Time Course of Recovery From Resistance Exercise With Different Set Configurations

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Abstract

Pareja-Blanco, F, Rodríguez-Rosell, D, Aagaard, P, Sánchez-Medina, L, Ribas-Serna, J, Mora-Custodio, R, Otero-Esquina, C, Yáñez-García, JM, and González-Badillo, JJ. Time course of recovery from resistance exercise with different set configurations. *J Strength Cond Res* 34(10): 2867–2876, 2020—This study analyzed the response to 10 resistance exercise protocols differing in the number of repetitions performed in each set (R) with respect to the maximum predicted number (P). Ten males performed 10 protocols (R(P): 6(12), 12(12), 5(10), 10(10), 4(8), 8(8), 3(6), 6(6), 2(4), and 4(4)). Three sets with 5-minute interset rests were performed in each protocol in bench press and squat. Mechanical muscle function (countermovement jump height and velocity against a 1 $m \cdot s^{-1}$ load, V_1-load) and biochemical plasma profile (testosterone, cortisol, growth hormone, prolactin, IGF-1, and creatine kinase) were assessed at several time points from 24-hour pre-exercise to 48-hour post-exercise. Protocols to failure, especially those in which the number of repetitions performed was high, resulted in larger reductions in mechanical muscle function, which remained reduced up to 48-hour post-exercise. Protocols to failure also showed greater increments in plasma growth hormone, IGF-1, prolactin, and creatine kinase concentrations. In conclusion, resistance exercise to failure resulted in greater fatigue accumulation and slower rates of neuromuscular recovery, as well as higher hormonal responses and greater muscle damage, especially when the maximal number of repetitions in the set was high.

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Introduction

Designing a resistance training (RT) program is a complex process, which has traditionally been considered more of an art than a scientific task. The manipulation of various RT variables (exercise type and order, loading, number of repetitions and sets, rest durations, and movement velocity) determines the acute responses of the neural, endocrine, and musculoskeletal systems, which have pivotal influences on the magnitude of long-term training adaptation (1). The actual number of repetitions performed in a set compared with maximum number that can be completed (i.e., proximity to muscle failure) may be a critical variable determining the adaptations to strength training (21). A close relationship has been observed between the percentage of velocity loss incurred in a set and the percentage of completed repetitions with respect to the maximum number of repetitions that can be performed ($R^2 \sim 0.96$) (7), allows for determination of the percentage of the maximum possible number of repetitions that have been completed from the velocity loss incurred in the set (7). In the squat exercise, a velocity loss of 40–50% in the set means that the set has been conducted to, or very close to, muscle failure, whereas a velocity loss of 20% means that it has been performed using ~50% of the possible repetitions (5,20,25). Pareja-Blanco et al. (21) recently compared the effects of 2 squat training programs that only differed in the magnitude of repetition velocity loss reached in each set: 20% vs. 40%. It was found that although a 40% velocity loss (close to muscle failure) could maximize the hypertrophic response, it also resulted in a fast-to-slow shift in muscle phenotype, whereas a velocity loss of 20% (which corresponded to performing approximately half the possible number of repetitions per set) prevented this reduction in the

fastest IIX fiber-type pool and resulted in similar or even superior strength gains, especially in high-velocity actions such as the vertical jump.

Traditionally, it has been hypothesized that training to failure elicits greater hypertrophic adaptations because of greater mechanical tension, metabolic stress, secretion of growth-promoting hormones, and muscle damage (4,28). It is suggested that acute hormonal elevations increase the likelihood of interaction with receptors (2), which is likely to have relevance for tissue growth and remodeling (13). The greater mechanical and metabolic stress induced when RT is performed to failure (25) may evoke elevated secretion of growth-promoting hormones (testosterone, growth hormone [GH], and insulin-like growth factor [IGF-1]) and catabolic hormones (cortisol). However, few data exist on the hormonal response to different repetition schemes leading to muscular failure vs. not leading to contraction failure. This knowledge along with the assessment of selected indicators of muscle damage (creatine kinase [CK]) may explain the different magnitudes of hypertrophic adaptations observed in response to different RT schedules. However, performing repetitions to failure causes a decrease in intramuscular adenosine triphosphate (ATP) and phosphocreatine (PCr) concentrations (9), as well as increases in blood ammonia that could indicate an accelerated purine nucleotide degradation (9,25), suggesting that the recovery course is increased as the repetition number approaches failure. In fact, previous studies have shown reductions in the ability to rapidly apply force for up to 48 hours after resistance exercise to failure against 70 and 80% of 1 repetition maximum (1RM), which could negatively interfere with other components of training (5,17,20).

In light of these considerations, a more detailed knowledge of the time course of recovery from the most widely used RT intensities leading either to failure or not to failure will enable strength and conditioning coaches as well as sport scientists, to objectively establish the time of recovery that will allow athletes to attain greater neuromuscular performance in an upcoming competition event or the next workout. Inadequate recovery after training results in fatigue or underperformance. Therefore, the aim of this study was to analyze the time course of recovery following 10 resistance exercise protocols differing in terms of loading magnitude (70, 75, 80, 85, and 90% of estimated 1RM) and the number of repetitions left in reserve in the set (to failure vs. half-maximal number of repetitions per set) in the fundamental RT exercises of bench press (BP) and full squat (SQ). Several assessment time points up to 48 hours after exercise were established to evaluate the mechanical and hormonal response, along with muscle damage in an acute protocol in an attempt to advance our understanding of the overall recovery status after RT.

Methods

Experimental Approach to the Problem

Over a period of 20 weeks, 10 distinct protocols were conducted, which differed in the number of repetitions (R) actually performed in each set regarding the maximum predicted number of repetitions (P) (R(P): 12(12), 6(12), 10(10), 5(10), 8(8), 4(8), 6(6), 3(6), 4(4), and 2(4)). These protocols thus differed in loading magnitude (70, 75, 80, 85, and 90% of estimated 1RM) and the number of repetitions left in reserve (to failure vs. half-maximal number of repetitions per set). The same number of exercise sets (3) and interset rests (5 minutes) were used in all protocols. In the half-maximal repetition protocols, subjects were able to complete all repetitions per set with the assigned load, whereas during protocols to failure, most of the subjects could not complete the scheduled repetitions because of fatigue (Table 1). These protocols were composed of the BP followed by the SQ, with a 10-minute rest between exercises. This order was chosen to avoid the higher metabolic stress associated with the SQ exercise (greater amount of muscle mass involved) compared with the BP (25) potentially negatively influencing performance in the latter exercise. All these protocols were conducted 14 days apart in separate trials in a randomized order. This study was part of a larger research project, and parts of the data related to the 12(12), 6(12), 8(8), and 4(8) protocols have been published previously (5,20).

To have a reference about the actual 1RM and their respective relative loads, an initial strength assessment was performed 1 week before the first trial. However, daily changes in the actual 1RM may evoke that the current 1RM may not correspond with that measured on previous days or weeks. In an attempt to solve this, a velocity-based approach was used, which allows us to determine, in real time, whether the proposed load (kg) for a given training session actually represents the effort (%1RM) that was intended (6,26). Therefore, relative loads for each protocol were determined from the load-velocity relationship because it has been shown that there is a very close relationship between %1RM and velocity ($R^2 = 0.95–0.98$) in both BP and SQ exercises (6,26). This allows for making adjustments to the training load at any time, resulting in better individualized training. In this regard, the warm-up period of the training session can serve to check whether or not the athlete is lifting the loads at the expected velocities, making the appropriate changes accordingly (increasing or decreasing the absolute loads to be used in that session).

To compare the mechanical and biochemical responses, as well as the time course of recovery following each protocol analyzed, subjects underwent a battery of measurements at different time points: pre-exercise (Pre), post-exercise (Post), 6 hours-Post, 24 hours-Post, and 48 hours-Post. Vertical countermovement jump (CMJ) height and the individual absolute load (kg) that elicited a 1 $m \cdot s^{-1}$ mean propulsive velocity (V_1-load) were measured at Pre. Then, CMJ height and velocity attained against that same absolute load were measured again at the different time points (Figure 1). These mechanical measurements have been described in detail elsewhere (5,20). The V_1-load was chosen because it

Table 1. Descriptive characteristics of each resistance exercise protocol.*†‡

Protocols	Reps	Fastest-V ($m \cdot s^{-1}$)	Slowest-V ($m \cdot s^{-1}$)	Mean-V ($m \cdot s^{-1}$)	MeanLoss-V (%)
BP					
12(12)	10.3 ± 1.2	0.63 ± 0.04	0.15 ± 0.05	0.42 ± 0.05	64.1 ± 5.1
10(10)	9.0 ± 1.3	0.58 ± 0.03	0.18 ± 0.06	0.40 ± 0.04	60.0 ± 9.2
8(8)	7.6 ± 0.6	0.50 ± 0.04	0.16 ± 0.03	0.36 ± 0.03	58.6 ± 5.0
6(6)	5.6 ± 0.5	0.46 ± 0.04	0.17 ± 0.04	0.33 ± 0.03	53.0 ± 9.0
4(4)	3.9 ± 0.2	0.35 ± 0.03	0.15 ± 0.04	0.28 ± 0.03	46.9 ± 9.7
6(12)	6.0 ± 0.0	0.65 ± 0.03	0.44 ± 0.05	0.56 ± 0.03	26.1 ± 7.0
5(10)	5.0 ± 0.0	0.59 ± 0.03	0.37 ± 0.05	0.47 ± 0.02	30.6 ± 7.3
4(8)	4.0 ± 0.0	0.50 ± 0.01	0.33 ± 0.04	0.43 ± 0.03	24.5 ± 4.3
3(6)	3.0 ± 0.0	0.44 ± 0.03	0.29 ± 0.04	0.38 ± 0.03	26.2 ± 8.9
2(4)	2.0 ± 0.0	0.34 ± 0.02	0.26 ± 0.03	0.32 ± 0.03	17.7 ± 4.8
SQ					
12(12)	11.1 ± 0.9	0.83 ± 0.03	0.37 ± 0.06	0.63 ± 0.05	45.2 ± 5.5
10(10)	9.7 ± 0.7	0.78 ± 0.04	0.39 ± 0.08	0.60 ± 0.04	43.0 ± 6.3
8(8)	7.4 ± 0.7	0.70 ± 0.04	0.31 ± 0.04	0.55 ± 0.03	44.1 ± 5.3
6(6)	5.9 ± 0.2	0.61 ± 0.04	0.38 ± 0.08	0.51 ± 0.04	36.0 ± 7.7
4(4)	3.7 ± 0.4	0.53 ± 0.03	0.32 ± 0.06	0.45 ± 0.04	34.7 ± 8.8
6(12)	6.0 ± 0.0	0.84 ± 0.03	0.63 ± 0.07	0.75 ± 0.04	20.4 ± 6.5
5(10)	5.0 ± 0.0	0.77 ± 0.03	0.60 ± 0.05	0.70 ± 0.04	17.0 ± 5.3
4(8)	4.0 ± 0.0	0.71 ± 0.04	0.49 ± 0.08	0.62 ± 0.04	22.7 ± 6.9
3(6)	3.0 ± 0.0	0.62 ± 0.04	0.46 ± 0.06	0.56 ± 0.03	18.1 ± 3.1
2(4)	2.0 ± 0.0	0.54 ± 0.02	0.42 ± 0.08	0.50 ± 0.04	17.1 ± 7.3

*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; BP = bench press; SQ = full squat.
†Data are mean ± *SD*, $n = 10$.
‡Velocities correspond to the mean concentric propulsive velocity of each repetition.

represents a sufficiently moderate loading intensity (~47% 1RM in BP and ~60% 1RM in SQ) (6,26), that allows for ready detection of the effect of fatigue on movement velocity, in addition to being possible to lift (following protocols to failure) and quick to establish as part of the warm-up (25). Blood sampling for the determination of testosterone, cortisol, GH, prolactin (PRL), IGF-1, and CK concentrations was performed at Pre, Post, and 48 hours-Post (Figure 1).

During their involvement in this study, the participants did not perform any other RT besides some abdominal and lower back strengthening exercises. Participants refrained from any strenuous physical activity for at least 4 days before each trial. All protocols were performed at the same time of the 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. Attention was paid to ensure that proper exercise lifting techniques were used, and detailed instruction was provided for the specific testing procedures.

Subjects

Ten men (age 22.1 ± 3.5 years [range 18–27 years], height 1.75 ± 0.07 m, and body mass 73.5 ± 10.7 kg) volunteered to participate in this study. Values are reported as mean ± *SD*. Subjects were physically active sports science students with RT experience ranging from 2 to 4 years, but they were not strength-trained athletes. Their 1RM strength was 101.7 ± 14.4 kg for SQ and 88.4 ± 19.0 kg for BP. After being informed about the experimental procedures and the potential risks of the investigation, the subjects gave their written informed consent to participate. No physical limitations, health problems, or musculoskeletal injuries that could affect testing were found after a medical examination. None of the participants were using drugs, medications, or dietary supplements known to influence physical performance. The present investigation was approved by the Research Ethics Committee of Pablo de Olavide University.

Procedures

Testing Procedures. A Smith machine with no counterweight mechanism (Multipower Fitness Line; Peroga, Murcia, Spain) was used for all sessions. The BP was performed imposing a momentary pause (~1.5 seconds) at the chest between the eccentric and concentric actions to minimize the contribution of the rebound effect and allow for more reproducible measurements (19). The SQ was performed with subjects starting from the upright position with the knees and hips fully extended, feet approximately shoulder-width apart, and the barbell resting across the back

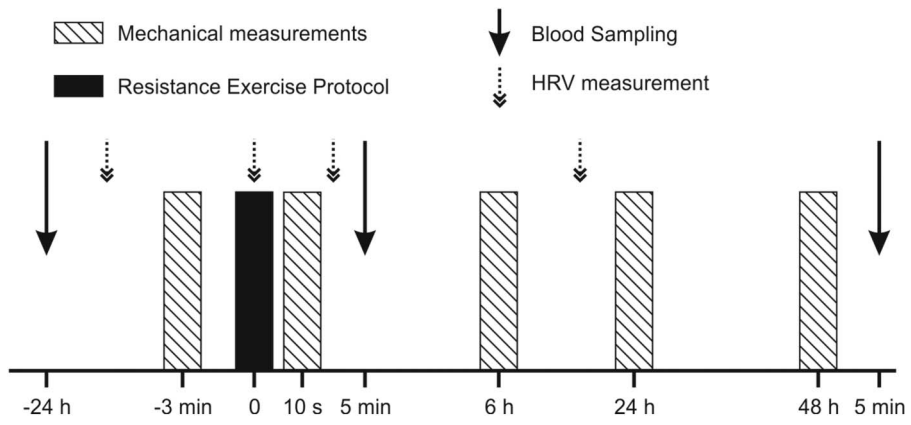

Figure 1. Mechanical measurements and blood collection at different time points to analyze responses following the 10 different resistance exercise protocols. HRV = heart rate variability.

at level of the acromion. Each subject descended at a controlled pace (0.40–0.70 $m \cdot s^{-1}$) until the tops of the thighs were 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 at maximal intended velocity. This execution technique was carefully reproduced in all protocols performed in the study. All barbell repetitions were recorded with a linear velocity transducer (T-Force System; Ergotech, Murcia, Spain). Instantaneous velocity was sampled at 1,000 Hz and smoothed using a fourth-order low-pass Butterworth filter with no phase shift and a 10-Hz cutoff frequency. The system's software automatically calculated the relevant kinematics of every repetition, provided auditory and visual velocity feedback in real time and stored data on disk for analysis. The reliability of this set-up has been documented elsewhere (25). During the final phase of the concentric phase, if the absolute movement velocity is high, the force applied by the athlete (F) against the external load of mass is negative, for braking the movement at the end of this phase. Thus, the concentric portion of a lift can be further subdivided into a "propulsive" ($F > 0$) and a "braking" ($F < 0$) phase (12). The velocity measures obtained in this study correspond to the mean velocity of the propulsive phase (MPV) of each repetition (27).

Resistance Exercise Protocol. All protocols were performed in the morning (10 AM) and always began with BP followed by SQ. Subjects warmed up for the BP by performing 3 minutes of upper-body joint mobilization exercises and 2 sets of 8 repetitions with a 20-kg barbell. A 10-minute rest period was established between BP and SQ exercises. After this rest period, subjects started the warm-up for the SQ, which consisted of: (a) 5-minute jogging at a self-selected easy pace, (b) two 30-m running accelerations, (c) 2 sets of 10 squats with no external load (i.e., own body mass), and (d) 5 CMJs with increasing intensity. Then, 3 maximal CMJs separated by 20-second rest periods were performed and the mean jump height taken as the pre-exercise reference value. Jump height was determined using an infrared timing system (Optojump; Microgate, Bolzano, Italy). To quantify the extent of neuromuscular fatigue induced by each protocol, both in BP and SQ, we 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-load) in a nonfatigued state, as described elsewhere (25). For the determination of the V_1-load in both BP and SQ, 3 sets of 6 down to 3 repetitions (2-minute interset rests) with increasing loads up to each subject's V_1-load were performed. The mean velocity of the 3 maximal intended repetitions with the V_1-load was registered as the pre-exercise reference value for this variable, determined with a precision of ± 0.04 $m \cdot s^{-1}$. Finally, the external load was progressively increased (in 2–3 sets of 3 repetitions each) up to the intensity scheduled for each protocol. Relative loads were determined from the load-velocity relationship because it has recently been shown that there is a very close relationship ($R^2 = 0.95$–0.98) between %1RM and MPV (6,26). Thus, the absolute load (kg) was individually adjusted to match the velocity associated (± 0.04 $m \cdot s^{-1}$) with the %1RM intended for the specific session, as follows: 0.62 and 0.84 $m \cdot s^{-1}$ for BP and SQ, respectively (70% 1RM ~ 12RM), 0.55 and 0.76 $m \cdot s^{-1}$ for BP and SQ (75% 1RM ~ 10RM), 0.47 and 0.68 $m \cdot s^{-1}$ for BP and SQ (80% 1RM ~ 8RM), 0.40 and 0.59 $m \cdot s^{-1}$ for BP and SQ (85% 1RM ~ 6RM), and 0.32 and 0.51 $m \cdot s^{-1}$ for BP and SQ (90% 1RM ~ 4RM). Subsequently, 3 sets separated by 5-minute rest were performed using the designated load. Immediately after completing the final repetition of the third set (the load was changed in 10–15 seconds with the help of trained spotters), subjects again performed 3 repetitions with

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

Protocols	Post	6 h-Post	24 h-Post	48 h-Post
BP V_1-load (%)				
12(12)	55.4 ± 13.2‡	92.9 ± 5.1§	94.5 ± 6.4	95.8 ± 4.6
10(10)	57.8 ± 12.9‡	91.7 ± 13.4	93.5 ± 7.3	98.2 ± 8.9
8(8)	56.7 ± 14.7‡	96.1 ± 7.4	96.2 ± 7.4	98.4 ± 6.2
6(6)	69.5 ± 8.7‡	95.8 ± 6.2	94.4 ± 7.6	97.2 ± 3.3
4(4)	80.5 ± 8.5‡‖¶	95.5 ± 7.4	95.7 ± 4.7	101.6 ± 5.0
6(12)	85.7 ± 6.5#‖¶**	101.4 ± 5.8	101.2 ± 5.6	102.4 ± 7.3
5(10)	86.5 ± 6.3#‖¶**††	101.4 ± 5.1	102.0 ± 4.7	100.8 ± 3.7
4(8)	88.9 ± 5.4#‖¶**††	100.8 ± 6.8	100.9 ± 5.9	104.9 ± 5.2
3(6)	87.8 ± 5.4#‖¶**††	98.6 ± 5.5	98.5 ± 5.4	102.2 ± 7.6
2(4)	94.7 ± 6.5‖¶**††	98.6 ± 4.2	100.9 ± 5.9	103.1 ± 6.9
SQ V_1-load (%)				
12(12)	70.0 ± 8.9‡	96.2 ± 9.0	93.7 ± 7.3	97.3 ± 6.6
10(10)	77.8 ± 7.0‡	95.9 ± 3.9	92.0 ± 2.6‡	96.8 ± 4.0
8(8)	73.9 ± 6.6‡	92.7 ± 7.9	95.5 ± 5.1	100.8 ± 5.5
6(6)	87.7 ± 10.6§‖	94.7 ± 5.0	93.3 ± 4.0§	98.5 ± 3.0
4(4)	80.2 ± 9.0#	98.3 ± 4.2	97.6 ± 4.3	101.1 ± 4.2
6(12)	86.3 ± 7.4‡¶	101.3 ± 3.6	100.4 ± 5.2	99.2 ± 7.3
5(10)	91.0 ± 3.9‡‖¶	97.2 ± 4.5	94.7 ± 3.4§	96.5 ± 4.1
4(8)	88.6 ± 6.5#‖¶	100.9 ± 7.8	98.8 ± 5.5	102.1 ± 7.6
3(6)	93.9 ± 6.7‖¶**	97.3 ± 4.1	101.5 ± 7.3	103.8 ± 5.8
2(4)	89.1 ± 4.9‡‖¶	97.8 ± 8.9	96.2 ± 3.5	100.1 ± 6.1
CMJ (%)				
12(12)	68.1 ± 11.2‡	92.9 ± 4.6#	92.8 ± 5.3§	95.7 ± 5.0
10(10)	68.8 ± 7.3‡	91.8 ± 6.4§	91.4 ± 3.9#	96.0 ± 4.5
8(8)	67.5 ± 5.3‡	91.5 ± 5.0#	93.9 ± 4.6§	95.6 ± 5.8
6(6)	75.1 ± 6.2‡	91.0 ± 7.7§	93.8 ± 2.2‡	96.3 ± 3.8
4(4)	76.7 ± 2.9‡	96.5 ± 4.2	95.6 ± 2.9#	101.6 ± 3.7
6(12)	78.5 ± 3.9‡¶	99.5 ± 3.3¶††	98.3 ± 3.4	101.6 ± 3.2
5(10)	78.6 ± 3.5‡	99.4 ± 2.9**	99.3 ± 3.0	101.5 ± 1.7
4(8)	78.0 ± 3.9‡	99.3 ± 3.2¶††	99.5 ± 3.9	101.9 ± 3.7
3(6)	79.7 ± 3.6‡¶	97.1 ± 2.8	96.9 ± 4.1	99.5 ± 3.1
2(4)	79.8 ± 3.4‡	95.6 ± 3.2§	95.5 ± 4.0	99.3 ± 2.4

*BP = bench press; V_1-load = velocity attained against the load that elicits a 1 $m \cdot s^{-1}$ in the pre-exercise, post warm-up condition; SQ = full squat; CMJ = countermovement jump.
†Data are mean ± *SD*, $n = 10$. Values are expressed as percentage of initial (Pre) measures.
‡Statistically significant differences with Pre at the corresponding time point: $p < 0.001$.
§Statistically significant differences with Pre at the corresponding time point: $p < 0.05$.
‖Indicates significant differences ($p < 0.05$) with 12(12) protocol, at the corresponding time point.
¶Indicates significant differences ($p < 0.05$) with 8(8) protocol, at the corresponding time point.
#Statistically significant differences with Pre at the corresponding time point: $p < 0.01$.
**Indicates significant differences ($p < 0.05$) with 10(10) protocol, at the corresponding time point.
††Indicates significant differences ($p < 0.05$) with 6(6) protocol, at the corresponding time point.

the V_1-load. Furthermore, after the SQ exercise, another 3 maximal CMJs, separated by 20-second rests, were performed. The V_1-load and CMJ mean values were obtained as acute post-exercise measures. Strong verbal encouragement and velocity feedback were provided in each repetition throughout all exercise sets.

At 4 PM in the evening (6 hours-Post), and at 10 AM on the following 2 days (24 hours-Post and 48 hours-Post), the V_1-load and CMJ measurements were repeated, as described above, to assess the time course of recovery following each specific protocol (Figure 1).

Mechanical Measurements of Fatigue. Three different methods were used to quantify the extent of fatigue induced by each protocol (25). 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

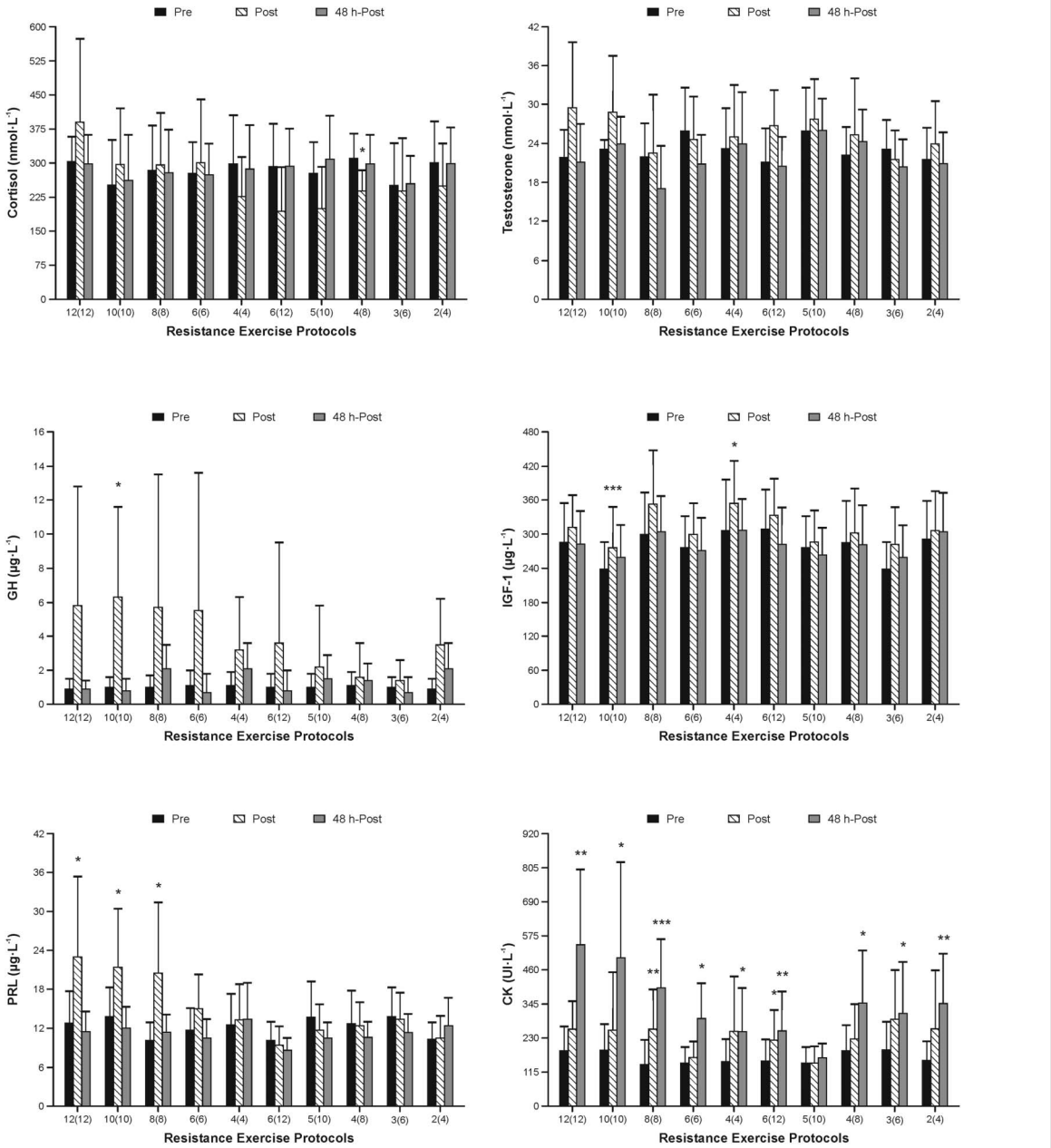

Figure 2. Blood concentration of the biochemical markers analyzed. Data are mean ± *SD*, $n = 10$. Pre = Pre-exercise value; Post = 5 minutes after exercise value; 48 h-Post = 48 hours after exercise value; GH = growth hormone; IGF-1 = insulin-like growth factor-1; PRL = prolactin; CK = creatine kinase. Statistically significant differences from Pre: *$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$.

averaged over the 3 sets. The second method examined the pre-to-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 hours before (Pre), 5 minutes after completion of the corresponding protocol (Post), and 48 hours-Post. Subjects rested seated for 30 minutes before pre-exercise 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 the day (±15 minutes) at the end of each protocol (11:30 AM) to minimize any bias in hormonal values because of circadian rhythms. Whole blood was centrifuged at 3,000 rpm (4° C) for 15 minutes, 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 (Elecsys 2010 autoanalyzer; Roche Diagnostics, Indianapolis, IN, USA). IGF-1 was measured by chemiluminescent immunometric assay (Immulite 2000 System; Siemens, Los Angeles, CA, USA). For testosterone, cortisol, GH, PRL, IGF-1, and CK assay sensitivities were 0.087, 8.5 nmol·L^{-1}, 0.03, 20, 0.047 μg·L^{-1}, and 45 IU·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 because it has been previously demonstrated that receptors in target tissues are exposed to serum levels of hormone (24).

Statistical Analyses

Values are reported as mean ± *SD*. All statistical analyses were performed using Statistical Package for the Social Sciences (SPSS) version 22 (IBM Corp., Armonk, NY, USA). At Pre, all data were normally distributed as determined by the Shapiro-Wilk test of normality. A factorial analysis of variance with repeated measures (protocol × time) was used to determine the statistical significance of our findings. Bonferroni post hoc analysis was performed when a significant interaction ($p \leq 0.05$) was observed. In the case of violation of the assumption of sphericity (Mauchly's sphericity test), significance was established using the Greenhouse-Geisser procedure.

Results

Descriptive Characteristics of the Resistance Exercise Protocols

The characteristics of each protocol are reported in Table 1 in terms of repetitions performed per set (reps) and actual repetition velocities. The fastest repetition did not differ from the expected target velocities corresponding to each %1RM. The mean velocity (the average of all repetitions performed during the 3 sets, Mean-V) and the lowest velocity measured in the 3 sets (Slowest-V) were lower when repetitions were performed to failure vs. half-maximal repetitions for each % 1RM (Table 1). The mean loss in repetition velocity (MeanLoss-V) was higher when the number of performed repetitions in the set was high (i.e., approaching muscle failure) and especially in those protocols that involved a high number of maximum repetitions, which occurred both in BP and SQ (Table 1).

Time Course of Mechanical Variables

Corresponding changes were observed for the loss in velocity pre-to-post exercise with the V_1-load (both in BP and SQ) and the decrease in CMJ height pre-post exercise (Table 2). Significant protocol × time interactions were observed for V_1-load in BP, V_1-load in SQ, and CMJ height. Several of the protocols performed until failure showed persisting impairments at the 24 hours-Post exercise time point compared with baseline values in velocity against V_1-load in SQ and CMJ height (Table 2).

Biochemical Response

Initial hormonal concentrations were within the normal range for physically active young men. Significant protocol × time interactions were observed for cortisol, testosterone, GH, PRL, and CK ($p < 0.05$). Only IGF-1 did not show significant protocol × time interactions. No significant increment was observed for cortisol concentration after exercise in any protocols. On the contrary, cortisol was significantly lower ($p < 0.05$) for 4(8) protocol with respect to baseline values. No changes were observed for testosterone concentration after exercise in any protocols (Figure 2). Growth hormone concentration after exercise increased ($p < 0.05$) in the 10(10) protocol. IGF-1 also showed significant enhancement ($p < 0.05$) following protocols to failure (10(10) and 4(4)), whereas for the nonexhausting protocols no changes were observed (Figure 2). Prolactin concentration increased ($p < 0.05$) after exercise when high-volume protocols were performed until failure (12(12), 10(10), and 8(8)), whereas remaining statistically unchanged in all protocols that were not performed to contraction failure (Figure 2). Creatine kinase increased significantly ($p < 0.05$) at 48 hours-Post in comparison with Pre-values for all protocols except for 5(10). The protocols to failure with greater numbers of repetitions (12(12), 10(10), and 8(8)) attained the greatest CK concentrations (>400 UI·L^{-1}).

Discussion

This study analyzed the mechanical and biochemical responses to manipulating the actual number of repetitions performed in each set relative to the maximum possible number that could be completed, using a velocity-based approach to RT, against a wide range of loading intensities (from 70 to 90% of 1RM). One strength of this study was that by monitoring repetition velocity and adjusting the actual loads to be lifted based on the load-velocity relationship (6,26), we made sure that all participants used a very similar relative load (%1RM) in each session (Table 1). Taken together, our results suggest that protocols performed to failure resulted in more pronounced fatigue and a slower rate of neuromuscular recovery accompanied by an amplified hormonal response and more marked signs of muscle damage, which was especially notable in high-volume protocols (12(12), 10(10), and 8(8)).

Muscle fatigue is defined as the decline in ability of a muscle to generate force, velocity, or power (18). High-volume protocols to failure (12(12), 10(10), and 8(8)) were characterized by substantial reductions in repetition velocity both in BP (~50–60%) and SQ (~40–50%), which means that the velocities of the last repetitions were very slow, and the force applied much lower than that applied in the first rep of the set (3). Previous studies have observed similar velocity losses, both in SQ and BP, as in the protocols used

in this study (7,25). On the other hand, in protocols in which only half of the maximal repetitions were performed, a MeanLoss-V of ~20 and ~25% was observed for SQ and BP, respectively (Table 1). In addition, the mean velocity of the last repetition in the set was very similar for all protocols to failure (SQ: 0.32–0.39 $m \cdot s^{-1}$; and BP: 0.15–0.18 $m \cdot s^{-1}$) in this study, which was in agreement with values reported for the 1RM load in these exercises (SQ: ~0.33 $m \cdot s^{-1}$; and BP: ~0.18 $m \cdot s^{-1}$) (6,26). These results indicate that the participants actually performed the exercise sets to muscle failure. Furthermore, the mean velocity during the 3 sets (MeanV) was lower in protocols to failure (Table 1). It has been reported that after RT programs, participants who experienced high magnitude of velocity loss during the set (~40% in SQ) showed a significant reduction of IIX fiber type, whereas those completing RT programs with a lower velocity loss (~20% in SQ) did not (21). In addition, the RT program that produced a 20% velocity loss during the set induced greater gains in performance, especially in high-velocity actions, when compared with RT with high-velocity loss (40%) (21). Considering these changes, fatiguing, high-volume RT might not provide the best strategy for maximizing strength gains in high-velocity muscle actions.

Similarly to MeanLoss-V, both loss of MPV against the V_1-load and decrease in CMJ height were higher when the number of performed repetitions approached failure, especially in those protocols that were characterized by a large number of repetitions (8–12) performed to failure (Table 2). It is worth noticing that baseline performance (MPV against V_1-load and CMJ height) was not fully restored until 48 h-Post following almost all protocols performed to failure (i.e., 12(12), 10(10), 8(8), and 6(6), Table 2). This observation could be of vital importance because residual fatigue may reduce the quality of subsequent training sessions, leading to compromised long-term adaptations (10,29). By contrast, initial performance was recovered at 6 hours-Post following almost all half-maximal repetitions protocols. A previous study (9) reported a near-complete depletion of PCr stores, a reduction in ATP (21%) and in the muscle total adenosine nucleotide pool, as well as high increases in inosine monophosphate (IMP). When RT sets were conducted to failure, whereas when the number of repetitions in each set was reduced by 50%, a much lower decrease in muscle PCr content (~15% vs. 80% decline) was observed, with no measurable changes in muscle ATP and IMP levels, blood levels of uric acid, and whole-body purine stores. This observation might explain the longer recovery times presently observed for protocols performed to failure because the replenishment of the muscle adenosine nucleotide pool may take up to several days to complete (30).

Hormonal mechanisms are part of a complex integrated signaling system that mediates changes in the metabolic and cellular processes of skeletal muscle and neural and connective tissue as a function of training (14). Thus, it is not surprising that there is a growing body of literature aiming to analyze the hormonal response after RT leading either to failure or not to failure (5,17,20). In this study, PRL concentration increased significantly when protocols were performed until failure using a high-volume protocol (12(12), 10(10), and 8(8)). The main functions of PRL in men are associated with the maintenance of homeostasis (23). Similar to our results, 2 previous studies (11,15) observed increases in PRL after RT performed to muscular failure. The difference between protocols leading to failure or not to failure may be explained by the homeostasis loss evoked by protocols to failure, whereas nonfailure protocols would allow for the maintenance of cellular homeostasis (9). The acute release of PRL has also been related to stress and heat; however, it is not known which activator is predominant in the regulation of PRL secretion during exercise (23). Prolactin showed a great sensitivity to stress induced by RT. Lactate concentration may also influence PRL release (16). Further studies should be performed in which the role played by the PRL is examined. In addition, GH and IGF-1 concentrations increased following the 10(10) protocol (Figure 2). Therefore, it seems that exercise that produces greater demands on anaerobic glycolysis, resulting in marked increases in hydrogen ion concentrations, may be the primary physiological cue for GH release (8). Furthermore, it seems that failure conditions with greater number of repetitions (12(12), 10(10), and 8(8)) produced the highest CK concentrations (>400 $UI \cdot L^{-1}$). These findings support the suggestion that protocols performed to failure at moderately heavy loads (70–80% 1RM) create a high mechanical and metabolic stress, hormonal responses, and muscle damage (28). By contrast (22), small or no changes were observed for cortisol and testosterone concentrations after exercise. We must acknowledge that the changes in concentrations of circulating anabolic hormones may not reflect anabolism at the tissue level because this is influenced by factors such as hormonal clearance rates, hormone degradation, and receptor-binding protein activation and regulation.

Our results indicate that resistance exercise performed to failure resulted in a greater level of neuromuscular/metabolic fatigue accompanied by a slower rate of neuromuscular recovery and amplified hormonal responses along with more marked signs of muscle damage, especially when high-volume protocols are performed (12(12), 10(10), and 8(8)). Such exercise conditions were characterized by a large impairment in force production, and consequently, a high degree of velocity loss during the set (BP: 50–60% and SQ: ~40–50%), which induced high levels of fatigue and prolonged recovery time. This adaptive environment may not be optimal for athletes who try to develop specific neuromuscular adaptations while trying to avoid excessive fatigue that could interfere with the development of other components of training (10,29).

Practical Applications

The results of this study contribute to improving our knowledge about the process and methodology of load monitoring in resistance exercise. This information provides meaningful feedback to strength and conditioning coaches about mechanical stimulus, hormonal response, and muscle damage induced by specific RT protocols in relation to the resulting deterioration in acute performance. By monitoring repetition velocity during resistance exercise, a limit of repetition velocity loss may be chosen beforehand depending on the specific training goal being pursued, the exercise to be performed, the training experience of the athlete and the strength requirements of the sport practiced. Resistance exercise leading to failure is characterized by a large degree of velocity loss during the sets (BP: 50–60% and SQ: 40–50%) and needs longer time periods for the recovery of neuromuscular function and hormonal homeostasis. However, resistance exercise with lower velocity losses (BP: 25% and SQ: 20%) would allow athletes to be in a better neuromuscular condition to undertake a new training session or competition in a shorter period of time. This methodology allows for adjustments to be made to the training load at any time, resulting in better individualized training.

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