s^{-1}$), 3 × 6 rep with ~70 % 1RM at HalfV (0.41 $m \cdot s^{-1}$), 3 × 3 rep with ~80 % 1RM at MaxV (0.68 $m \cdot s^{-1}$) and 3 × 3 rep with ~80 % 1RM at HalfV (0.34 $m \cdot s^{-1}$), using 3-min inter-set rests. Sessions were performed at the same time of day for each subject (± 1 h), under the same environmental conditions. A standardized warm-up protocol was strictly followed, always using the same absolute loads and number of sets and repetitions for each subject. The squat exercise was performed in a Smith machine, exactly as described for *Study I*. Subjects received verbal cues from researchers as well as auditory and visual feedback from the software of the dynamic measurement system in order to perform each repetition either at MaxV or HalfV according to the corresponding session.

Study I. Resistance training program

Descriptive characteristics of the RT program are presented in ▸ **Table 1**. Relative magnitude of training loads (percent of one-repetition maximum, %1RM), number of sets and repetitions and inter-set recoveries (3 min) were kept identical for both groups in each training session. Relative loads were determined from the load-velocity relationship for the squat since it has recently been shown that there exists a very close relationship between %1RM and mean velocity, which is distinctive of each RT exercise [11, 33]. Thus, a target mean propulsive velocity (MPV) to be attained in the first (usually the fastest) repetition of the first training set in each session was used as an estimation of %1RM, as follows: 0.98 $m \cdot s^{-1}$ (~60 % 1RM), 0.90 $m \cdot s^{-1}$ (~65 %

Table 1 Study I. Descriptive characteristics of the squat training program performed by the MaxV and HalfV groups.

Scheduled	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	
Sets × Reps	3×6	3×5	3×5	4×3	4×3	3×2	
	3×6	3×5	3×5	4×3	4×3	4×2	
	3×8	3×6	3×6	3×4	3×4	3×3	
Target MPV ($m\cdot s^{-1}$)	0.98	0.90	0.82	0.75	0.75	0.68	
	(~60% 1RM)	(~65% 1RM)	(~70% 1RM)	(~75% 1RM)	(~75% 1RM)	(~80% 1RM)	
Actually Performed							**Overall**
Reference rep's MPV ($m\cdot s^{-1}$)							
MaxV	1.00 ± 0.06	0.89 ± 0.04	0.87 ± 0.05	0.76 ± 0.03	0.79 ± 0.05	0.71 ± 0.02	0.84 ± 0.02
	(~58% 1RM)	(~66% 1RM)	(~67% 1RM)	(~74% 1RM)	(~73% 1RM)	(~78% 1RM)	(~69% 1RM)
HalfV	1.01 ± 0.06	0.93 ± 0.04	0.88 ± 0.04	0.77 ± 0.03	0.79 ± 0.04	0.69 ± 0.04	0.84 ± 0.02
	(~58% 1RM)	(~63% 1RM)	(~67% 1RM)	(~74% 1RM)	(~73% 1RM)	(~79% 1RM)	(~69% 1RM)
MPV all reps ($m\cdot s^{-1}$)							
MaxV	0.94 ± 0.07	0.84 ± 0.06	0.78 ± 0.07	0.70 ± 0.06	0.71 ± 0.05	0.63 ± 0.06	0.80 ± 0.13 ***
HalfV	0.51 ± 0.06	0.46 ± 0.04	0.41 ± 0.04	0.37 ± 0.03	0.37 ± 0.03	0.34 ± 0.03	0.43 ± 0.07
TUT all reps (s)							
MaxV	54.1 ± 16.7	47.4 ± 15.1	52.0 ± 16.8	43.3 ± 14.1	41.7 ± 13.3	30.4 ± 10.3	260.5 ± 22.7 ***
HalfV	81.8 ± 3.6	72.0 ± 3.2	78.4 ± 4.3	64.3 ± 3.9	65.9 ± 3.8	44.2 ± 2.9	383.5 ± 32.9

Data are mean ± SD

MaxV: Maximal concentric velocity (n = 10), HalfV: Half-maximal concentric velocity (n = 11)

TUT: Time Under Tension (concentric only), MPV: Mean Propulsive Velocity, reps: repetitions, Wk: week; subjects trained 3 sessions per wk

Reference rep: maximal intended velocity repetition performed at the end of each session's warm-up to ensure that the load (kg) to be used matched the velocity associated with the intended %1RM

Significant differences between MaxV and HalfV in mean overall values: *** $P < 0.001$

1RM), 0.82 $m\cdot s^{-1}$ (~70% 1RM), 0.75 $m\cdot s^{-1}$ (~75% 1RM) and 0.68 $m\cdot s^{-1}$ (~80% 1RM); i.e., a velocity-based training was actually performed, instead of a traditional loading-based RT program. Both MaxV and HalfV groups performed a maximal intended concentric velocity repetition (reference rep) at the end of their respective warm-up to ensure that the absolute load (kg) to be used precisely corresponded (± 0.03 $m\cdot s^{-1}$) to the velocity associated with the %1RM that was intended for that session. If this was not the case, the absolute load was individually adjusted (slightly lowered or increased) until it allowed the subject to match the target MPV. The MaxV group performed all their prescribed repetitions at maximal intended concentric velocity, whereas subjects in the HalfV group were required to intentionally reduce concentric velocity so that it corresponded to half the target MPV established for each training session. This was accomplished by using a linear velocity transducer (described later in detail) that registered the kinematics of every repetition and provided visual and auditory feedback in real-time so that subjects could adjust their concentric lifting velocity as required. A large computer screen was placed in front of the subjects so that it was easy for them to receive instant visual feedback on repetition velocity. Both groups performed the eccentric phase of each repetition at a controlled velocity (~0.50–0.65 $m\cdot s^{-1}$). Sessions took place at a neuromuscular research laboratory under the direct supervision of the investigators, at the same time of day (± 1 h) for each subject and under constant environmental conditions (20 °C, 60% humidity). Subjects were required not to engage in any other type of strenuous physical activity, exercise training or sports competition for the duration of the present investigation.

Study I. Testing procedures

Neuromuscular performance was assessed pre- (the week before) and post-training (the week after) using a battery of tests performed in a single session in the following order: 1) 20-m all-out running sprints; 2) countermovement vertical jumps (CMJ); and 3) a progressive isoinertial loading test for the individual load-velocity relationship and 1RM strength determination in the squat exercise.

Running sprints: Two 20-m sprints, separated by a 3-min rest, were performed in an indoor running track. Photocell timing gates were placed at 0, 10 and 20 m so that the times to cover 0–10 m (T10) and 0–20 m (T20) could be determined. A standing start with the lead-off foot placed 1 m behind the first timing gate was used. Subjects were required to give an all-out maximal effort in each sprint, and the best of both trials was kept for analysis. The same warm-up protocol which incorporated several sets of progressively faster 30-m running accelerations was followed in the pre- and post-tests. Sprint times were measured using photocells (Polifemo Radio Light, Microgate, Bolzano, Italy). Test-retest reliability for T10 and T20 as measured by the coefficient of variation (CV) was 1.7% and 1.0%, respectively. The intraclass correlation coefficients (ICC) were 0.859 (95% confidence interval, CI: 0.665–0.940) for T10 and 0.946 (95% CI: 0.872–0.977) for T20.

Vertical jumps: 5 maximal CMJ, separated by 30-s rest periods, were performed next. CMJ height was registered, the highest and lowest values were discarded, and the resulting average kept for analysis. Jump height was determined using an infrared timing system (Optojump, Microgate, Bolzano, Italy). CV for test-retest reliability was 1.6% and ICC was 0.996 (95% CI: 0.992–0.998).

Isoinertial squat loading test

The squat was performed with subjects starting from the upright position with the knees and hips fully extended, stance approximately shoulder-width apart and the barbell resting across the back at the level of the acromion. Each subject descended in a continuous motion until the top of the thighs were below the horizontal plane, the posterior thighs and shanks making contact with each other, then immediately reversed motion and ascended back to the upright position. Auditory feedback based on eccentric distance travelled was provided to help each subject reach his previously determined squat depth. Unlike the eccentric phase that was performed at a controlled mean velocity (~0.50–0.65 $m \cdot s^{-1}$), subjects were required to always execute the concentric phase of each repetition at maximal intended velocity. Initial load was set at 20 kg and was progressively increased in 10-kg increments until the attained MPV was < 0.8 $m \cdot s^{-1}$. Thereafter, load was individually adjusted with smaller increments (5 down to 2.5 kg) so that 1RM could be precisely determined. 3 repetitions were executed for light (≤ 50 % 1RM), 2 for medium (50–80 % 1RM) and only one for the heaviest loads (> 80 % 1RM). Strong verbal encouragement was provided to motivate participants to give a maximal effort. Inter-set recoveries ranged from 3 min (light) to 5 min (heavy loads). Only the best repetition at each load, according to the criteria of fastest MPV [34], was considered for subsequent analysis. A total of 8.2 ± 2.3 increasing loads were used for each subject. Warm-up consisted of 5 min of treadmill running at 10 $km \cdot h^{-1}$, 5 min of lower-body joint mobilization exercises, and 2 sets of 8 and 6 squat repetitions (3-min rests) with loads of 20 and 30 kg, respectively. The exact same warm-up and progression of absolute loads were repeated in the post-test for each subject. In addition to 1RM strength, 3 other variables derived from this test were used for analysis in *Study I*: i) average MPV attained against all absolute loads common to pre- and post-tests (AV); ii) average MPV attained against absolute loads common to both tests that were moved faster than 1 $m \cdot s^{-1}$ (AV > 1); and iii) average MPV attained against absolute loads common to both tests that were moved slower than 1 $m \cdot s^{-1}$ (AV < 1). These outcome variables were chosen in an attempt to analyse the extent to which the distinct training interventions (MaxV vs. HalfV) affected the different parts of the load-velocity relationship (i.e., velocity developed against light versus heavy loads). A Smith machine (Multipower Fitness Line, Peroga, Murcia, Spain) with no counterweight mechanism was used for testing and training. A dynamic measurement system (T-Force System, Ergotech, Murcia, Spain) automatically calculated the relevant kinematic parameters of every repetition, provided auditory and visual velocity feedback in real-time and stored data on disk for analysis. This system consists of a linear velocity transducer interfaced to a personal computer by means of a 14-bit resolution analogue-to-digital data acquisition board and custom software. Instantaneous velocity was sampled at 1 000 Hz and subsequently smoothed using a 4^{th} order low-pass *Butterworth* filter with no phase shift and a cut-off frequency of 10 Hz. Reliability of this system has been recently reported elsewhere [32]. The velocity measures used in this study correspond to the mean velocity of the propulsive phase of each repetition [34]. The propulsive phase was defined as that portion of the concentric phase during which barbell acceleration is greater than acceleration due to gravity. Time under tension (TUT) was calculated as the sum of the concentric duration (in milliseconds) of every repetition.

Study II. Acute metabolic response

Whole capillary blood samples were collected from a hyperemised earlobe at rest (pre) as well as 1 min (lactate, ammonia) and 30 min (uric acid) post-exercise. The Lactate Pro LT-1710 (Arkray, Kyoto, Japan) portable analyser was used for lactate measurements. Ammonia was measured using PocketChem BA PA-4130 (Menarini Diagnostics, Italy). To measure uric acid, a Reflotron (Boehringer Mannheim, Germany) analyser was used. Analysers were calibrated before each exercise session according to the respective manufacturer's specifications.

Study II. Mechanical measurements of fatigue

2 methods were used to quantify the extent of neuromuscular fatigue induced by each RT protocol. The first method examined the pre-post exercise percent change in velocity attained against the individually determined load that elicited a ~1.00 $m \cdot s^{-1}$ MPV (V_1), as described elsewhere [32]. The second method involved the calculation of percent change in CMJ height. At the end of the warm-up, and again ~70 s following each exercise protocol (after blood sampling), each subject performed 3 maximal-effort CMJ (15 s rests) followed by 3 consecutive repetitions against the V_1 load. The average values of these 3 jumps and three repetitions were considered for the calculation of pre-post percent changes, respectively, for each variable.

Statistical analysis

Values are reported as mean ± standard deviation (SD). Statistical significance was established at the $P < 0.05$ level. Inferential statistics based on interpretation of magnitude of effects were calculated using a custom-built spreadsheet for the analysis of controlled trials [15]. The remaining statistical analyses were performed using SPSS software version 18.0 (SPSS Inc., Chicago, IL).

Study I

Homogeneity of variance across groups (MaxV vs. HalfV) was verified using the *Levene*'s test. Independent sample *t*-tests were conducted to examine inter-group differences at pre-training. Data were first analysed using a 2 × 2 factorial ANOVA with repeated measures with Bonferroni's *post-hoc* comparisons using one inter-factor (MaxV vs. HalfV) and one intra-factor (Pre vs. Post-training). In addition to this null hypothesis testing, data were assessed for clinical significance using an approach based on the magnitudes of change [3, 16]. Effect sizes (ES) were calculated using *Hedge*'s *g* in order to estimate the magnitude of the training effect on the selected neuromuscular variables within each group, as follows: g = (mean MaxV – mean HalfV)/combined SD. The standardized difference or ES for changes between the MaxV and HalfV groups in each dependent variable was calculated on log-transformed values using the pooled pre-training SD [7]. For inter-group comparisons, the chance that the true (unknown) values for each velocity condition were *beneficial/better* (i.e., greater than the smallest practically important or worthwhile effect [0.2 × between-subject SD, based on *Cohen*'s ES principle [7]), *unclear* or *detrimental/worse* for performance was calculated. Quantitative chances of *beneficial/better* or *detrimental/worse* effect were assessed qualitatively as follows: < 1 %, almost certainly not; 1–5 %, very unlikely; 5–25 %, unlikely; 25–75 %, possible; 75–95 %, likely; 95–99 %, very likely; and > 99 %, almost certain. If the chances of having *beneficial/better* or *detrimental/worse* were both > 10 %, the true difference was assessed as *unclear* [3, 16].

Study II

A 2 × 3 intra-intra factorial ANOVA with Bonferroni's *post-hoc* comparisons was used to compare differences across the three different RT protocols analysed (3 × 8 rep ~60 % 1RM, 3 × 6 rep ~70 % 1RM, and 3 × 3 rep ~80 % 1RM) and two velocity conditions (MaxV vs. HalfV).

Table 2 Study I. Changes in selected neuromuscular performance variables from pre- to post-training for each group.

	MaxV				HalfV				Changes observed for MaxV vs. HalfV	
	Pre	Post	Δ (%)	ES	Pre	Post	Δ (%)	ES	Standardized (Cohen) differences (90% CI)	Percent changes of better/trivial/worse effect
CMJ (cm)	36.6 ± 4.5	39.9 ± 5.8 ***	8.9	0.63	40.7 ± 6.3	41.7 ± 6.7#	2.4	0.15	0.38 (0.15 to 0.61)	91/9/0
T10 (s)	1.80 ± 0.07	1.75 ± 0.06 **	−2.8	0.77	1.78 ± 0.07	1.76 ± 0.09	−1.1	0.25	0.26 (−0.22 to 0.74)	59/36/6
T20 (s)	3.09 ± 0.10	3.04 ± 0.10 *	−1.6	0.50	3.07 ± 0.13	3.02 ± 0.12 *	−1.6	0.40	0.01 (−0.42 to 0.40)	19/59/21
1RM (kg)	89.2 ± 15.9	105.2 ± 18.0 ***	18.0	0.94	94.8 ± 17.0	104.0 ± 17.0 **	9.7	0.54	0.36 (0.01 to 0.71)	79/21/1
AV ($m \cdot s^{-1}$)	1.03 ± 0.05	1.18 ± 0.11 ***	14.6	1.76	1.06 ± 0.08	1.14 ± 0.10 **	7.5	0.88	0.90 (0.07 to 1.72)	92/6/2
AV>1 ($m \cdot s^{-1}$)	1.19 ± 0.03	1.32 ± 0.10 ***	10.9	1.76	1.21 ± 0.08	1.27 ± 0.08	5.0	0.75	0.98 (−0.80 to 2.04)	89/7/3
AV<1 ($m \cdot s^{-1}$)	0.85 ± 0.03	1.00 ± 0.10 ***	17.6	2.03	0.84 ± 0.03	0.95 ± 0.09 **	13.1	1.64	1.45 (−0.42 to 3.32)	87/6/7

Data are mean ± SD; ES = Effect Size; Δ = Pre-Post Change; CI = Confidence Interval
MaxV: Maximal concentric velocity (n = 10), HalfV: Half-maximal concentric velocity (n = 11)
1RM: one-repetition maximum squat strength, CMJ: countermovement jump height, T10: 10 m sprint time, T20: 20 m sprint time
AV: average MPV attained against absolute loads common to pre- and post-test in the squat progressive loading test
AV>1: average MPV attained against absolute loads common to pre- and post-test that were moved faster than 1 $m \cdot s^{-1}$
AV<1: average MPV attained against absolute loads common to pre- and post-test that were moved slower than 1 $m \cdot s^{-1}$
Intra-group significant differences from Pre- to Post-training: *P<0.05, **P<0.01, ***P<0.001
Significant group × time interaction (P<0.05)

Results

Study I

No significant differences between the MaxV and HalfV groups were found at pre-training (Pre) for any of the variables analysed. MaxV trained at a significantly faster average MPV than HalfV (0.80 ± 0.13 vs. 0.43 ± 0.07 $m \cdot s^{-1}$, respectively; P < 0.001) whereas HalfV spent significantly more concentric time under tension (TUT) than MaxV (383.5 ± 32.9 s vs. 260.5 ± 22.7 s, respectively; P < 0.001) (**Table 1**). Compliance with the RT program was 97.2 % of all sessions scheduled for the MaxV group and 92.4 % for the HalfV group. Actual mean MPV and TUT values for each week and overall training program are reported in **Table 1**. Mean values, percent changes from pre- to post-training (Post) and effect sizes for all variables analysed are reported in **Table 2**.

Study I. Isoinertial strength assessments

Training resulted in a significant increase in 1RM squat strength for both MaxV (18.0 %) and HalfV (9.7 %) groups (**Table 2**). A trend toward a significant 'group' x 'time' interaction was noted for 1RM (P = 0.084) and AV (P = 0.076). There was no 'group' x 'time' interaction for AV > 1 (P = 0.11) and AV < 1 (P = 0.19). Greater intra-group ES in all isoinertial strength variables were found for MaxV when compared to HalfV. Large *Cohen* ES (> 0.80) were observed for changes in AV, AV > 1 and AV < 1 variables for MaxV compared to HalfV (**Table 2**). Results for inter-group analysis are illustrated in **Fig. 1**. Practically worthwhile differences between the MaxV and HalfV training groups seemed to be evident as supported by the magnitude of the ES and qualitative outcomes, suggesting likely true changes.

Study I. Vertical jump and sprint ability

A significant 'group' × 'time' interaction was observed for CMJ height (P = 0.011) (**Table 2**), whereas no significant interactions were found for T10 (P = 0.34) or T20 (P = 0.97). Change in individual CMJ values from Pre to Post is shown in **Fig. 2**. MaxV training seemed to result in a likely better effect on CMJ height performance than HalfV, whereas the beneficial effects of MaxV compared to HalfV on T10 and, especially, T20 were not clear (**Fig. 1**).

Study II. Acute metabolic response

Lactate was significantly higher for MaxV vs. HalfV for the 3 RT protocols analysed. Ammonia was significantly higher for the MaxV condition following 3 × 8 with ~60 % 1RM (P < 0.001) and 3 × 6 with ~70 % 1RM (P < 0.05), i.e., those protocols where a higher number of repetitions were completed in each set. Significant 'velocity' x 'protocol' interactions are reported in **Table 3**.

Study II. Mechanical measurements of fatigue

Pre-post changes in the velocity attained against the V1 load were small (≤ 5 %) and not significantly different between MaxV and HalfV, with no significant 'velocity' × 'protocol' interactions observed (**Table 3**). Significantly higher reductions in pre-post exercise CMJ height (P < 0.05) were found for MaxV compared to HalfV following the 3 × 8 with ~60 % 1RM and 3 × 6 with ~70 % 1RM protocols.

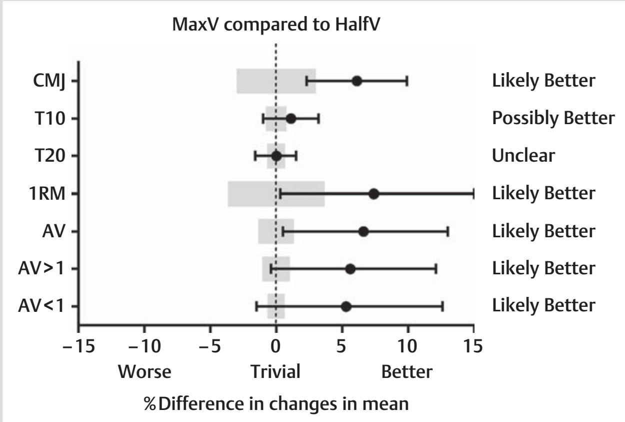

Fig. 1 Effect of the MaxV compared to HalfV squat training on selected variables of dynamic neuromuscular performance. Bars indicate uncertainty in the true mean changes with 90 % confidence intervals. Trivial (shaded) areas were calculated from the smallest worthwhile change (see Methods).

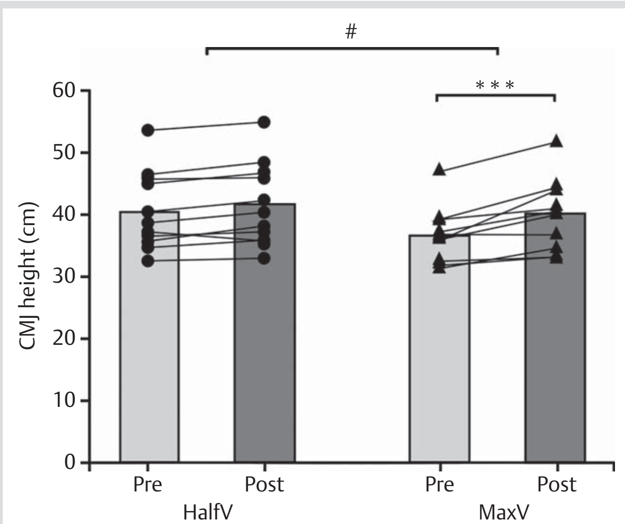

Fig. 2 Changes in vertical jump performance (CMJ height) following 6 wk of velocity-based squat training. MaxV: Maximal concentric velocity (n = 10), HalfV: Half-maximal concentric velocity (n = 11). *** significantly different from pre- to post-training (P < 0.001) # significant group × time interaction (P < 0.05).

Discussion

To our knowledge, this is the first study that has analysed the effect of 2 isoinertial RT programs equivalent in all training variables except in movement velocity on several measures of dynamic neuromuscular performance, while also describing the acute metabolic and mechanical response to the resistance exercise protocols employed. The main finding of *Study I* was that the actual velocity at which loads were lifted during squat training had a differential effect on the resulting neuromuscular adaptations. Thus, performing repetitions at maximal concentric velocity (MaxV) compared to intentionally slower at half-velocity (HalfV) resulted in a likely more beneficial effect on squat performance (1RM strength as well as the velocity attained against all loads, from light to heavy) and CMJ height. The effectiveness of MaxV vs. HalfV squat training on short-distance (20 m) sprint performance was, however, unclear. *Study II* showed slightly superior metabolic stress (blood lactate and ammonia) and mechanical fatigue (CMJ height loss) for MaxV vs. HalfV, but since post-exercise metabolite levels were low to moderate for both velocity conditions, it seems likely that metabolic factors did not play a decisive role in the resulting adaptations. Therefore, it is reasonable to suggest that the different results obtained by the MaxV and HalfV groups in terms of muscle strength and performance gains were due to the distinct velocities used in training.

Following the 6-week (18 sessions) training intervention, the percent changes and effect sizes for the MaxV training group approximately doubled those of the HalfV group for most of the variables analysed (▶ **Table 2**). A significant 'group' × 'time' interaction was found for CMJ height and this interaction for 1RM and AV was very close to statistical significance. In addition to quantifying the change in 1RM squat strength, we assessed the change in velocity developed against all (AV), 'light' (AV > 1) and 'heavy' (AV < 1) loads common to the pre- and post-tests in an attempt to analyse the extent to which the 2 training interventions affected the different parts of the load-velocity curve. Inferential statistics based on interpretation of magnitude of effects revealed that likely better effects were to result in CMJ, 1RM, AV, AV > 1 and AV < 1 variables for MaxV training compared to HalfV (▶ **Table 2** and ▶ **Fig. 1**). We used this approach because traditional statistics often do not indicate the magnitude of an effect, which is typically more relevant to athletic performance than any statistically significant effect [16]. The fact that both MaxV and HalfV groups obtained the greatest improvements against AV < 1, i.e., loads lifted at velocities slower than 1.00 $m \cdot s^{-1}$, which were those used in training (▶ **Table 1**), is in agreement with the velocity-specificity principle and supports previous research findings [21]. To our knowledge, only one previous isoinertial study performed a somewhat similar analysis to ours [2] although in that study all groups trained using maximal intended velocity actions while differing in the loads used (heavy vs. negligible), and no velocity-specific adaptations were found. The improvements observed for the MaxV condition in the present study are remarkable considering that: i) training consisted of only one exercise, the full squat (no additional jump or sprint training was undertaken); ii) few repetitions and moderate loads were used, with exercise sets ending well ahead of reaching failure (▶ **Table 1**); and iii) low to moderate metabolite levels of lactate, ammonia and uric acid were elicited by the type of exercise protocols performed (▶ **Table 3**).

A unique and important aspect of this investigation was that movement velocity was measured and registered for every repetition by means of a linear velocity transducer. The strict control of the actual repetition velocities performed by the 2 experimental groups enabled us to isolate the effect of the variable of interest, in this case movement velocity, on the observed changes in performance. However, in the majority of previous isoinertial research actual training velocities were not quantified [2, 5, 10, 17, 19, 20, 25, 26, 28, 30, 35, 40], and most studies identified movement velocity with lifting cadence [10, 25, 26, 28, 30, 35, 40], which seems both incorrect and insufficient because: i) for a longer limb the same lifting cadence represents a much greater linear velocity than for a shorter limb [29]; and ii) when either the magnitude of the load is high (≥ ~80 % 1RM) or the number of repetitions approaches muscle failure, a subject becomes unable to follow the imposed lifting cadence due to fatigue [23, 36]. As can be appreciated in ▶ **Table 1**, both the number of repetitions per set (from 8 down to 2) and the magnitude of the loads used (60–80 % 1RM) in this study were moder-

Table 3 Study II. Metabolic and mechanical variables following each RT protocol in the 2 exercise conditions (n = 8).

	MaxV	HalfV	P-value
	Lactate (mmol·L^{-1})		
Rest	1.1 ± 0.3	1.0 ± 0.3	NS
3 × 8 with 0.98 m·s^{-1} load (~60 % 1RM)	4.7 ± 2.0	3.2 ± 1.7	< 0.001
3 × 6 with 0.82 m·s^{-1} load (~70 % 1RM)	3.9 ± 1.2	3.1 ± 1.4	< 0.05
3 × 3 with 0.68 m·s^{-1} load (~80 % 1RM)	2.0 ± 0.7 #§	1.8 ± 0.7#§	< 0.05
	Ammonia (μmol·L^{-1})		
Rest	31.0 ± 9.3	26.7 ± 9.4	NS
3 × 8 with 0.98 m·s^{-1} load (~60 % 1RM)	40.8 ± 5.3	18.0 ± 4.2	< 0.001
3 × 6 with 0.82 m·s^{-1} load (~70 % 1RM)	39.4 ± 11.2	28.4 ± 7.1 #	< 0.05
3 × 3 with 0.68 m·s^{-1} load (~80 % 1RM)	22.1 ± 5.0 #§	18.0 ± 4.3 §	NS
	Uric Acid (μmol·L^{-1})		
Rest	299.5 ± 76.0	315.0 ± 58.8	NS
3 × 8 with 0.98 m·s^{-1} load (~60 % 1RM)	314.3 ± 66.8	334.1 ± 65.5	NS
3 × 6 with 0.82 m·s^{-1} load (~70 % 1RM)	323.0 ± 64.3	302.0 ± 79.7	NS
3 × 3 with 0.68 m·s^{-1} load (~80 % 1RM)	325.6 ± 70.3	289.3 ± 63.0	NS
	Pre-post change (%) in velocity against the V_1 load		
3 × 8 with 0.98 m·s^{-1} load (~60 % 1RM)	0.5 ± 5.6	3.4 ± 4.3	NS
3 × 6 with 0.82 m·s^{-1} load (~70 % 1RM)	3.7 ± 3.9	3.4 ± 5.5	NS
3 × 3 with 0.68 m·s^{-1} load (~80 % 1RM)	5.0 ± 3.8	0.8 ± 3.7	NS
	Pre-post change (%) in CMJ height		
3 × 8 with 0.98 m·s^{-1} load (~60 % 1RM)	13.1 ± 5.1	9.7 ± 3.3	< 0.05
3 × 6 with 0.82 m·s^{-1} load (~70 % 1RM)	14.2 ± 4.1	11.7 ± 5.4	< 0.05
3 × 3 with 0.68 m·s^{-1} load (~80 % 1RM)	10.4 ± 3.6	8.3 ± 5.2	NS

Data are mean ± SD
MaxV: Maximal concentric velocity, HalfV: Half-maximal concentric velocity
Significant velocity × protocol interaction (P < 0.05) with 3 × 8 ~60 % 1RM
§ Significant velocity × protocol interaction (P < 0.05) with 3 × 6 ~70 % 1RM

ate. This was an important and necessary requisite so that subjects in the HalfV condition could be able to complete all scheduled repetitions at the intended slow velocity, whereas subjects in the MaxV group could actually perform most of their repetitions at high velocities, without being forced to unintentionally and drastically reduce velocity due to fatigue.

Previous isoinertial research comparing the effects of 'fast' vs. 'slow' training velocities on strength gains has employed different approaches. A group of studies compared 'super slow' vs. 'traditional' RT. 'Super slow' training is characterized by using deliberately slow muscle actions (~10 s concentric and ~4–10 s eccentric durations) whereas in 'traditional' training ~2 s concentric and ~2–4 s eccentric actions are usually employed. The vast majority of this research has shown that 'traditional' RT is a superior exercise modality for inducing neuromuscular adaptations [31, 36]. Another group of studies compared 'fast' (either maximal intended or not) vs. intentionally 'slow' movement velocities on strength performance. Some of these studies found greater strength gains when performing the repetitions at fast velocities [17, 20, 25–27] while others did not find differences between 'fast' and 'slow' training [10, 30, 35, 40]. A plausible explanation to why several studies did not find superior strength gains when lifting loads faster may be that in most of them repetitions were performed to or next to muscle failure [2, 9, 25, 26, 30, 40]. When such exhaustive efforts are performed, repetition velocity progressively and unintentionally decreases so that the velocities attained in the last repetitions of each set become very similar between the 'fast' and 'slow' groups, therefore tending to equalize the overall training velocities [9]. Since, as already mentioned, most if not all previous studies did not quantify actual training velocities, it was not possible to establish meaningful relationships between movement velocity and the observed changes in neuromuscular performance. This situation does not occur in our study where the significantly different overall mean repetition velocities attained by the MaxV (0.80 m·s^{-1}) and HalfV (0.43 m·s^{-1}) groups confirm that the exercise sessions were performed at the desired target velocities (▶ **Table 1**) and that these exercise conditions could indeed be considered 2 distinct training stimuli.

With regards to time spent under tension, our results show that concentric TUT was ~47 % longer when the loads where lifted intentionally slower at HalfV compared to MaxV (▶ **Table 1**) but, apparently, this did not result in any beneficial effect on muscle strength. As some authors have noticed, manipulation of this particular variable and its effects on strength performance are yet not fully understood [8, 36]. The present findings seem to suggest that actual movement velocity is of greater importance than TUT for inducing neuromuscular adaptations directed towards improving athletic performance. Although the neurophysiological mechanisms by which movement velocity influences strength adaptation were not investigated in the present study, training with maximal intended concentric velocity in each repetition could result in a greater and/or more effective recruitment of fast-twitch muscle fibres [4, 39], changes in myosin heavy chain isoform composition [1], increases in tendon-aponeurosis stiffness [6] and an increased calcium sensitivity of the contractile apparatus [38].

Of interest to coaches and strength and conditioning professionals should be the effects of RT on sports performance rather than solely on muscle development and hypertrophic adaptations. However, very little scientific evidence exists on the effect of movement velocity on measures of dynamic athletic performance [5, 19, 20, 24, 25]. In the present study, the improvements in running sprint performance were small and neither statistically nor practically different between MaxV and HalfV (▶ **Table 2** and ▶ **Fig. 1**). These improvements (1–3 %) are similar to those observed in other studies [5, 24] but were obtained with a lower degree of effort during RT and without sprint training. However, significantly greater improvements in CMJ height were observed for the MaxV vs. HalfV group (Fig. 2). Interestingly, as can be appreciated in Fig. 2, the subjects with a higher CMJ at pre-training in the MaxV group were those who obtained the greatest improvements in jumping performance. This may suggest that among subjects with similar RT experience, those with a higher initial performance may be the best responders to training performed at maximal velocity. However, in the HalfV group, no clear effect on jumping performance was observed even for the subjects with higher initial CMJ scores. In previous research, no clear differences were found between 'fast' and 'slow' velocity training [19,25,28,40]. One possible reason for this lack of differences could once again be the degree of effort reached in each training set, as already explained. In the present study, less than half the maximum possible number of repetitions were completed in any set, which is not common practice in RT. This implies that when the last repetitions of a set are being performed in the MaxV condition, only moderate levels of velocity loss and metabolic stress occur [12,32]. A low to moderate degree of fatigue together with the possibility of a preferential activation of type II muscle fibers [4,39] may provide a favourable environment for rapid force production adaptations to occur. Conversely, when exercise sets are performed to muscle failure [19,25,28,40] actual training velocities end up being very similar between the 'fast' and 'slow' groups, and high levels of metabolic and mechanical fatigue are experienced [12,32]. The fact that MaxV squat training resulted in a greater transfer effect over the CMJ compared to sprint running might be related to the principle of training specificity. Thus, greater biomechanical similarities seem to exist between the squat and the CMJ (i.e., triple extension of hip, knee and ankle joints; force simultaneously applied with both feet; larger ground contact time; etc.).

Several studies have analysed the acute effect of repetition velocity during RT on blood lactate concentration. However, only one of these studies [23] equated exercise volume and loading magnitude between at least 2 of the 3 protocols examined, so that the differences could be mainly attributed to movement velocity. Mazzetti et al. [23] reported higher blood lactate levels when loads were lifted slowly (~2 s concentric duration) as is traditional compared to explosively, which differs from the higher lactate values for MaxV vs. HalfV observed in the present study (Table 3). However, Mazzetti et al. [23] also found a higher energy expenditure with fast explosive compared to slow muscle contractions, which seems to be a contradictory result. This increased energy expenditure was attributed to a greater activation of fast-twitch muscle fibres when each repetition is performed at maximal intended velocity, since human fast muscle fibres have an energy expenditure 3–4 times greater than slow fibres [14]. This same argument, together with the fact that type II fibres possess greater glycolytic power, could be valid for explaining the higher lactate concentrations observed for the MaxV condition in *Study II* (Table 3).

The metabolic stress and degree of fatigue induced by the RT protocols used in this investigation are far from those typically associated with exhaustive resistance training [12,32]. Post-exercise lactate levels were moderate whereas blood ammonia and uric acid were low and close to normal resting values, even in the MaxV condition. Blood uric acid remained within the normal resting range for this group of young male adults ($313 \pm 66\,\mu mol \cdot L^{-1}$) for all protocols analysed (Table 3). The observed values for these metabolites are very similar to those previously reported for RT protocols in which only half the maximum possible number of repetitions were performed in each training set [32]. Taken together, our findings show that the type of training performed by the MaxV group was highly effective because it provided significant squat strength gains together with noticeable improvements in vertical jump and, to a lesser extent, sprint ability, and yet it was metabolically well tolerated. These seem important issues for conditioning in competitive sports where it is usually necessary to maximize neuromuscular adaptations while trying to avoid excessive fatigue that could interfere with the development of other components of physical fitness (e.g. endurance) or negatively affect technical, tactical or recovery aspects of training.

The results of this study clearly indicate that RT intensity is more than solely the magnitude of the load (% 1RM) being lifted, as it is often assumed, and that the velocity at which loads are actually lifted influences the resulting training effect. Therefore, movement velocity should be considered an important component of resistance exercise intensity, and effort should be made to specify the actual training velocities used in future RT research. Quantification of the actual repetition velocities developed during RT will provide us with a more complete and precise understanding of the resistance exercise stimulus.

In conclusion, the findings of the present study suggest that performing repetitions at maximal concentric velocity (MaxV) compared to intentionally slower (HalfV) may provide a superior stimulus for inducing neuromuscular adaptations directed towards improving athletic performance. Thus, MaxV training resulted in likely more effective gains than HalfV in 1RM strength, velocity developed against any given load in the squat exercise and CMJ. It was, however, unclear whether MaxV was superior to HalfV for improving short-distance (20 m) sprint running. Our results also seem to indicate that provided actions are performed at maximal intended velocity, only moderate loads and few repetitions are necessary to considerably improve maximum strength and, more importantly for sports performance, to allow a positive transfer or carry-over effect to actions such as vertical jumping and sprinting. In addition, velocity-specific adaptations were observed since both experimental groups obtained the greatest improvements in squat performance at the velocities used in training. Finally, movement velocity seemed to be of much greater importance than TUT for inducing strength adaptations.

Conflict of interest: The authors declare no conflicts of interest.

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