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Neuromuscular, Perceptual and Lactate Responses after Different Squat Protocols Differing in Effort Level, Relative Load, Volume and Set Structure: A Case Report Series

Daniel Varela-Olalla[1]*, Juan Del Campo-Vecino[1] and Carlos Balsalobre-Fernández[1]

[1]*Applied Biomechanics and Sports Technology Research Group, Department of Physical Education, Sport and Human Movement, Universidad Autónoma de Madrid, Madrid, Spain*

**Corresponding Author: dvarel23@gmail.com*

ABSTRACT

This study aims to test differences in fatigue after six squat protocols performed with different set configurations. Trained males (n = 4; 20.25 ± 2.60 years; 82.13 ± 13.67 kg; 179.00 ± 6.98 cm) performed different protocols with 50% of one repetition maximum (1RM) and 85% 1RM equalizing volume for the same relative load: training to failure (TF) protocols (resistance training protocols [RTPs] 1 and 2), half-maximum repetition protocols (RTP3 and 4), and cluster set protocols (RTP5 and 6). Mechanical performance based on movement velocity, jump height and isometric force, lactate, and perceptual fatigue were analyzed during protocols and again at post 0, 24, and 48 hours implementing a case series approach. TF RTPs showed the greatest impairments for all subjects. RTP1 showed the greatest overall impairments with some subjects being unable to complete the protocol or some of the post-tests. In summary, TF generate the greatest fatigue, with half-maximum repetitions and cluster protocols reducing these responses in a meaningful way.

Keywords: Squat, Resistance training, Fatigue, Neuromuscular fatigue, Perceptual fatigue.

INTRODUCTION

Resistance training is widely recognized as one of the most effective methods for enhancing fitness, health, and sports performance [9,25,29]. Therefore, it is essential to ensure the proper programming of training variables to achieve the desired outcomes, such as maximal strength or hypertrophy [21,29]. In this regard, ensuring a proper stimulus-to-fatigue ratio is critical, and the most effective approach to achieving this is through the application of a fatigue management framework that monitors individual responses to training [15,20].

Fatigue involves a plethora of physiological, psychological, cognitive, subjective, and biomechanical factors, which can be divided into neuromuscular fatigability, cognitive fatigue, and subjective or perceptual fatigue [3,6,7,23]. For that reason, a combination of subjective and objective fatigue indexes is recommended [16,24], which underscores the importance of developing

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comprehensive fatigue monitoring strategies.

Previous literature has shown that neuromuscular performance tends to decline more significantly when low loads are taken to or near failure, particularly when associated with higher training volumes, mechanical stress, and greater training densities [10,11,22,29,38,39,47,48,50]. In addition, perceptual fatigue responses seem to be influenced by the relative load, with heavier loads (even without reaching failure) inducing higher perception of effort (RPE), whereas low loads to failure result in higher ratings of perceived discomfort (RPD) and pain with similar RPE compared to heavier loads to failure [8,44,48].

On the other hand, there is some evidence suggesting that personality traits and coping strategies may affect subjective response to training [35,40,42], potentially affecting the overall training stimulus. In fact, models including sensory, affective and cognitive dimensions have been proposed to better assess perceived fatigue [51].

Finally, it has been argued that in sport science, particularly in sports performance, we deal with groups of n = 1 cases that necessitate individualized interpretation of training responses, and we should combine case-by-case data analysis with group statistics [52]. For that reason, case studies and case series may be of great relevance for theory building and testing, as demonstrated by previous research in sports science and other health-related fields [4,31,33,48]. Presenting athlete-specific data through case-study designs and z-score standardizations provides a robust framework for interpreting individual physiological adaptations that are often masked by averages [28,46]. The use of z-scores allows practitioners to quantify the magnitude of an individual's change relative to a specific population's baseline or intra-individual variability [28,46]. By transforming raw metrics into standardized units, we can objectively differentiate true biological responses from typical measurement errors [18]. However, the application of these metrics has been underutilized in studying fatigue responses to training, presenting great potential for individualizing training programs as recommended in some research [48].

The main objective of this paper is to compare, on a subject-by-subject basis, the fatigue levels induced by six resistance training protocols (RTPs) performed with different relative loads (low vs high loads), proximity to failure (effort level), and intra-set rest (set density) in the squat (SQ) exercise. Our initial hypothesis is that training to failure (TF) with low load resistance training will induce higher overall fatigue levels, while adding intra-set rest will decrease fatigue, provided that mechanical output (volume, time under tension, force, impulse) is equalized to TF for the same relative load.

MATERIAL AND METHODS

Experimental Design

The study is part of a larger project and similar data regarding responses after bench press (BP) have been published previously [48]. A randomized, cross-sectional quasi-experimental design was adopted to investigate acute fatigue responses to six RTPs in SQ:

RTP1: 3 sets to failure; 50% 1RM; 3 min inter-set
RTP2: 3 TF sets; 85% 1RM; 3 min inter-set rest.
RTP3: 6 sets with half-RTP1 mean set repetitions; 50% 1RM; 3 min inter-set rest.
RTP4: 6 sets with half-RTP2 mean set repetitions; 85% 1RM; 3 min inter-set rest.
RTP5: 1 cluster set (2 + 2 +…) equalizing RTP1 total repetitions; 50% 1RM; 30 s intra-set rest.
RTP6: 1 cluster set (1 + 1 +…) equalizing RTP2 total repetitions; 85% 1RM; 30 s intra-set rest.

Two familiarization sessions were conducted to determine the individual load–velocity relationship (L-V) and one repetition maximum (1RM), to familiarize subjects with all fatigue tests, and to record anthropometric characteristics. The eight sessions spanned 7–8 weeks. RTP1 and RTP2 were performed firstly in a random order to fix the total number of session repetitions and then the remaining RTPs were conducted randomly. Readiness was assessed prior to each RTP. Acute fatigue responses were tested by measuring velocity loss (VL) during sets, and against 1 $m \cdot s^{-1}$ and 0.5 $m \cdot s^{-1}$ loads (VL1, VL0.5), changes incountermovement jump (CMJ) height, isometric belt SQ (ISOSQ) and hand grip force (HGF) pre-session, immediately post-session, and 24 h post-session. Metabolic responses were assessed by measuring lactate (La) concentration 4 min post-session. RPE and RPD, were rated after each set and delayed-onset muscle soreness (DOMS) and perceived fatigue were provided by subjects 24 and 48 h post-session. All RTPs were performed at the same time of the day for each subject.

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Participants

All subjects participated voluntarily and were recruited by an advertisement posted at the authors' university and on social media. The sample comprised four recreationally trained males (age: 20.25 ± 2.60 years; body mass: 82.13 ± 13.67 kg; height: 179.00 ± 6.98 cm; 127.50 ± 6.45 kg 1RM–SQ; 1.56 ± 0.16 1RM–SQ/body mass). The inclusion criteria were: (i) aged between 18 and 40 years; (ii) having at least one year of experience performing SQ; (iii) absence of any musculoskeletal disorder and not having suffered any injury in the past six months; (iv) not suffering from any condition that restricts physical activity, nor having received any type of medical order not to perform physical activity and/or exercise; (v) not currently or previously using any drugs, medication, or other doping substances with performance-enhancement results. Participants were asked to refrain from any physical activity 24 h prior to RTPs and to avoid taking any supplements during this study, but nutritional control was not applied. This study was conducted in accordance with the Declaration of Helsinki (except pre-registration) and was approved by the institutional research ethics committee of the authors' university (reference number: CEI-114-2255).

Familiarization Sessions

Participants undertook two familiarization sessions separated by at least 96 h, to ensure proper technique and to become familiarized with neuromuscular tests and RPE/RPD (1–10) scales. In the first familiarization session anthropometric measures were taken. Then, participants completed a standard incremental loading test to determine their 1RM and individual L-V. In the second session only the 1RM/L-V testing was repeated. In the first familiarization session the position and set-up for the ISOSQ test was established. Detailed descriptions of the procedure for the incremental test used to establish 1RM and L-V have been provided elsewhere [50]. All repetitions were recorded at 1000 Hz with a linear position transducer (Vitruve, previously Speed4Lift), validated previously [34], connected to an iPhone 12 using the Vitruve application v.4.27.1. Velocity data corresponded to the repetition mean propulsive velocity (MPV).

Protocol Procedures

Subjects rated their readiness using a smartphone-based app (Readiness v.3.0.3) on arrival. Then, they performed a standardized whole-body warm-up (3 min of rowing and 5 min of joint mobility, 2 sets of 10 repetitions of squats with the 20 kg barbell, 2 sets of 5 CMJs; 90 s inter-set rest) followed by two trials of ISOSQ, two trials of HGF, and two trials of CMJs with 1 min rest in between, with the best trial used for further analysis. Thereafter, an exercise-specific warm-up was conducted (4 sets of 10-5-3-1 repetitions with 20 kg, 45–60–80%RM; 2 min inter-set rest) followed by two sets of 2 and 1 repetition with maximum intent, adjusting loads to an MPV of 1 and 0.5 $m \cdot s^{-1}$, respectively with 2 min inter-set rest. The best repetition of each trial was considered for subsequent analysis. Five minutes later, the corresponding RTP was conducted with the absolute loads being set based on the individual L-V. Repetitions were performed with maximum intent. MPV of the best (MPVbest) and last (MPVlast) repetition of each set, along with the meanMPV of the sets were considered. Velocity loss (VL) was calculated as: 100 × [MPVbest – MPVlast]/MPVbest. RPE and RPD were rated after each set and then averaged for the whole session. After 24 h, subjects returned to the laboratory to repeat neuromuscular testing. Subjects rated DOMS and perceived fatigue at 24 and 48 h. Post-test battery procedure is presented in Figure 1. Subjects were asked to refrain from any lower body strenuous activity 24-h before each trial.

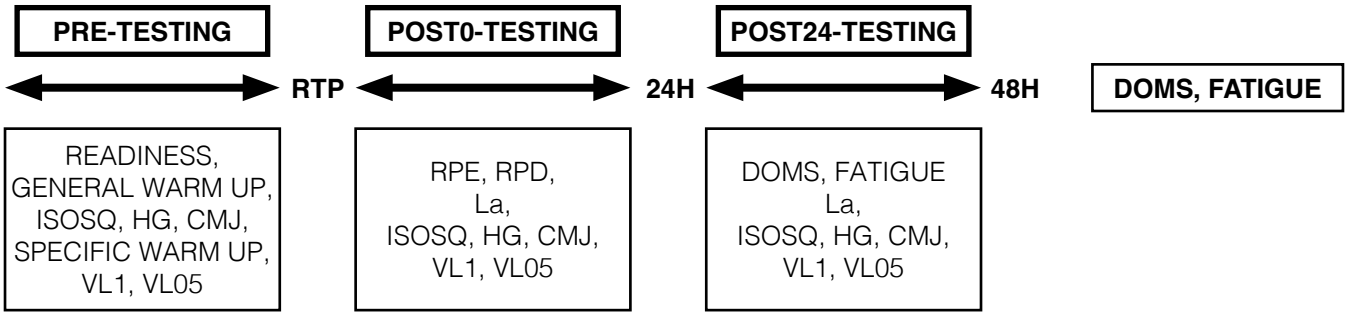

Figure 1. Procedural overview of study design and experimental protocols. CMJ, countermovement jump; DOMS, delayed-onset muscle soreness; FATIGUE, perceived fatigue; HGF, hand-grip force; ISOSQ, maximum isometric squat force; La, lactate; RPE, rate of perceived effort; RPD, rate of perceived discomfort; RTP, resistance training protocol; VL1, velocity loss against 1 $m \cdot s^{-1}$ load; VL0.5, velocity loss against 0.5 $m \cdot s^{-1}$ load.

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Neuromuscular Measures of Fatigue

Countermovement jump

CMJ height was measured using the MyJump 2 iOS app on an iPhone 12, with calculation descriptions and validation published elsewhere [2]. Participants were instructed to lower their bodies to the ground and reverse the direction of movement as fast as possible, pushing off straight upward and maintaining hands on the hips throughout the movement. CMJ change (%) was calculated as follows:

$$100 \times [\text{CMJ post} - \text{CMJ pre}]/\text{CMJ pre}$$

Velocity loss during sets and against 1 m·s^{-1} and 0.5 m·s^{-1} Loads

The mean VL across all sets was calculated for the analysis as explained before. VL from pre- to post-test with 1 and 0.5 m·s^{-1} loads (VL1 and VL0.5) werecalculated as follows:

$$100 \times [\text{MPVpost} - \text{MPVpre}]/\text{MPVpre}$$

Isometric belt squat

The ISOSQ test was performed with the subject placed on a dual force platform (force plates, FP; two separate platforms of 36.2 x 61 cm each, Hawkin Dynamics Inc., Maine, USA) with a sampling rate of 1000 Hz placed over a handmade wooden platform attached to one end of a chain, the other end of the chain was attached to a belt placed on the subject's hips. Subjects were allowed to wear a folded towel or jacket to reduce discomfort from the belt. During familiarizations, the link on which the chain was hooked ensuring a knee angle of 110°, was fixed with a self-selected foot width. Subjects were asked to keep the torso as vertical as possible. Subjects were instructed to push as hard as possible in a ramp contraction and to maintain maximal effort for approximately 5 s. Verbal encouragement was provided to ensure maximum intention of the subjects. Two trials of the test were performed with 1 min of rest. The best attempt was considered for analysis, and the percentage change was calculated using an equation similar to that for VL and CMJ. In each session, the FPs were calibrated according to the manufacturer's instructions, and the force values were calculated considering the weight of the system based on the vertical, anteroposterior and mediolateral components.

Hand-grip force

HGF of the dominant arm was measured using a hand-held dynamometer (5001 Grip-A, Takei, Japan). The subject started with the elbow at about 90° positioned close to the trunk, then was required to move the hand toward the thigh while squeezing the dynamometer, with maximum force achieved once the device was parallel to the leg. The subject was instructed to avoid any trunk movement and maintain a neutral palm position (palm facing the leg). Two trials of the test were performed with 1 min of rest in between, and the best trial was considered for analysis. The percentage change was also calculated as for VL1, VL0.5, CMJ and ISOSQ.

For changes in CMJ, VL1, VL0.5, ISOSQ and HGF negative values represent a reduction in performance and positive values correspond to potentiation effects.

Blood lactate

Blood lactate samples were taken 4 min after each RTP with capillary blood samples (5 µL) collected from the index finger of the right hand and immediately analyzed using the Lactate Pro Portable Analyzer (Arkray, Kyoto, Japan).

Subjective Measures of Fatigue

Rate of perceived effort and discomfort

RPE and RPD scales were assessed after each set and then averaged for each session. Original scales of 11 items from 0 to 10 points were modified, allowing for intermediate ratings (e.g., RPE 4.5) since subjects perceived this to represent their sensations in a more precise way compared to the original scales. This approach has been used previously [48,49]. Maximum effort should be achieved when lifting the 1RM in familiarization sessions, and during the two RTPs to failure, effort was fixed at 10, which facilitated comparison for the remaining RTPs.

Delayed-onset muscle soreness and perceived fatigue

A single-item questionnaire with Likert scales on DOMS and perceived fatigue was provided to the subjects 24 and 48 h after each RTP. Intermediate ratings were allowed as in previous studies [48].

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Time under tension and force/impulse calculation

Concentric TUT was calculated by multiplying concentric repetition time by the mean set repetitions (mean set TUT), or by the total RTP repetitions (total TUT). Calculations of concentric force were made by multiplying average force (AF) of one repetition by the total repetitions (session force) or session TUT (session impulse, IMP), and by the mean set repetitions (set force) or TUT (set IMP). For practical purposes, values were divided by 100. The estimation of AF was conducted using basic physics laws as follows:

$$[\text{load (KG)} \times \text{mean MPV } (m \cdot s^{-1})/\text{repetition time (s)}] + [\text{load (kg)} \times 9.8\ m \cdot s^{-2}]$$

Effort index

The calculation of EI was conducted for each set and analyses were made based on mean EI and the maximum set EI of the session. The equation used was:

$$VL \times MPVbest$$

Statistical Analysis

Data are presented as means and standard deviations (SDs) with coefficients of variation (CVs). For the case series, the main analysis of the individual response was carried out using z-scores. First, z-scores relative to the group average were calculated for each RTP. Second, z-scores were calculated based on the average of the six RTPs to assess the deviation of each individual RTP response from the subject's mean across all sessions. The z-scores were calculated as (subject value – group mean value)/group standard deviation, as recommended for sport science analyses [18,28,46,52].

RESULTS

Descriptive characteristics of the six RTPs are presented in Table 1 and absolute scores for each subject can be found in Table 2. For subsequent analysis, hand grip testing did not show any meaningful information and added no value to the comprehensive analysis of fatigue; for that reason, results regarding this variable are not presented to facilitate reading.

Case Series Analysis

Descriptive explanations with summaries for all subjects appear in Table 3, with main results discussed in the second paragraph of the "Discussion" section. Z-scores comparing individual values with respect to the group response for neuromuscular and perceptual fatigue variables appear in Table 4. Z-scores comparing individual responses after each RTP respect the averaged responses of the six RTPs for the same subject appear in Table 5.

DISCUSSION

The present study aims to describe, on a subject-by-subject basis, the acute neuromuscular and perceptual fatigue responses of six RTPs of the SQ exercise. This analysis evaluates the effects of equated volume load, but differing effort levels, set volume, relative load, and set configurations. The main findings, based on the most common responses observed across all subjects, were as follows: i) TF protocols induce higher fatigue responses; ii) TF protocols using light-loads induce the most significant fatigue responses, even when compared to high-load TF; iii) only EI and RPE seem to be different between NTF loading conditions, being the former greater for light-loads and RPE higher for high-loads; iv) for NTF, RPD tends to be higher with light-loads; v) performing all repetitions using a cluster set structure reduces the magnitude of fatigue responses versus TF, though comparisons with respect to NTF present divergent results; vi) light-load cluster training produce grater fatigue responses, approaching TF-like responses for VL1, VL0.5 and DOMS; vii) fatigue measures were almost completely recovered at 24 h after all RTPs. These findings suggest that to mitigate fatigue symptoms following resistance training, prioritizing high-load protocols, utilizing half the maximum volume per set, and incorporating intra-set rest whenever possible, is advisable. However, to confirm this statement, studies with similar designs and larger sample sizes should be conducted.

In a more individual analysis, the strongest subject (subject 2, relative strength z-score: 1.31) was unable to complete RTP1 due to maximum discomfort in the lower back before reaching real failure, defined as the inability to lift the weight with his lower-body, making it impossible for him to perform RTP3 and RTP5. Moreover, this subject does not present any similar problem during RTP2,

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Table 1. Descriptive characteristics of the six RTPs.

VARIABLES	RTP 1	RTP 2	RTP 3	RTP 4	RTP 5	RTP 6
Total kg	3967.50 ± 351.63 (8.9)	1495.63 ± 413.98 (27.7)	4165.00 ± 280.76 (6.7)	1578.75 ± 280.76 (19.2)	4310.00 ± 512.93 (11.9)	1468.13 ± 379.39 (25.8)
Total reps	66.33 ± 8.39 (12.6)	13.75 ± 4.27 (31.1)	68.00 ± 9.17 (13.5)	15.00 ± 3.46 (23.1)	66.67 ± 8.08 (12.1)	13.75 ± 4.27 (31.1)
MPVmean	0.59 ± 0.05 (7.7)	0.35 ± 0.04 (12.1)	0.81 ± 0.09 (10.5)	0.41 ± 0.05 (12.2)	0.83 ± 0.06 (7.3)	0.43 ± 0.05 (10.6)
MPVbest	0.79 ± 0.09 (11.0)	0.44 ± 0.06 (14.1)	0.91 ± 0.08 (8.6)	0.43 ± 0.05 (11.5)	0.97 ± 0.03 (3.1)	0.48 ± 0.05 (10.3)
MPVlast	0.35 ± 0.02 (6.0)	0.29 ± 0.03 (8.7)	0.73 ± 0.10 (13.5)	0.39 ± 0.05 (13.2)	0.81 ± 0.12 (14.9)	0.39 ± 0.03 (8.1)
Fset1	13619.7 ± 1108.0 (8.1)	4983.0 ± 1379.7 (27.7)	7473.7 ± 478.7 (6.4)	2648.8 ± 516.8 (19.5)	1406.5 ± 209.1 (14.9)	1097.3 ± 96.7 (8.8)
Fset2	16132.7 ± 2856.6 (17.7)	9534.7 ± 3430.4 (36.0)	6371.7 ± 813.7 (12.8)	4307.3 ± 1078.2 (25.0)	1161.8 ± 78.1 (6.7)	1700.2 ± 350.2 (20.6)
Fsession1	40860.3 ± 3323.5 (8.1)	14943.5 ± 4141.5 (27.7)	44840.7 ± 2870.0 (6.4)	15890.3 ± 3100.7 (19.5)	46599.3 ± 5923.3 (12.7)	14829.2 ± 3907.6 (26.4)
Fsession2	48400.3 ± 8567.6 (17.7)	28595.5 ± 10299.4 (36.0)	38232.0 ± 4881.6 (12.8)	25844.7 ± 6469.7 (25.0)	38657.3 ± 4425.4 (11.4)	22552.3 ± 5887.2 (26.1)
meanTUT	26.27 ± 5.95 (22.6)	8.84 ± 3.70 (41.9)	9.73 ± 2.13 (21.9)	4.12 ± 1.43 (34.7)	1.66 ± 0.13 (7.6)	1.55 ± 0.29 (18.7)
totalTUT	78.83 ± 17.84 (22.6)	26.51 ± 11.11 (41.9)	58.37 ± 12.78 (21.9)	24.69 ± 8.57 (34.7)	55.72 ± 10.22 (18.3)	20.98 ± 7.11 (33.9)

Data are presented as mean ± SD (CV). RTP, resistance training protocol; MPVmean, mean Mean Propulsive Velocity of the sets; MPVbest, Mean Propulsive Velocity of the best repetition of the sets; MPVlast, Mean Propulsive Velocity of the last repetition of the sets; Fset1, Average Concentric Force per epetition × set repetitions; Fset2, Average Concentric Force per repetition × set TUT; Fsession1, Average Concentric Force per repetition × session repetitions; Fsession2, Average Concentric Force per repetition × session TUT; meanTUT, Mean Concentric Time Under Tension of the sets; totalTUT, Total Concentric Time under tension of the session.

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Table 2. Individual scores for each subject after the six RTPs.

	VL	EI	RPE	RPD	La	CMJ	CMJ 24	VL1	VL1 24	VL0.5	VL0.5 24	ISOSQ	ISOSQ 24	DOMS	DOMS 24	FAT	FAT 24
SUBJECT 1																	
RTP1	60.67	50.36	10.00	8.17	17.00	-17.98	-4.77	-7.22	5.15	4.35	-4.35	-15.87	-9.07	6.50	3.00	6.00	3.00
RTP2	26.67	11.47	10.00	3.00	11.70	-7.97	8.15	-0.96	2.88	-5.45	-12.73	-4.03	-3.95	3.50	2.00	5.00	3.00
RTP3	16.50	16.50	4.83	3.08	13.40	-4.71	1.55	-9.01	1.80	-7.41	-22.22	14.40	20.30	4.50	2.00	4.00	3.00
RTP4	8.90	4.09	8.33	2.00	3.90	-12.04	6.40	-15.65	-3.48	-17.65	-3.92	-20.92	-2.78	2.50	1.50	3.00	3.00
RTP5	8.00	8.00	5.00	4.00	4.80	-15.83	-6.06	-7.00	0.00	-28.85	-21.15	-7.00	-0.12	8.00	2.00	5.00	3.00
RTP6	17.78	8.00	9.00	3.00	4.50	-6.29	4.57	-5.15	8.24	0.00	-2.27	-2.64	4.20	3.50	2.00	3.00	1.50
SUBJECT 2																	
RTP1	n.a																
RTP2	43.01	21.94	10.00	4.67	9.20	-8.95	-4.53	-7.22	-7.22	-7.69	-19.23	9.13	9.04	5.00	2.00	5.00	3.00
RTP3	n.a																
RTP4	8.44	3.97	6.50	4.33	5.90	-7.68	-1.52	-6.19	-4.12	-20.41	-28.57	-7.17	-25.78	7.50	4.00	5.00	5.00
RTP5	n.a																
RTP6	27.27	15.00	9.00	5.50	6.80	-5.77	-2.91	-9.38	-4.17	-8.00	-58.00	-6.66	-8.27	7.00	2.00	5.00	6.50
SUBJECT 3																	
RTP1	56.61	48.12	10.00	9.50	14.20	-24.37	-7.48	-16.04	2.83	3.85	3.85	-32.26	-25.48	6.00	6.00	4.50	4.00
RTP2	36.51	16.06	10.00	5.67	12.70	-7.80	3.14	-7.00	3.00	4.35	32.61	3.15	0.58	3.50	2.00	4.00	3.00
RTP3	22.86	19.66	5.17	6.92	8.40	-6.40	4.81	-4.12	15.46	-11.54	7.69	-11.92	17.39	6.50	5.00	7.00	6.00
RTP4	14.34	6.31	6.00	2.17	3.70	0.00	2.99	4.17	3.13	4.44	13.33	27.05	15.62	4.50	1.00	4.00	1.50
RTP5	12.77	12.00	5.00	7.50	5.10	-4.51	3.34	-15.53	11.65	-2.04	20.41	-11.98	8.50	6.50	4.00	5.00	5.00
RTP6	10.42	5.00	8.50	3.00	3.30	4.56	0.16	3.00	-2.00	23.40	17.02	17.32	26.50	2.50	1.50	3.00	1.50
SUBJECT 4																	
RTP1	50.18	34.62	10.00	9.67	13.20	-14.77	5.38	-17.71	-4.17	-100.00	-14.00	-10.92	13.84	7.00	6.00	6.00	5.00
RTP2	27.83	10.02	10.00	3.00	8.40	-11.57	-8.23	-8.51	-5.32	-12.24	-8.16	9.76	-9.45	4.00	3.00	3.00	4.00
RTP3	22.82	19.85	4.33	1.50	8.10	-5.00	0.00	-7.22	-2.06	-27.45	-21.57	-7.67	21.37	3.50	4.00	6.00	5.00
RTP4	14.76	5.31	6.50	1.17	3.10	1.69	3.37	-9.90	-3.96	-23.40	-6.38	-21.69	5.73	6.00	4.00	3.00	3.00
RTP5	30.61	30.00	6.50	4.00	3.10	-9.44	-6.33	-12.63	-11.58	-54.35	-13.04	5.77	13.99	7.50	8.00	5.00	4.00
RTP6	18.18	8.00	9.00	4.00	3.00	-15.49	4.85	-12.24	-5.10	-25.00	0.00	-9.26	12.12	4.50	5.00	5.00	3.00

RTP, resistance training protocols; VL, velocity loss; EI, effort index; RPE, mean RPE of the sets; RPD, mean RPD of the sets; La, lactate concentration; CMJ, variation in countermovement jump height immediately post; CMJ24, variation in countermovement jump height post 24 h; VL1, mean propulsive velocity loss with 1 m·s^{-1} load immediately post; VL1_24, mean propulsive velocity loss with 1 m·s^{-1} load post 24 h; VL0.5, mean propulsive velocity loss with 0.5 m·s^{-1} load immediately post; VL0.5_24, mean propulsive velocity loss with 0.5 m·s^{-1} load post 24 h; ISOSQ, variation in isometric squat force immediately post; ISOSQ24, variation in isometric squat force post 24 h; DOMS24, delayed onset muscle soreness post 24 h; DOMS48, delayed onset muscle soreness post 48 h; FAT24, perceived fatigue post 24 h; FAT48, perceived fatigue post 48 h.

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Table 3. Case series summary.

Case	Report summary
Subject 1	Higher RPE values during NTF at high relative loads (RTP4) Higher tendency to overall performance loss in CMJ at post24 Lower tendency to overall performance loss against 1 m·s^{-1} load at post0 and post24 Higher performance loss against 0.5 m·s^{-1} load at post24 compared to post0 Generally lower RPD values
Subject 2	Inability to complete RTP1 due to intolerable RPD levels Higher EI for cluster protocol at high relative loads Higher La values at high loads except for RTP2 Higher tendency for performance loss in ISOSQ at post24 at high relative loads Generally higher RPD values at high relative loads
Subject 3	Lower tendency for overall performance loss against 1 m·s^{-1} load at post0 and post24 Lower tendency for overall performance loss against 0.5 m·s^{-1} load at post0 and post24 Lower overall RPE values, especially at RTP6 Greater potentiation in ISOSQ after NTF protocols with high loads (RTP4 and RTP6) at post0 Lower tendency for performance loss in ISOSQ at post24
Subject 4	Maximal performance loss (failed test) at 0.5 m·s^{-1} load after RTP1 Greater performance loss in CMJ after RTP2 Greater tendency to overall performance loss against 0.5 m·s^{-1} load at post0, especially after protocols with low relative loads Generally lower RPD values Lower tendency to performance loss in ISOSQ at post24

VL, velocity loss; EI, effort index; TF, training to failure; NTF, training not to failure; CMJ, countermovement jump; DOMS, delayed onset muscle soreness; La, lactate; RPE, perceived exertion scale; RPD, perceived discomfort scale; ISOSQ, isometric squat.

so he only performed the heavy-load conditions. Additionally, subject 4 (relative strength z-score: –0.25), the one with larger SQ depth, was unable to perform the VL0.5 test post-RTP1 and exhibited the most significant neuromuscular impairments overall. Subject 3 (relative strength z-score: –0.19) tended to show neuromuscular potentiation at post24 after all RTPs, despite showing relevant impairments at post0, except for RTP4 and RTP6. This subject generally showed the highest RPD, DOMS and perceived fatigue after light-load RTPs. For the three heavy-load RTPs, subject 2 showed the highest RPD, DOMS and perceived fatigue.

All subjects exhibited the most pronounced fatigue responses after low–load TF (subject 2 was unable to complete RTP1 and subject 4 could not lift the 0.5 m·s^{-1} load after RTP1), which is in line with our previous case report paper on BP [48] and corroborates findings from other cross-sectional studies involving both upper- and lower-limb exercises [8,21,38,39,44]. Comparing RTPs with the same relative load, TF resulted in higher neuromuscular and perceptual fatigue compared to NTF and cluster sets, consistent with previous research [10,11,21,22,38,39,48]. However, the combination of the present data with our previous research [48] suggests that fatigue responses for cluster RTPs may differ between BP and SQ, depending on the relative load, with BP being more affected by high-loads and SQ by low-loads. Nevertheless, both cluster RTPs allow for better maintenance of mechanical output and lower immediate metabolic and perceptual responses than TF in both exercises, as previously shown [10,11,22,47,48,50]. In addition, CMJ results after BP in our previous paper [48] and the lack of relevant changes for hand grip strength after SQ indicate that non-local fatigue was not induced by our RTPs.

Based on our results, the heightened fatigue in longer, light-load sets may be theoretically attributed to greater cytosolic substrate depletion and metabolite accumulation (e.g., H^+ and P_i), which is hypothesized to inhibit voluntary activation and cross-bridge force [12,53]. We further speculate that prolonged time under tension and mechanical stress (i.e., higher IMP) could impair Ca^{2+} release and reuptake kinetics [1,19,41,43,45]. Furthermore, while not directly measured, muscle damage could potentially result from calpain protease activation triggered by excessive intracellular Ca^{2+} and reactive species during TF [17,36,37]. The discrepancy between BP and SQ responses after cluster sets using high or low loads may be attributed to the larger muscle mass involved in SQ, which could be more susceptible to higher volumes, regardless of intra-set rest. Another possibility may be that, due to bipedal locomotion, human upper–

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Table 4. Z-scores for main fatigue variables comparing individual values with respect to the averaged value of the group.

SUBJECT		VL	EI	La	RPE	RPD	CMJ	CMJ24	VL1	VL1_24	VL0.5	VL0.5_24	ISOSQ	ISOSQ24
1	RTP1	0.92	0.70	1.12	n.a	-1.15	0.22	-0.37	1.14	0.80	0.58	0.05	0.42	-0.11
	RTP2	-0.89	-0.63	0.59	n.a	-0.83	0.64	1.15	1.47	0.85	-0.03	-0.46	-1.53	-0.38
	RTP3	-1.16	-1.15	1.15	0.12	-0.27	0.73	-0.23	-0.90	-0.36	0.76	-0.60	1.40	0.29
	RTP4	-0.80	-0.75	-0.20	1.46	-0.31	-1.16	1.10	-1.05	-0.39	-0.27	0.14	-0.77	-0.06
	RTP5	-0.77	-0.74	0.44	-0.57	-0.58	-1.04	-0.55	1.09	0.00	-0.02	-0.75	-0.35	-1.07
	RTP6	-0.09	-0.24	0.06	0.48	-0.75	-0.07	0.78	0.12	1.47	0.12	0.26	-0.22	-0.30
2	RTP1	–	–	–	–	–	–	–	–	–	–	–	–	–
	RTP2	1.23	1.32	-0.64	n.a	0.44	0.07	-0.56	-0.39	-1.03	-0.35	-0.74	0.83	1.28
	RTP3	–	–	–	–	–	–	–	–	–	–	–	–	–
	RTP4	-0.93	-0.86	1.43	-0.32	1.41	-0.49	-1.32	0.08	-0.57	-0.49	-1.29	-0.08	-1.36
	RTP5	–	–	–	–	–	–	–	–	–	–	–	–	–
	RTP6	1.28	1.42	1.39	0.48	1.37	0.00	-1.23	-0.52	-0.56	-0.28	-1.45	-0.61	-1.16
3	RTP1	0.15	0.44	-0.30	n.a	0.48	-1.09	-0.77	-0.42	0.32	0.57	0.97	-1.38	-0.94
	RTP2	0.39	0.22	1.08	n.a	1.20	0.74	0.47	-0.32	0.87	1.37	1.47	-0.24	0.20
	RTP3	0.58	0.53	-0.53	0.93	1.11	-1.14	1.09	1.08	1.13	0.37	1.15	-0.88	-1.11
	RTP4	0.80	1.25	-0.37	-0.81	-0.19	0.70	0.06	1.33	1.50	1.47	1.15	1.66	0.99
	RTP5	-0.37	-0.40	0.71	-0.57	1.15	0.95	1.15	-0.88	1.00	1.01	1.13	-1.01	0.15
	RTP6	-1.16	-0.94	-0.64	-1.52	-0.75	1.26	-0.40	1.35	-0.20	1.28	0.85	1.69	1.23
4	RTP1	-1.07	-1.15	-0.81	n.a	0.68	0.87	1.13	-0.72	-1.12	-1.15	-1.03	0.96	1.05
	RTP2	-0.74	-0.90	-1.03	n.a	-0.83	-1.43	-1.06	-0.77	-0.68	-1.00	-0.27	0.95	-1.09
	RTP3	0.57	0.63	-0.63	-1.07	-0.84	0.41	-0.86	-0.18	-0.77	-1.13	-0.56	-0.52	0.82
	RTP4	0.93	0.35	-0.86	-0.32	-0.93	0.96	0.17	-0.36	-0.53	-0.72	0.00	-0.81	0.43
	RTP5	1.13	1.14	-1.14	1.15	-0.58	0.09	-0.60	-0.21	-1.00	-0.99	-0.38	1.36	0.92
	RTP6	-0.03	-0.24	-0.81	0.48	0.10	-1.19	0.85	-0.95	-0.71	-1.12	0.33	-0.86	0.24

RTP, resistance training protocols; CMJ, countermovement jump; CMJ24, variation in countermovement jump height post 24 h; EI, effort index; ISOSQ, maximum isometric squat force; ISOSQ24, variation in isometric squat force post 24 h; La, lactate; RPE, rate of perceived effort; RPD, rate of perceived discomfort; VL, velocity loss during sets; VL1, velocity loss against 1 m·s^{-1} load; VL1_24, mean propulsive velocity loss with 1 m·s^{-1} load post 24 h; VL0.5, velocity loss against 0.5 m·s^{-1} load; VL0.5_24, mean propulsive velocity loss with 0.5 m·s^{-1} load post 24 h

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Table 5. Z-scores comparing each RTP's values with respect to the averaged value of the six RTPs for the same subject.

SUBJECT		VL	EI	La	RPE	RPD	CMJ	CMJ24	VL1	VL1_24	VL0.5	VL0.5_24	ISOSQ	ISOSQ24
1	RTP1	1.92	1.98	1.40	0.90	1.95	-1.34	-1.09	0.06	0.67	1.11	0.75	-0.80	-1.03
	RTP2	0.18	-0.29	0.45	0.90	-0.40	0.53	1.10	1.35	0.11	0.31	-0.18	0.16	-0.53
	RTP3	-0.34	0.01	0.75	-1.28	-0.36	1.14	-0.02	-0.31	-0.16	0.14	-1.24	1.66	1.84
	RTP4	-0.72	-0.72	-0.96	0.20	-0.85	-0.23	0.81	-1.68	-1.45	-0.70	0.80	-1.22	-0.41
	RTP5	-0.77	-0.49	-0.80	-1.21	0.06	-0.94	-1.31	0.10	-0.60	-1.61	-1.12	-0.08	-0.15
	RTP6	-0.27	-0.49	-0.85	0.48	-0.40	0.84	0.50	0.48	1.43	0.75	0.99	0.27	0.27
2	RTP1	–	–	–	–	–	–	–	–	–	–	–	–	–
	RTP2	0.97	0.92	1.11	0.83	-0.27	-0.93	-1.02	0.23	-1.15	0.60	0.79	1.15	0.79
	RTP3	–	–	–	–	–	–	–	–	–	–	–	–	–
	RTP4	-1.03	-1.07	-0.82	-1.11	-0.84	-0.13	0.97	0.86	0.59	-1.15	0.33	-0.60	0.33
	RTP5	–	–	–	–	–	–	–	–	–	–	–	–	–
	RTP6	0.06	0.15	-0.29	0.28	1.11	1.06	0.05	-1.10	0.56	0.56	-1.12	-0.55	-1.12
3	RTP1	1.73	1.91	1.35	1.09	1.33	-1.81	-1.92	-1.16	-0.44	0.01	-1.17	-1.42	-1.79
	RTP2	0.61	-0.11	1.03	1.09	-0.04	-0.14	0.44	-0.12	-0.41	0.05	1.65	0.21	-0.36
	RTP3	-0.15	0.11	0.11	-0.97	0.40	0.00	0.81	0.21	1.50	-1.34	-0.80	-0.48	0.56
	RTP4	-0.63	-0.73	-0.90	-0.62	-1.30	0.65	0.41	1.16	-0.39	0.06	-0.24	1.31	0.46
	RTP5	-0.71	-0.37	-0.60	-1.04	0.61	0.19	0.49	-1.10	0.92	-0.51	0.45	-0.49	0.07
	RTP6	-0.85	-0.81	-0.98	0.45	-1.00	1.11	-0.22	1.02	-1.18	1.72	0.12	0.86	1.06
4	RTP1	1.81	1.36	1.62	0.99	1.88	-0.87	0.95	1.11	0.37	-1.84	-0.47	-0.45	0.40
	RTP2	0.03	-0.65	0.46	0.99	-0.29	-0.38	-1.38	2.78	0.01	0.87	0.32	1.33	-1.80
	RTP3	-0.36	0.15	0.39	-1.47	-0.78	0.63	0.03	0.63	1.01	0.40	-1.49	-0.17	1.11
	RTP4	-1.00	-1.03	-0.81	-0.53	-0.88	1.65	0.60	-1.14	0.43	0.53	0.56	-1.38	-0.37
	RTP5	0.25	0.98	-0.81	-0.53	0.04	-0.05	-1.05	1.17	-1.91	-0.43	-0.34	0.99	0.41
	RTP6	-0.73	-0.81	-0.84	0.56	0.04	-0.98	0.86	1.66	0.08	0.48	1.42	-0.31	0.24

RTP, resistance training protocols; CMJ, countermovement jump; CMJ24, variation in countermovement jump height post 24 h; EI, effort index; ISOSQ, maximum isometric squat force; ISOSQ24, variation in isometric squat force post 24 h; La, lactate; RPE, rate of perceived effort; RPD, rate of perceived discomfort; VL, velocity loss during sets; VL1, velocity loss against 1 m·s^{-1} load; VL1_24, mean propulsive velocity loss with 1 m·s^{-1} load post 24 h; VL0.5, velocity loss against 0.5 m·s^{-1} load.; VL0.5_24, mean propulsive velocity loss with 0.5 m·s^{-1} load post 24 h

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limb may be less adapted to high-effort loads and more fatigable, and does not benefit as much as the lower limb from the better reperfusion and metabolic recovery (i.e., PCr) during clusters. From a perceptual perspective, both the higher RPE and RPD could reduce exercise tolerance during sets and reduce motivation and volitional performance, as proposed by several authors [5,13,14,26,27,32].

In summary, in the four subjects that make up our sample, performing resistance training to failure induces the greatest fatigue response. These impairments are more pronounced when low-loads are used, with high perceptual responses. Moreover, when only half of the maximum possible repetitions are performed, fatigue responses tend to be similar across relative loads. Both NTF and cluster sets significantly reduce fatigue responses; however, with low loads, cluster sets seem to be more demanding. To minimize fatigue, TF training should be avoided and differences in perceptual responses between protocols should be considered. Finally, although overall results are very similar, some inter-individual differences exist. Conducting individual analyses in relation to the group mean or comparing responses of the same subject after different protocols, as performed in this study, may be the best option for better fatigue management and training individualization. Moreover, the findings of our preliminary work are context-specific (mainly due to the small sample size and the training background of the participants) and warrant further confirmation through replication with larger sample sizes.

PRACTICAL APPLICATION

To mitigate acute fatigue, practitioners should prioritize high-load protocols, utilize approximately half of the maximum possible repetitions per set, and incorporate intra-set rest (clusters) whenever possible. These strategies appear most effective for maintaining mechanical output; however, the observed inter-individual variability suggests that these recommendations should be tailored to the athlete's individual responses to training protocols. Low-load TF training should be prescribed with caution and limited to specific cases where high absolute loads cannot be used and it is necessary to achieve high levels of effort with an objective such as increasing muscle mass. An integrative approach using mechanical variables, especially VL and IMP, combined with perceptual indexes, especially RPE, is recommended to identify the level of fatigue imposed during resistance training. Conducting individual response analysis applying metrics such as z-scores would help identify which individuals are more susceptible to fatigue after specific training sessions, or which training sessions pose the greatest physiological and perceptual stress for a particular individual. This would facilitate the individualization and prescription of training based on fatigue management in resistance training. The first proposal (z-scores based on group averages) could be most useful in team sports when large groups of athletes must perform the same resistance training program, and we need to know the individual response to different types of sessions. The second one (z-scores based on individual responses after different training sessions) may be more suitable in individual sports or in team sports when it is possible to train athletes individually.

LIMITATIONS

The main limitations of this work are: (i) the sample size; (ii) the fact that no direct physiological measures (e.g., muscle properties, neural factors) were taken apart from those for La; (iii) the lack of dissociation between local and systemic or muscular and cardiorespiratory RPE; (iv) only two relative loads were implemented; and (v) the relative strength of the sample. The last two limitations make it difficult to extrapolate the results to other population subgroups and other relative loads.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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ETHICAL APPROVAL

This study was conducted in accordance with the Declaration of Helsinki (except pre-registration) and was approved by the institutional research ethics committee of the author's university (reference number: CEI-114-2255).

DATA AVAILABILITY STATEMENT

Data are available from the corresponding author upon reasonable request.

AUTHOR CONTRIBUTIONS

Daniel Varela-Olalla: conceptualization, methodology, formal analysis, investigation, resources, data curation, writing-original draft preparation, visualization, project administration.
Juan del Campo-Vecino: conceptualization, methodology, investigation, resources, writing-review and editing, visualization, supervision, project administration.
Carlos Balsalobre-Fernández: conceptualization, methodology, investigation, resources, writing-review and editing, visualization, supervision, project administration.

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