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Short-term Recovery Following Resistance Exercise Leading or not to Failure

How does manipulating the 'level of effort' impact post-exercise recovery?
What are potential implications for optimizing athletic performance?

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Key words

- athletic performance
- heart rate variability
- heart rate complexity
- hormonal response
- neuromuscular fatigue
- strength training

Abstract

This study analyzed the time course of recovery following 2 resistance exercise protocols differing in *level of effort*: maximum (to failure) vs. half-maximum number of repetitions per set. 9 males performed 3 sets of 4 vs. 8 repetitions with their 80% 1RM load, 3×4(8) vs. 3×8(8), in the bench press and squat. Several time-points from 24 h pre- to 48 h post-exercise were established to assess the mechanical (countermovement jump height, CMJ); velocity against the 1 m·s⁻¹ load, V₁-load), biochemical (testosterone, cortisol, GH, prolactin, IGF-1, CK) and heart rate variability (HRV) and complexity (HRC) response to exercise. 3×8(8) resulted in greater neuromuscu-

lar fatigue (higher reductions in repetition velocity and velocity against V₁-load) than 3×4(8). CMJ remained reduced up to 48 h post-exercise following 3×8(8), whereas it was recovered after 6 h for 3×4(8). Significantly greater prolactin and IGF-1 levels were found for 3×8(8) vs. 3×4(8). Significant reductions in HRV and HRC were observed for 3×8(8) vs. 3×4(8) in the immediate recovery. Performing a half-maximum number of repetitions per set resulted in: 1) a stimulus of faster mean repetition velocities; 2) lower impairment of neuromuscular performance and faster recovery; 3) reduced hormonal response and muscle damage; and 4) lower reduction in HRV and HRC following exercise.

Introduction

Resistance training (RT) is recognized as an effective method for increasing strength and muscle hypertrophy, and it has been deemed a key component of exercise programs designed for improving health status and overall fitness. Since the neuromuscular system specifically adapts to the stimuli it is faced with [43], knowledge of the mechanical and physiological responses to RT is essential to improve our understanding of the mechanisms underlying the process of training adaptation. Among the main resistance exercise variables that can be manipulated to configure the mechanical stimulus, the actual number of repetitions performed in a set in relation to the maximum number that can be completed (i.e., proximity to muscle failure), recently termed '*level of effort*' [39], has received scarce research attention but seems an important aspect to take into account when prescribing RT aimed at optimizing functional adaptations and improving neuromuscular performance. Several studies have suggested that, among other factors, the

time needed for recovery may significantly increase as the repetition number approaches failure [14, 15, 39]. However, the impact of exercising to muscle failure vs. ending each set several repetitions shy of failure on recovery has not yet been addressed.

It is speculated that there might be an optimal level of induced neuromuscular fatigue after each RT session to maximize adaptation. Although some studies [1, 8] suggest that muscle failure may be needed to maximize muscle mass and strength, increasing evidence seems to indicate that reaching repetition failure during an exercise set may not necessarily improve the magnitude of strength gains [9, 10], especially when training is not solely aimed at muscle hypertrophy but, rather, it must serve to develop specific neuromuscular adaptations to improve athletic performance. It has been shown that performing repetitions to failure causes a marked disruption of cellular homeostasis, as reflected by a near-complete depletion of phosphocreatine stores, a significant reduction of adenosine triphosphate and muscle total adenine nucleotide pool, as well

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as very high increases in inosine monophosphate and muscle lactate [14], thereby suggesting that such protocols may require longer recovery times [14, 15, 39]. However, little is known about the time of course of recovery following RT protocols performed with different *levels of effort*.

The mechanical stimulus associated with RT and their interaction with other hormonal and metabolic factors appears to be key stimuli for neuromuscular adaptations to occur [7]. The total volume of exercise and the number of sets performed in a training session also seem to play an important role, influencing the response of hormones such as testosterone, growth hormone (GH), and cortisol [28, 36, 42].

Heart rate variability (HRV) refers to the amount of heart rate fluctuation around the mean heart rate [45]. It can be determined non-invasively from electrocardiogram recordings, resulting in a R-R interval time series [45]. Analysis of HRV in the time and frequency domains has been used to study the response of the cardiac autonomic system to physical activity [19, 20, 23, 26]. Nevertheless, a loss of information regarding cardiac autonomic fluctuations might happen if only linear methods are used, since physiological control mechanisms under healthy conditions exhibit complex dynamics [5]. The loss of variability and complexity in physiological systems may be a dynamic biomarker of aging and disease [6]. Recently, a complexity index (CI) was introduced to measure the complexity of physiological time series, such as beat-to-beat heart rate fluctuations [4]. CI has been proposed as a marker of integrated cardiac regulation; the higher the complexity of the system the greater its functionality [4]. Several studies have analyzed the acute effect of RT on HRV [23, 25, 27, 31], however the effects of RT on heart rate complexity (HRC) have received less attention [19, 20, 23, 25]. Given the non-stationarity of the heart rate signal following a stressor, and the scarce information available regarding the effects of RT on cardiovascular autonomic modulation, it was thought of interest to analyze the linear and nonlinear dynamics of fluctuations in cardiovascular control following 2 resistance exercise protocols (REP) differing in the number of repetitions actually performed in each set in relation to the maximum number of repetitions that can be completed.

The stress associated to resistance exercise requires rapid coordinated adjustments in the hormonal and cardiac autonomic systems which are crucial for the maintenance of homeostasis in response to increased metabolic demands [2]; the hypothalamus plays a key role in the proper integration and control of these systems [30]. However, to the best of our knowledge, no direct relationship between cardiac autonomic activity and other responses to resistance exercise, such as changes in hormonal and mechanical variables have been described. Since the acute and delayed mechanical, hormonal and HRV response to failure vs. non-failure resistance exercise protocols has not been addressed in detail, the purpose of this study was to analyze the

time course of recovery following 2 distinct REP in terms of the *level of effort* required: maximum (to failure) vs. half-maximum number of repetitions per set in the fundamental RT exercises of bench press (BP) and full back squat (SQ). Several assessment time points from 24 h pre- to 48 h post-exercise were established to evaluate the mechanical, biochemical and HRV and HRC response to each REP in an attempt to advance in our understanding of the overall short-term recovery following RT. A secondary purpose was to examine the relationships existing between the changes in mechanical, biochemical and cardiovascular autonomic response to failure vs. non-failure resistance exercise.

Materials and Methods

Subjects

9 men (age 23.3 ± 3.9 years, height 1.75 ± 0.03 m, body mass 75.3 ± 9.2 kg) volunteered to participate in this study. Subjects were physically active sports science students with a RT experience ranging from 2 to 4 years (1–3 sessions per week). One-repetition maximum (1RM) strength was 108.7 ± 15.5 kg for the SQ and 88.4 ± 21.6 kg for the BP 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 were found after a medical examination. None of the subjects was taking drugs, medications or dietary supplements known to influence physical performance. The present investigation met the ethical standards of this journal [18] and was approved by the Research Ethics Committee of Pablo de Olavide University.

Experimental design

Following familiarization and initial strength assessment, subjects undertook 2 REP performed 14 days apart in separate trials. 3 exercise sets with the same load (corresponding to 80% 1RM) and 5 min inter-set rests were used in both trials. The protocols only differed in the actual number of repetitions performed in each set in relation to the maximum possible number of repetitions. The first REP demanded a maximum *level of effort*, 3 sets of 8 repetitions to failure, $3 \times 8(8)$, whereas in the second REP only half the maximum number of repetitions were performed in each set, $3 \times 4(8)$.

In order to compare the mechanical, biochemical and HRV response, as well as the time course of recovery following the 2 REP analyzed, subjects underwent a battery of measurements at different time points: pre-exercise (Pre), post-exercise (Post), 6h-Post, 24h-Post and 48h-Post (► Fig. 1). Vertical counter-movement jump (CMJ) height and the individual load (kg) that elicits a $\sim 1.00 \text{ m} \cdot \text{s}^{-1}$ (V_1 -load) mean barbell propulsive velocity

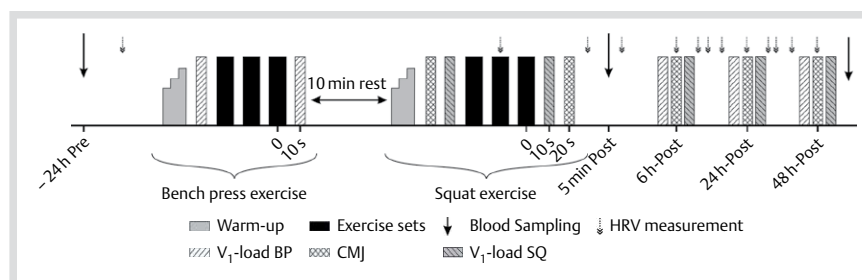


Fig. 1 Schematic representation and timeline of study design. Mechanical, biochemical, and autonomic cardiovascular measurements at different time points were performed to analyze the time course of recovery following 2 resistance exercise protocols: $3 \times 4(8)$ vs. $3 \times 8(8)$. Each protocol was comprised of the bench press followed by the squat exercise.

(hereafter, velocity) were assessed at Pre, Post, 6 h-Post, 24 h-Post and 48 h-Post. These mechanical measurements have been previously described [35, 39]. The V_1 -load was chosen because it is a sufficiently high velocity, which is attained against medium loads (~47% 1RM in BP and ~60% 1RM in SQ) [34, 35, 39], and it allows a good expression of the effect of fatigue on velocity, besides being relatively easy to move and quick to determine as part of the warm-up [39]. Blood sampling for the determination of testosterone, cortisol, GH, prolactin (PRL), insulin-like growth factor-1 (IGF-1) and creatine kinase (CK) concentrations was performed at Pre, Post and 48 h-Post. HRV and HRC measurements are described later in detail.

During the course of the present study subjects did not perform any other RT besides some abdominal and lower back strengthening exercises. Participants abstained from any strenuous physical activity for at least 4 days before each trial. The 2 REP were performed at the same time of day for each subject and under controlled environmental conditions (20–22°C and 55–65% humidity) in a research laboratory. Subjects underwent 4 familiarization sessions 2 weeks before the start of the first trial. These sessions were supervised by researchers, and attention was paid to proper exercise lifting technique and instruction on testing procedures. An initial strength assessment was performed one week before the first trial.

Testing procedures

Initial strength assessment

Individual load-velocity relationships and 1RM strength were determined using a progressive isoinertial loading test in the BP and SQ exercises, in that order. The warm-up and testing protocols were identical to those described elsewhere [39]. Relative loads were determined from the load-velocity relationship for the BP and SQ 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 [12, 40]. In the progressive loading test, we verified that the velocity corresponding to 80% 1RM was similar ($0.48 \pm 0.03 \text{ m} \cdot \text{s}^{-1}$ for BP and $0.70 \pm 0.03 \text{ m} \cdot \text{s}^{-1}$ for SQ) to those reported by previous studies [12, 35, 40]. The BP was performed imposing a momentary pause (~1.5 s) at the chest between the eccentric and concentric actions to minimize the contribution of the rebound effect and allow for more reproducible measurements [34]. The SQ was performed starting from the upright position with the knees and hips fully extended. Each subject descended in a continuous motion until the top of the thighs got below the horizontal plane, then immediately reversed motion and ascended back to the upright position. Subjects were required to always execute the concentric phase of either BP or SQ in an explosive manner, at maximum intended velocity. This execution technique for the BP and SQ was exactly reproduced on the 2 REP under study.

Resistance exercise protocol

Both REP were performed in the morning (10 AM) and were comprised of the BP followed by the SQ, with a 10 min rest between exercises (► Fig. 1). Subjects warmed up for the BP by performing 3 min upper-body joint mobilization exercises and 2 sets of 8 repetitions with a 20 kg barbell. The warm-up for the SQ consisted of: 1) 5 min jogging at a self-selected easy pace, 2) two 30 m running accelerations, 3) 2 sets of 10 squats with no external load (own body mass), and 4) 5 CMJs with increasing intensity. Then, 3 maximum CMJ, separated by 20 s rests, were performed and the mean jump height taken as the pre-exercise

reference value. In both BP and SQ, the determination of the V_1 -load followed. For this purpose, 3 sets of 6 down to 3 repetitions (2 min inter-set rests) with increasing loads up to each subject's V_1 -load were performed. The mean velocity of the 3 maximum intended repetitions with the V_1 -load in each exercise was registered as the pre-exercise reference value for this variable, determined to a precision of $\pm 0.03 \text{ m} \cdot \text{s}^{-1}$. Finally, load was progressively increased (in 2–3 sets of 3 repetitions each) up to 80% 1RM. The 3 sets of the corresponding REP were performed next. Immediately after completing the last repetition of the third set (load was changed in 10–15 s with the help of trained spotters), subjects performed again 3 repetitions with the V_1 -load. Furthermore, after the SQ exercise, another 3 maximum CMJs, separated by 20 s rests, were performed (► Fig. 1). The V_1 -load and CMJ mean values were taken as the immediately post-exercise measures. Strong verbal encouragement and velocity feedback in every repetition were provided throughout all exercise sets. At 4 PM in the evening (6 h-Post), and at 10 AM of the following 2 days (24 h-Post and 48 h-Post), the V_1 -load and CMJ measurements were repeated, exactly as described above, in order to assess the state of neuromuscular recovery following each REP.

Mechanical measurements of fatigue

3 different methods were used to quantify the extent of neuromuscular fatigue induced by each REP [39]. The first method analyzed the decline in repetition velocity during the 3 consecutive exercise sets and was calculated as the percent loss in mean propulsive velocity from the fastest to the slowest repetition of each set and averaged over the 3 sets. The second method examined the pre-post exercise change in velocity attained against the V_1 -load. The third method analyzed the change in CMJ height pre-post exercise.

Blood collection and analysis

Blood sampling took place 24 h before (Pre), 5 min after completion of the corresponding REP (Post), and 48 h-Post. Subjects rested seated for 30 min before the first blood collection. Samples were drawn from an antecubital forearm vein using a 20-gauge needle connected to Vacutainers®. The Pre (baseline) samples were drawn at the same time of day (± 15 min) that the REP (10 AM) to minimize the bias in hormonal values due to the circadian rhythm. Whole blood was centrifuged at 3000 rpm (4°C) for 15 min and the resultant serum was then removed and stored at -20°C . Samples were assayed in duplicate, thawed only once, and decoded only after the analyses were completed (i.e., blinded analysis procedure). Concentrations of total testosterone, cortisol, GH, PRL and CK were measured using electrochemiluminescence immunoassays on the Elecsys 2010 autoanalyzer (Roche Diagnostics, Indianapolis, USA). IGF-1 was measured by chemiluminescent immunometric assay on the Immulite 2000 System (Siemens, Los Angeles, USA). For testosterone, cortisol, GH, PRL, IGF-1 and CK assay sensitivities were $0.087 \text{ nmol} \cdot \text{L}^{-1}$, $8.5 \text{ nmol} \cdot \text{L}^{-1}$, $0.03 \mu\text{g} \cdot \text{L}^{-1}$, $20 \mu\text{g} \cdot \text{L}^{-1}$, $0.047 \mu\text{g} \cdot \text{L}^{-1}$ and $45 \text{ IU} \cdot \text{L}^{-1}$; with an intra-assay coefficient of variation of 2.0, 1.7, 2.3, 2.9, 1.3 and 1.8%, respectively. Concentrations are reported uncorrected for plasma volume changes.

Analysis of the R-R interval time series

For the time domain analysis, the natural logarithm of the root mean square of successive differences in R-R intervals ($\text{Ln}r\text{MSSD}$) was calculated. HRC was measured using the complexity index

(CI_{1-5}) [4] derived from the multiscale entropy method [5]. This algorithm quantifies the information content of the signal. Given a one-dimensional discrete time series $\{x_1, x_2, \dots, x_N\}$, such as beat-to-beat time interval series, the calculation of the CI comprises the following steps: 1) a coarse-graining procedure used to construct a set of derived time series $\{y(\tau)\}$, representing the system's dynamics at different time scales (τ), according to the equation:

$$y_j^{(\tau)} = 1/\tau \sum_{i=(j-1)\tau+1}^{j\tau} x_i, 1 \leq j \leq N/\tau;$$

2) the quantification of the degree of irregularity of each coarse-grained time series, which can be accomplished using an entropy measure such as Sample Entropy (SampEn) [37], that is the negative of the natural logarithm of the conditional probability that sequences matching point wise for m consecutive data points, within a tolerance r , also match for $m+1$ data points; and 3) the CI_{1-5} was computed by summing SampEn values for scales 1–5. To calculate SampEn, we used $m=2$ and $r=0.15$.

The time series extended to 3 days, from 24 h pre- to 48 h post-exercise. Each time series was divided in 13 temporal segments of $3 \cdot 10^3$ data points, and once we coarse-grained them up to scale 5, the shortest time series had 600 points. These temporal segments were as follows: 1) during sleep, the night before the REP (when heart rate was at its lowest); 2a) during the REP (from the highest measured heart rate backwards), 2b) immediately post-exercise, 2c) in the recovery phase after the REP; 3a) at 6 h-Post, during the V_1 -load and CMJ assessments, 3b) immediately post-assessment, 3c) in the recovery phase after the 6 h-Post assessment; 4) during sleep, the night after the REP; 5a) at 24 h-Post, during the V_1 -load and CMJ assessments, 5b) immediately post-assessment, 5c) in the recovery phase after the 24 h-Post assessment; 6) during sleep, 2 nights after the REP; and 7) at 48 h-Post, during the V_1 -load and CMJ assessments.

Measurement equipment

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 only wearing underclothes. CMJ height was determined using an infrared timing system (Optojump, Microgate, Bolzano, Italy). A Smith machine with no counterweight mechanism (Multipower Fitness Line, Peroga, Murcia, Spain) was used for all testing and exercise sessions. A dynamic measurement system (T-Force System, Ergotech, Murcia, Spain) automatically calculated the relevant kinematics of every repetition, provided auditory and visual velocity feedback in real-time and stored data for analysis. This system consists of a linear velocity transducer interfaced to a computer by means of a 14-bit analog-to-digital acquisition board and custom software. Instantaneous velocity was sampled at 1000 Hz and smoothed with a 4th order low-pass Butterworth filter with no phase shift and 10 Hz cut-off frequency. Reliability of this system has been reported elsewhere [39]. All reported repetition velocities in this study correspond to the mean concentric velocity of the propulsive phase [41].

Measurement of consecutive R-R intervals was used as representative of the autonomic nervous system output. R-R intervals were collected using a heart rate (HR) recorder (Firstbeat Bodyguard, Firstbeat Technologies Ltd., Jyväskylä, Finland). This device attaches directly to cleaned skin with 2-lead Ag/AgCl

electrodes and starts recording data automatically. Subjects wore the recorder uninterruptedly from 24 h before to 48 h post-exercise. Noise and ectopic heart beats were identified and automatically eliminated by the acquisition software. Data were also inspected visually for possible artefacts. Analysis algorithms for LnrMSSD, SampEn and CI_{1-5} were implemented in Matlab 7.11 R2010b.

Statistical analyses

Values are reported as mean \pm standard deviation (SD). Statistical significance was established at $P < 0.05$. Differences between the 2 REP, 3 \times 8(8) vs. 3 \times 4(8), at Pre were assessed with a one-way analysis of variance (ANOVA). Homogeneity of variance across groups was verified using the *Levene's* test. The distribution of each variable was examined with the *Shapiro-Wilk* normality test. A factorial ANOVA with repeated measures with *Bonferroni* adjustment was used to examine the effects of the 2 REP across time on mechanical, biochemical and HRV responses. The *Greenhouse-Geisser* adjustment for sphericity was calculated. Linear regressions with *Pearson's* coefficients (r) and 90% confidence intervals (90% CI) were calculated to establish relationships between the changes induced by both REP combined in all measured variables. In addition to this null hypothesis testing, data were assessed for clinical significance using an approach based on the magnitudes of change [22]. The standardized differences between REP (ES, 90% CI) were calculated using the pooled SD. For between-REP comparison, the probabilities of *better* (i.e., greater than the smallest worthwhile change [$0.2 \times$ between subjects SD, based on the *Cohen's d* principle]), *similar*, or *worse* differences between the groups were calculated. Quantitative chances of *better* or *worse* effect were assessed qualitatively: <1%, almost certainly not; 1–5%, very unlikely; 5–25%, unlikely; 25–75%, possibly; 75–95%, likely; 95–99%, very likely; and >99%, almost certain [22]. If the chances of having *better* (faster) or *worse* (slower) recovery were both >5%, the true difference was assessed as unclear [22]. Magnitude of correlations was interpreted as described elsewhere [22]. Inferential statistics based on interpretation of magnitude of effects were calculated using a purpose-built spreadsheet for the analysis of controlled trials [21]. The rest of statistical analyses were performed using SPSS software version 18.0 (SPSS Inc., Chicago, IL).

Results

All variables were normally distributed and homoscedasticity across exercise protocols was verified. No significant differences between 3 \times 8(8) and 3 \times 4(8) were found at Pre for any of the variables analyzed.

Descriptive characteristics of the 3 \times 4(8) and 3 \times 8(8) REP

Characteristics of each REP are reported in **Table 1** in terms of repetitions performed per set (reps) and actual repetition velocities. In the 3 \times 4(8) REP subjects were able to complete all reps with the assigned load (total number of reps: 12.0 ± 0.0 both for BP and SQ), whereas during 3 \times 8(8) most of the subjects could not complete the 8 reps due to fatigue. Thus, the number of reps decreased for 3 \times 8(8) as sets progressed: 1st set 7.7 ± 1.0 , 2nd set: 7.4 ± 0.7 , 3rd set: 7.2 ± 1.4 reps (total number of reps: 22.3 ± 2.0) for SQ; and 1st set: 7.9 ± 0.3 , 2nd set: 7.7 ± 0.7 , 3rd set: 7.1 ± 1.2 reps (total number of reps: 22.7 ± 1.9) for BP. The fastest repetition did

Table 1 Descriptive characteristics of each resistance exercise protocol.

	Bench Press			Squat		
	3×4(8)	3×8(8)	P-value	3×4(8)	3×8(8)	P-value
Reps	4.0±0.0	7.6±0.6	<0.001	4.0±0.0	7.4±0.7	<0.001
Fastest-V (m·s ⁻¹)	0.49±0.01	0.47±0.03	0.07	0.70±0.04	0.70±0.03	0.54
Slowest-V (m·s ⁻¹)	0.35±0.04	0.16±0.04	<0.001	0.47±0.09	0.31±0.04	0.001
Mean-V (m·s ⁻¹)	0.44±0.03	0.34±0.03	<0.001	0.61±0.03	0.53±0.03	0.009
MeanLoss-V (%)	24.4±4.1	61.2±4.3	<0.001	23.1±8.3	44.5±5.1	<0.001
MaxLoss-V (%)	34.5±6.9	69.6±7.2	<0.001	36.6±9.8	57.7±4.8	<0.001

Data are mean±SD, n=9

Reps: repetitions performed in each set

Fastest-V: highest velocity measured in the 3 sets

Slowest-V: lowest velocity measured in the 3 sets

Mean-V: mean velocity of all repetitions during the 3 sets

MeanLoss-V: mean percent loss in velocity from the fastest to the slowest repetition over the 3 sets

MaxLoss-V: maximum percent loss in velocity from the fastest to the slowest repetition over the 3 sets

Velocities correspond to the mean concentric propulsive velocity of each repetition

P-value indicates the magnitude of the significance between the 2 resistance exercise protocols, 3×4(8) vs. 3×8(8)

Table 2 Comparison of changes in mechanical indicators of neuromuscular fatigue following each resistance exercise protocol.

	3×4(8)	3×8(8)	P-value	Changes observed for 3×4(8) vs. 3×8(8)	
				Standardized (Cohen) differences (90% CI)	Percent chances of better/similar/worse effect
BP V₁-load (%)					
Post	88.9±5.4	56.7±14.7	<0.001	2.91 (2.15 to 3.67)	100/0/0 Most likely
6h-Post	100.8±6.8	96.1±7.4	0.27	0.66 (-0.38 to 1.66)	78/14/8 Unclear
24h-Post	100.9±5.9	96.2±7.4	0.24	0.70 (-0.33 to 1.70)	80/13/7 Unclear
48h-Post	104.9±5.2	98.4±6.2	0.07	1.14 (0.13 to 2.14)	84/4/2 Likely
SQ V₁-load (%)					
Post	88.6±6.5	73.9±7.0	<0.001	2.18 (1.61 to 2.75)	100/0/0 Most likely
6h-Post	100.9±7.8	92.7±8.4	0.003	1.01 (0.56 to 1.46)	100/0/0 Most likely
24h-Post	98.8±5.8	95.5±5.4	0.26	0.59 (-0.32 to 1.50)	78/15/7 Unclear
48h-Post	102.1±7.6	100.8±5.8	0.61	0.19 (-0.48 to 0.86)	49/36/15 Unclear
CMJ (%)					
Post	78.0±4.1	67.5±5.7	0.003	8.16 (4.56 to 11.76)	100/0/0 Most likely
6h-Post	99.3±3.4	91.5±5.3	0.001	1.75 (1.10 to 2.40)	100/0/0 Most likely
24h-Post	99.5±3.9	93.9±5.9	0.04	1.12 (0.27 to 1.97)	96/3/1 Very likely
48h-Post	101.9±4.0	95.6±6.1	0.04	1.22 (0.29 to 2.13)	96/3/1 Very likely

Data are mean±SD, n=9

Values are expressed as percentage of initial (Pre) measures

BP: bench press; SQ: squat; CMJ: countermovement jump; V₁-load: velocity attained against the load that elicits a 1 m·s⁻¹ in the pre-exercise, post warm-up, condition. See text for details

P-value indicates the magnitude of the significance between the 2 resistance exercise protocols, 3×4(8) vs. 3×8(8), at the corresponding time point

not differ between REP in SQ or BP and matched the aforementioned expected target velocities corresponding to 80% 1RM. Mean velocity during the 3 sets was significantly lower for 3×8(8) vs. 3×4(8) in the SQ and BP, respectively (○ **Table 1**).

Mechanical measurements of fatigue

Relative loss of velocity within a set (mean of the 3 sets) was significantly higher for 3×8(8) compared to 3×4(8) for both exercises (○ **Table 1**). ○ **Table 2** shows the changes in the mechanical variables analyzed. Significant REP x time interactions ($P<0.05$) were observed for CMJ height and V₁-load both in BP and SQ. For V₁-load in the BP, comparisons between protocols showed that 3×8(8) resulted in a significantly greater performance impairment than 3×4(8) at Post and almost reached statistical significance at 48 h-Post ($P=0.07$). No significant differences were observed for this variable at 6 h-Post and 24 h-Post. Pairwise comparisons for V₁-load in the SQ revealed that 3×4(8) resulted in lower performance impairment than

3×8(8) at Post and 6 h-Post. These differences tended to disappear at 24 h-Post and 48 h-Post and a beneficial effect (i.e., faster recovery) of 3×4(8) over 3×8(8) was unclear (○ **Table 2**). Impairments in CMJ height were significantly higher for 3×8(8) vs. 3×4(8) at all post-exercise time points (Post, 6 h-Post, 24 h-Post and 48 h-Post; ○ **Table 2**).

Biochemical response

○ **Table 3** shows the biochemical markers analyzed. Significant REP x time interactions ($P<0.05$) were observed for CK, PRL and testosterone. At Post, 3×8(8) resulted in significantly greater PRL and IGF-1 concentrations than 3×4(8). At 48 h-Post, 3×4(8) resulted in significantly greater testosterone and cortisol levels than 3×8(8).

Analysis of the R-R interval time series

Due to missing data in one participant's HR recordings, the final sample size for the HRV and HRC analyses was 8 subjects. Sig-

Table 3 Blood concentration of the biochemical markers analyzed.

	Cortisol (nmol · L ⁻¹)			CK (UI · L ⁻¹)			GH (µg · L ⁻¹)		
	3 × 4(8)	3 × 8(8)	P-value	3 × 4(8)	3 × 8(8)	P-value	3 × 4(8)	3 × 8(8)	P-value
Pre	309.0 ± 55.2	284.2 ± 99.3	0.32	156.8 ± 86.5	139.6 ± 84.2	0.53	2.2 ± 4.7	1.0 ± 1.5	0.39
Post	240.0 ± 44.1 *	295.2 ± 113.1	0.15	226.9 ± 117.5	260.0 ± 134.0 **	0.14	1.6 ± 2.0	5.5 ± 8.0	0.12
48 h-Post	223.5 ± 41.4 *	168.3 ± 34.8 * * #	0.01	348.0 ± 177.6 *	398.9 ± 164.4 * * *	0.06	2.4 ± 2.0	3.1 ± 3.4	0.39
	IGF-1 (µg · L ⁻¹)			PRL (µg · L ⁻¹)			Testosterone (nmol · L ⁻¹)		
	3 × 4(8)	3 × 8(8)	P-value	3 × 4(8)	3 × 8(8)	P-value	3 × 4(8)	3 × 8(8)	P-value
Pre	284.7 ± 73.5	299.4 ± 73.6	0.45	12.7 ± 5.1	10.1 ± 2.8	0.06	22.2 ± 4.2	21.8 ± 5.2	0.82
Post	301.8 ± 78.2	352.6 ± 94.8	0.008	12.4 ± 3.6	20.5 ± 10.9 *	0.03	25.3 ± 8.7	22.5 ± 9.0	0.07
48 h-Post	280.8 ± 69.8	304.1 ± 32.8	0.13	10.6 ± 2.4	11.4 ± 2.7	0.43	24.3 ± 4.9	17.0 ± 6.6	0.002

Data are mean ± SD, n=9

P-value indicates the magnitude of the significance between the 2 resistance exercise protocols, 3 × 4(8) vs. 3 × 8(8), at the corresponding time point

Statistically significant differences with Pre at the corresponding time point: * P<0.05, ** P<0.01, *** P<0.001

Statistically significant differences with Post at the corresponding time point: # P<0.05

CK: creatine kinase; GH: growth hormone; IGF-1: insulin-like growth factor-1; PRL: prolactin

nificant REP × time interactions ($P < 0.05$) were observed for LnrMSSD and SampEn. 3 × 8(8) resulted in significantly lower LnrMSSD, SampEn and CI_{1-5} values than 3 × 4(8) during (2a) and immediately post-exercise (2b, **Fig. 2**). Furthermore, 3 × 8(8) resulted in significantly lower LnrMSSD and SampEn values than 3 × 4(8) in the recovery phase (2b and 2c temporal segments) following the REP session (**Fig. 2a, b**).

Relationship between variables

When data from the 2 REP were pooled, significant relationships were observed between mean percent velocity loss in SQ and relative loss of CMJ height at Post ($r = 0.78$), 6 h-Post ($r = 0.76$), 24 h-Post ($r = 0.67$) and 48 h-Post ($r = 0.61$). Mean velocity loss also showed significant correlations with the relative change in several hormonal and enzyme concentrations at Post (cortisol: $r = 0.55$, PRL: $r = 0.48$, and CK: $r = 0.51$), and at 48 h-Post (testosterone: $r = -0.70$ and CK: $r = 0.52$). Relative loss of CMJ height at 6 h-Post significantly correlated with the changes during the REP (2a temporal segment) in LnrMSSD ($r = -0.55$), SampEn ($r = -0.59$) and with the changes in CI_{1-5} at 2a ($r = -0.63$), 2b ($r = -0.60$) and 2c temporal segments ($r = -0.49$).

Changes in cortisol concentration at Post significantly correlated with changes in CI_{1-5} at 2a ($r = -0.52$, $P < 0.05$). Changes in GH at Post also correlated with the changes in SampEn ($r = -0.62$) and CI_{1-5} ($r = -0.64$) during the REP. Correlations between selected biochemical markers (testosterone, CK, PRL) and the measured HRV and HRC variables (LnrMSSD, SampEn, CI_{1-5}) are reported in **Fig. 3**. Individual changes in PRL at Post showed a significant correlation with the changes in LnrMSSD during the REP (2a) and the following recovery (temporal segments 2b and 2c) ($r = -0.55$, -0.69 and -0.63 , respectively). Changes in testosterone at Post correlated negatively with the changes observed in LnrMSSD during the REP (2a) and with SampEn and CI_{1-5} in almost all temporal segments analyzed during the following 48 h (**Fig. 3a**). Changes in testosterone concentration at 48 h-Post correlated with the changes in LnrMSSD during the previous night ($r = 0.49$). CK at 48 h-Post showed negative relationships with LnrMSSD during the REP (2a) and immediately Post (2b), and with SampEn and CI_{1-5} during the following 2 recovery temporal segments (**Fig. 3b**). PRL at 48 h-Post showed negative correlations with the changes in LnrMSSD at almost all temporal segments analyzed (**Fig. 3c**).

Discussion

The present study described the mechanical, biochemical and autonomic cardiovascular response to manipulating the 'level of effort' (actual number of repetitions performed in relation to the maximum possible number) in each resistance exercise set. The time course of recovery up to 48 h post-exercise following 2 distinct REP, 3 × 8(8) vs. 3 × 4(8), was compared. Taken together, our results suggest that 3 × 8(8) resulted in a higher autonomic cardiovascular and biochemical stress, as well as in greater fatigue and slower rate of neuromuscular recovery than 3 × 4(8). While it may seem obvious that halving the maximum possible number of repetitions per set induces greater fatigue, the important findings of this study are the implications this may have for the subsequent recovery. Recovery is when body structures and systems are repaired and rebuilt, and when actual adaptation occurs. Reducing to half the maximum number of repetitions per set allowed the attainment of faster mean training velocities (**Table 1**) and favored a quicker recovery in the hours following the exercise session, as suggested by the mechanical (**Table 2**), biochemical (**Table 3**) and autonomic cardiovascular (**Fig. 2**) variables. To our knowledge, this is the first study to examine the relationships existing between the autonomic cardiovascular response and changes in selected biochemical and neuromuscular performance measures following resistance exercise.

To ensure that the absolute load chosen for each REP closely corresponded to the level of effort that was intended, load was carefully adjusted from each subject's load-velocity relationship. Hence, we verified that the expected target velocities corresponding to 80% 1RM (~ 0.68 for SQ and ~ 0.47 m · s⁻¹ for BP) were met (**Table 1**). In agreement with previous research [14, 15, 35, 39], we observed that repetition velocity declined progressively during the sets in both REP. Mean velocity loss within each set was very different ($P < 0.001$) between protocols in both the SQ (23 vs. 45%) and BP (24 vs. 61%), for 3 × 4(8) vs. 3 × 8(8) respectively; values which are in line with those previously reported [39]. This resulted in a mechanical stimulus comprised of faster movement velocities for 3 × 4(8) compared to 3 × 8(8). As expected, fatigue from previous sets prevented subjects from performing all scheduled repetitions in subsequent sets in the 3 × 8(8) protocol. Furthermore, and since the 80% 1RM and 8RM loads do not necessarily constitute the same loads for every subject, a velocity-based approach provides very useful information about the real effort performed during an exercise

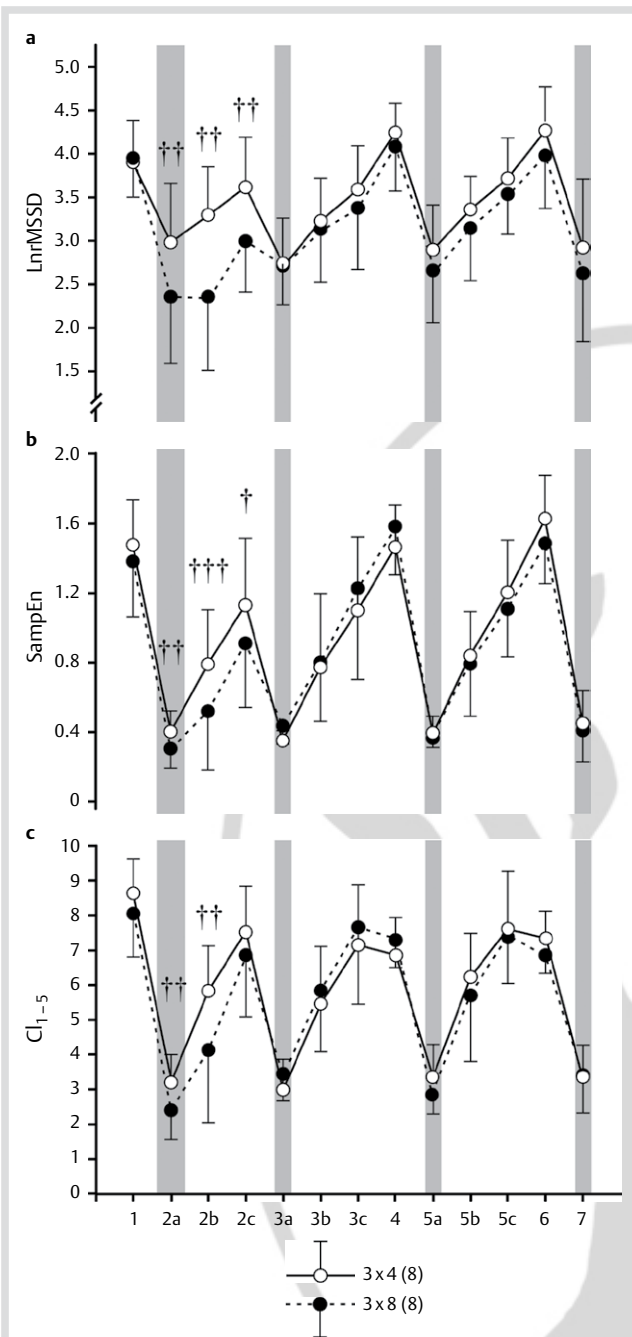


Fig. 2 Time course of the 3 autonomic cardiovascular variables analyzed. **a** Natural logarithm of the root mean square of differences in R-R intervals (LnRMSSD); **b** Sample Entropy (SampEn); **c** Complexity Index (CI_{1-5}). 13 temporal segments (1, 2a, 2b, 2c, 3a, 3b, 3c, 4, 5a, 5b, 5c, 6, 7) covering from 24 h pre- to 48 h post-exercise were established (see Methods for details). Vertical shaded areas indicate the segments corresponding to exercise. Statistically significant differences between $3 \times 4(8)$ and $3 \times 8(8)$ at the corresponding temporal segment: † $P < 0.05$, †† $P < 0.01$, ††† $P < 0.001$.

set [39]. Since the mean velocity attained during the last repetition of a set to failure and that attained with the 1RM are very similar [24], the velocity of the last completed repetition in a set indicates how many additional repetitions are left in reserve. Therefore, this study provides very accurate and complete information about the effort actually performed, as it can be observed in **Table 1**.

Reductions in the velocity attained against the V_1 -load in the SQ and BP were higher for $3 \times 8(8)$ vs. $3 \times 4(8)$ throughout the 48 h post-exercise recovery period (**Table 2**). It is worth noticing that, while the velocity against the V_1 -load in both BP and SQ was already recovered at 6 h-Post after $3 \times 4(8)$, initial neuromuscular performance was not fully restored until 48 h-Post following the $3 \times 8(8)$ protocol. These results are even more evident for jumping ability. Thus, CMJ height did not return to pre-exercise values at 48 h following $3 \times 8(8)$, whereas for $3 \times 4(8)$ initial CMJ performance was already recovered at 6 h-Post. This seems to indicate that the “explosiveness” or ability to rapidly develop force with the lower limbs may be considerably compromised up to 48 h following resistance exercise to failure. Likewise, the significant ($P < 0.01$ – 0.001) relationships observed between the changes in mean velocity loss in SQ and CMJ height seem to indicate that the fatigue incurred during the exercise sets, assessed through velocity loss, may determine physical performance up to 48 h-Post. Consequently, resistance exercise characterized by great reductions in repetition velocity, as it occurs in the typical, to failure, body-building routines, may considerably increase the amount of time needed for recovery, as previously suggested [14, 15, 39]. It is for these reasons that setting a certain percent velocity loss threshold during RT seems a plausible way to avoid performing unnecessarily slow and fatiguing repetitions that may not be contributing to the desired training effect. A velocity-based resistance training approach has been proposed as a novel, comprehensive and rational alternative to traditional RT [39].

Little is known about the hormonal response to manipulating the ‘level of effort’ during RT. In the present study, the $3 \times 8(8)$ protocol resulted in significantly greater IGF-1 levels at Post compared to $3 \times 4(8)$. Although not statistically significant, likely due to the limited sample size and large individual variations that usually exist in endocrine responses, post-exercise GH levels were higher for $3 \times 8(8)$ vs. $3 \times 4(8)$ (**Table 3**). Previous research [39] has shown that blood lactate and ammonia considerably increase as the number of repetitions in a set approaches muscle failure. This fact might explain the greater GH and IGF-1 concentrations observed for $3 \times 8(8)$ compared to $3 \times 4(8)$ in the present study, since exercise that induces marked increases in H^+ and lactate seems to mediate GH release from the pituitary gland [13], and GH is considered the principle stimulator of IGF-1 secretion by the liver [33]. Likewise, the $3 \times 8(8)$ protocol resulted in significantly greater increases than $3 \times 4(8)$ in PRL at Post. The acute PRL response to RT has been poorly studied. Similar to the present findings, PRL has been shown to increase following RT to failure [29]. Even though the physiological significance of PRL in response to exercise is unclear, the main functions of this hormone in response to stress seem to be associated with the maintenance of homeostasis [38]. The differing PRL response to the 2 REP analyzed in this study might be explained by the disruption of cellular homeostasis and state of energy deficiency [14] induced by exercising to muscle failure in the $3 \times 8(8)$ protocol. Similar to GH, PRL has also been shown to be influenced by lactate [32]. In this line, it has been reported that performing repetitions to failure causes a marked disruption to the muscle energy balance and an important depletion of muscle purines, whereas performing a half-maximum number of repetitions per set allows the maintenance of cellular homeostasis [14, 15, 39]. It has been well documented that the replenishment of the muscle adenine nucleotide pool is a time-consuming and slow process that may take up to several days to

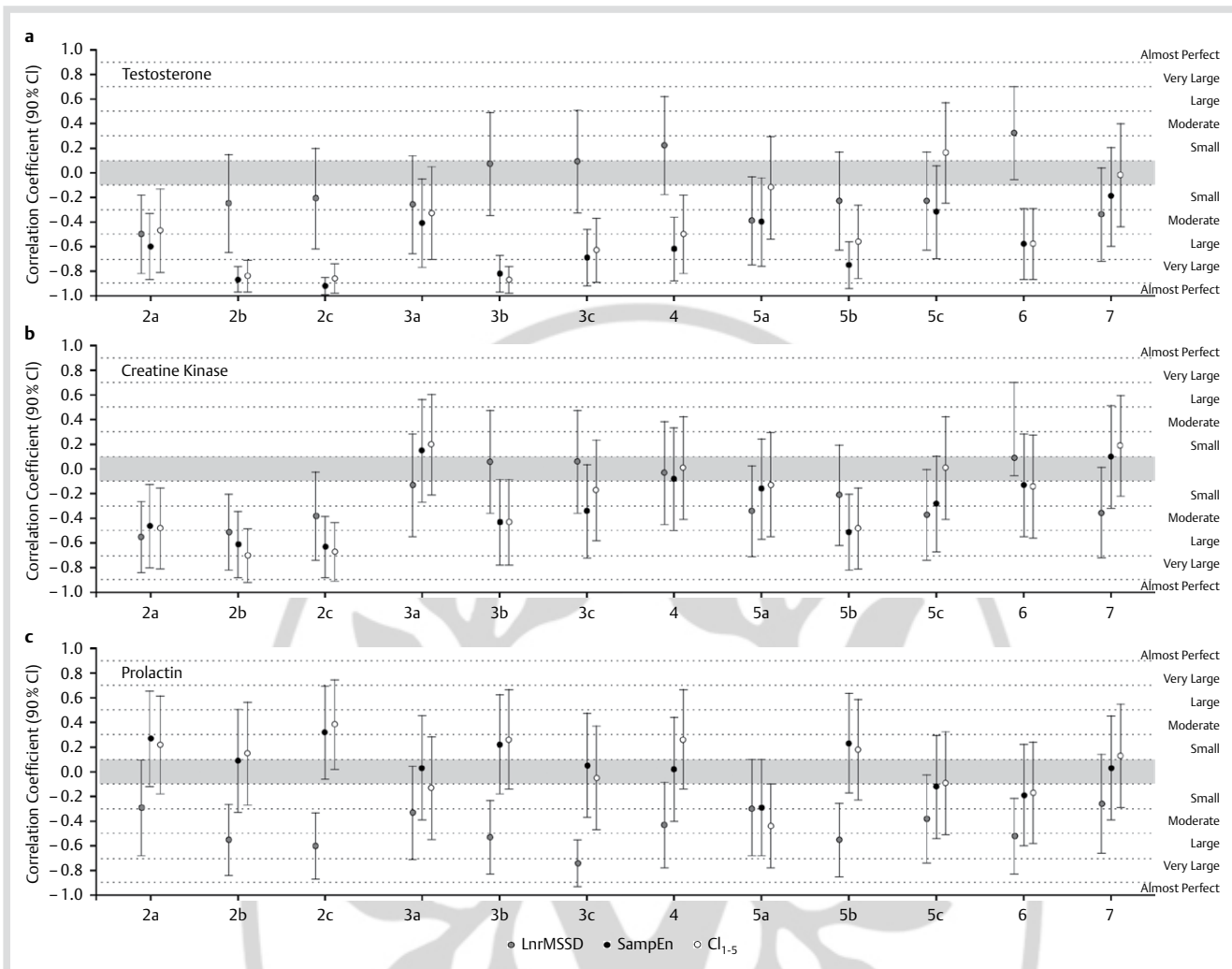


Fig. 3 Correlation coefficients (90% CI) describing the relationships between the changes in autonomic cardiovascular variables (LnrMSSD, SampEn and Cl_{1-5}) and the changes in the concentration of: **a** Testosterone at Post; **b** Creatin Kinase at 48 h-Post; and **c** Prolactin at 48 h-Post. Correlations were obtained from the combined data from both $3 \times 4(8)$ and $3 \times 8(8)$ resistance exercise protocols.

complete [44], thus increasing the recovery needs following exercise. These results are also in agreement with the greater CK levels observed for $3 \times 8(8)$ vs. $3 \times 4(8)$ at 48 h-Post (Table 2), since the elevation of plasma CK is considered evidence of skeletal muscle damage [3]. Interestingly, $3 \times 8(8)$ resulted in significantly lower testosterone and cortisol levels than $3 \times 4(8)$ at 48 h-Post. Reduced resting testosterone levels have been observed after RT leading to muscle failure, and have been suggested to be markers of overtraining [16,17]. In line with our findings, a similar decrease in the exercise-induced cortisol response was reported several days after extenuating bouts of resistance exercise [11,29]. These studies [11,29] also showed a reduction in post-exercise lactate and GH levels after high-volume fatiguing resistance exercise. This response has been attributed to an altered hypothalamic and/or hypophysis function [11]. In this regard, we observed a positive correlation between the changes in testosterone at 48 h-Post and the changes in LnrMSSD during the previous night ($r=0.49$, $P<0.05$). Thus, subjects with lower testosterone values at 48 h-Post, induced by the $3 \times 8(8)$ protocol, also showed lower HRV. Furthermore, the relationship observed between velocity loss and the changes in testosterone at 48 h-Post ($r=-0.70$) suggest that greater velocity loss during the set, like that induced by the $3 \times 8(8)$ protocol,

results in lower testosterone at 48 h-Post, even below resting levels. All these observations might reflect a temporal status of fatigue, sometimes termed overreaching [17]. It is well known that an imbalance between training and recovery can lead to overreaching and, eventually, to a more serious and dreaded condition known as the overtraining syndrome.

Repetition velocity loss showed significant correlations with the relative change in the biochemical response at Post (cortisol: $r=0.55$, PRL: $r=0.48$, and CK: $r=0.51$), and 48 h-Post (CK: $r=0.52$). In accordance with these results, a previous study [1] observed a significant relationship between the loss in maximum isometric force and the changes in cortisol following RT to muscle failure ($r=0.55$). Other study [39] also reported high correlations between velocity loss and metabolic (lactate, ammonia) measures of fatigue. All these findings suggest that monitoring repetition velocity during RT may serve as a non-invasive and objective measure to quantify the mechanical fatigue induced by resistance exercise, which seems to be related to the hormonal stress induced by the exercise.

Research investigating the effects of RT on HRV is still scarce [23,25,27,31]. A loss of information regarding cardiac autonomic fluctuations might happen if only linear methods are used, since a great deal of information in the HRV signal spectra

is not solely harmonic [5]. Thus, there is a growing body of literature aiming to analyze the acute effects of RT on HRC [19,20,23,25]. However, these studies have used only the SampEn measure to analyze the complexity of the R-R signal, an algorithm that quantifies the degree of irregularity of a time series on the shortest time scale but fails to quantify its information content on longer time scales [6]. In the present study, in addition to SampEn, the CI_{1-5} was calculated using the multiscale entropy method in order to quantify the degree of irregularity over a broader range of time scales. Moreover, few studies have compared the effect of different configurations of the resistance exercise stimulus on HRC response [23,26]. In the present study, both $3 \times 8(8)$ and $3 \times 4(8)$ protocols induced acute decreases in HRV and HRC following resistance exercise (shaded grey areas in **Fig. 2**). However, significantly lower HRV and HRC values were observed for $3 \times 8(8)$ compared to $3 \times 4(8)$ during and immediately post-exercise. It is suggested that factors like hydrogen ions and inorganic phosphate might play a role in the reduction of HRV [26]. In this regard, the high levels of blood lactate and ammonia, together with the significant depletion in PCr stores and the total adenine nucleotide pool reported during RT to failure [14,39] might explain the lower HRV and HRC observed for the $3 \times 8(8)$ REP. These results suggest that, in addition to a greater mechanical fatigue (**Table 2**) and hormonal response (**Table 3**), RT to muscle failure results in a greater reduction of HRV and HRC when compared to performing a half-maximum number of repetitions per set.

The stress associated with physical exercise induces a complex body's response by different systems, in particular the autonomic nervous system and the endocrine system, which act to restore the homeostasis [2]. Since both systems are connected through the hypothalamus [30], it would be expected an interconnection of mechanical, hormonal and cardiovascular autonomic variables in response to exercise. However, the possible relationships existing between mechanical and hormonal measures and HR-derived indices in response to RT remain largely unknown. In the present study, the relative loss of CMJ height at 6h-Post correlated negatively ($P < 0.05$) with the changes in HRV and HRC (LnMSSD, SampEn and CI_{1-5}) at Post and during the subsequent recovery (2a, 2b and 2c temporal segments). These findings indicate that subjects experiencing greater CMJ height loss at 6h post-exercise are the ones who showed greater reductions in HRV and HRC during the recovery from resistance exercise. The correlations between individual changes in performance and HRV could be the result of a complex interaction between neural and humoral regulatory mechanisms [2]. Moreover, changes in HRV and HRC measures showed negative relationships with the concentration of several hormones at Post (GH, cortisol, PRL and testosterone) and with CK at 48h-Post. As explained above, decreases of pH produced by hydrogen ions might have an influence on HRV [26]. Furthermore, the accumulation of hydrogen ions produced by an increase in lactate concentration has been postulated as a trigger mechanism of the main stress-related hormones, such as GH, cortisol, PRL and testosterone [1, 13, 29, 38]. From our findings demonstrating a relationship between several hormones and HRV, it is plausible to hypothesize that an increased muscle acidity induced by resistance exercise would stimulate metaboreceptors that would send feedback to the central nervous system and hypothalamus leading to a modulation of the endocrine and autonomic cardiac systems.

In conclusion, the findings of the present study suggest that when the number of repetitions per set is halved in relation to the maximum (to failure) number that can be completed: 1) a stimulus comprised of faster mean repetition velocities is performed; 2) a lower impairment of neuromuscular performance and faster post-exercise recovery is achieved; 3) a reduced hormonal response and muscle damage are experienced; and 4) a lower reduction in HR variability and complexity is observed following exercise. Furthermore, the relationships observed between the HR-derived indices, the mechanical indicators of fatigue and the changes in several hormonal concentrations show a complex response from the neuromuscular, endocrine and autonomic cardiovascular systems to the stress induced by RT. A question that remains, and one that must be addressed by future experimental research, is whether reducing to half the number of repetitions performed in each exercise set is enough stimulus to obtain the strength gains and neuromuscular adaptations required to enhance athletic performance.

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