Title

Effects of active vs. passive interset rest among physiological and perceptual outcomes in bench press exercise

Titre

Effets de la récupération active vs passive sur des résultats physiologiques et perceptifs entre les séries au développé-couché

Short title

Active vs. passive interset rest in bench press

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Summary

Objectives: The aim of this study was to compare the effects between 2-min active and 2-min passive interset rest among intra and interset velocity and power loss, blood lactate level, and effort perception in young resistance-trained male during bench press exercise.

Equipment and methods: Nineteen volunteers completed a maximal power test for bench press to determine the optimal load for maximum power production. Separated by, unless, 72 hours all participants realised two resistance training bouts consisting of 2x8 repetitions at maximal velocity using the optimal load for maximal power, and a 3rd set until muscle failure, with 2-min interset rest passive or active, where participants completed repetitions in vertical chest press at a controlled velocity during active protocol. We measured power and velocity for each repetition using a lineal encoder, and we calculate intraset loss for both outcomes with two different equations. We also measured blood lactate levels and rate of perceived exertion before and after each set, and during recovery period after the last set.

Results: There was a lower intraset velocity and power loss for active interset rest compared to passive, being these differences statistically significant for the 1st set ($P < 0.05$) as confirmed by T-test for repeated measures. We also found only for the passive protocol a significant increase in blood lactate levels when comparing the values post set and before the consecutive set ($P < 0.01$), showing a significant increase during the interset rest period (post set 1 – pre set 2; and post set 2 – pre set 3). Moreover, blood lactate levels were significantly higher in passive compared to active before starting the 3rd set ($P < 0.01$). There were no significant differences for rate of perceived exertion between both protocols.

Keywords: Resistance training, Athletic performance, Muscle strength, Rest

Résumé

Objectifs: Le but de cette étude est de comparer, entre 2 minutes de récupération active et 2 minutes de récupération passive, l'effet que celle-ci aura sur la vitesse et la perte de puissance pendant et entre chaque série, le niveau d'acide lactique, ainsi que la perception de l'effort chez un jeune homme entraîné lors de l'exercice de développé couché.

Matériels et méthodes: Dix-neuf volontaires ont effectué un test de puissance maximale au développé couché afin de déterminer la charge optimale pour atteindre la puissance maximum. Séparés par pas moins de 72h, tous les participants ont effectué 2 circuits d'entraînement de force composés de 2x8 répétitions à vitesse maximale en utilisant la charge optimale pour puissance maximale, puis une troisième série jusqu'à épuisement musculaire, en comptant 2 minutes de récupération passive ou active entre chaque set, au cours desquelles les participants ont réalisé des répétitions verticales de développé couché à vitesse contrôlée pendant le protocole actif. Nous avons mesuré la puissance et la vitesse pour chaque répétition en utilisant un codeur linéaire puis, nous avons calculé la perte entre chaque série pour les deux résultats à l'aide de deux différentes équations. Nous avons également mesuré le niveau d'acide lactique dans le sang et le taux de perception à l'effort avant et après chaque série puis lors de la phase de récupération après le dernier set.

Résultats: La perte de vitesse et de puissance est moins élevée quand la récupération est active en comparaison avec une récupération passive, ces différences ayant statistiquement du sens pour la première série ($P < 0.05$) puisque confirmé par le T-test à mesures répétées. Nous avons également remarqué, pour le protocole passif uniquement, une hausse considérable du niveau d'acide lactique dans le sang en comparant avec les valeurs trouvées après la première série et avant le set suivant ($P < 0.01$), montrant une augmentation significative pendant la phase de récupération entre deux sets (post série 1 – pré série 2; post série 2 – pré série 3). De plus, le niveau d'acide lactique dans le sang était beaucoup plus élevé pour la récupération passive en comparaison avec la récupération active avant même de commencer la 3ème série ($P < 0.01$). Il n'y a pas eu de grande différence au niveau du taux de perception à l'effort entre les deux protocols.

Mots-clés: Entraînement de force, Performance athlétique, Force musculaire, Récupération

1. Introduction

Nowadays, resistance training is one of the most important training modes to enhance performance in any sport discipline [1], as well as to improve health in general population due to the wide range of benefits that it presents at a multi-organ level [2]. From all outcomes that we have to take into consideration in order to design resistance training programmes, interset rest is one of the key factors to achieve training goals and it should receive more attention from researchers [3]. Some investigations have analysed different types of recovery between sets in resistance training, but most of them have focused on evaluating how intervals of different duration influence on physiological and/or performance outcomes to determine the optimal rest time between sets according to the training goals [4-10]. In addition, it should be noted that there is significant heterogeneity in these investigations, not only in the people which has been investigated (men and women, age differences, different levels of physical condition, etc.), but also in the measured outcomes (maximum number of repetitions that the person is able to complete, mean velocity or power, blood lactate levels, etc.).

In sport performance, one of the key factors that coaches and trainers pursue is to produce the maximum strength in the minimum time, and this fact is related to muscle power (P), where both force (F) and velocity (V) are involved ($P = F \cdot V$). The production of maximum muscle power mainly depends on the metabolic pathways that arise in skeletal muscle cell cytoplasm, classically known as "anaerobic", where the phosphagen system [adenosine triphosphate (ATP) and phosphocreatine (PCr), ATP-PCr] stands out [11]. Therefore, the interset rest should allow the maximum restore of this system to be able to perform as much as possible during successive sets in a resistance training.

In the first 30 seconds of recovery after a brief and intense effort, such as performing a set during resistance training, 50% of the baseline levels of PCr can be restored; and after 2 minutes we could have resynthesized up to the 90% [12]. The synthesis of PCr is mediated by the "aerobic" metabolic pathways, therefore oxygen is required to restore the phosphagen system used during a completed effort. Thus, with an active recovery between sets in resistance exercises we may enable the irrigation of musculoskeletal tissue to improve the supply of oxygen to the muscle cells that could help phosphagen system restoration. With this, performance in successive sets during resistance training could be improved [13, 14].

In 1995, Hannie et al. [15] examined the effects of exercising at moderate intensity using a cycloergometer between sets when doing bench press exercise, and they were the first to show that active rest could enhance recovery during interset period when comparing with passive traditional rest. In this lane, Latella et al. [14] published a systematic review about the effects of different interset strategies in resistance training, and they concluded that active stimulus could improve performance and physiological outcomes but there is a wide range of stimulus that have been analysing, such as stretching, aerobic exercise, massage, etc.; and it is difficult to obtain practical applications for coaches to implement these strategies in their training programs.

When comparing active interset rest in resistance training, one of the approaches that has been studied is to maintain the activation in the same muscles that are mainly recruited during the exercise evaluated [16-19]. Scudese et al. [16] analysed the effects of active and passive interset rest during bench press exercise, being the active interset rest based on the same exercise but without any additional load (only the own arms weight). These authors showed that there were no differences between protocols in performance outcomes, and they concluded that active rest could increase fatigue when comparing with passive [16]. A few years later, Scudese et al. [17] investigated the effects of active and passive interset rest in lower-body using a similar experimental design, and they also concluded that there were no differences between active or passive strategies. However, Berlanga et al. [18] recently published an original research where they found a less intraset power loss for active interset rest when comparing with passive, without differences among perceptual outcomes. In the same vein, Timon et al. [19] demonstrated that an active interset rest using whole-body vibration focused on the same muscles that performed the exercise, may be an appropriate strategy to be implemented by untrained individuals to increase performance. Then, it seems that more research in this field is needed to help coaches to select the optimal interset rest strategies for their athletes during training sessions.

Thus, the aim of this study was to compare the effects of active interset rest between passive among kinematics, physiological and perceptual outcomes during the bench press exercise in young resistance-trained male. It was hypothesized that active interset rest minimizes intra and interset velocity and power loss, and reduces effort perception in comparison to passive interset rest in young resistance-trained male.

2. Materials and Methods

2.1. Subjects

A randomized cross-over design was used to compare the effects of active vs. passive interset rest during bench press exercise; thus, all participants completed both experimental conditions. All volunteers signed an informed consent and all procedures were in accordance with the Code of Ethics of the World Medical Association [20]. Data management was realized according to the current Organic Act on Data Protection; and this study belongs to a line of research approved by the Research Ethics Committee from the Francisco de Vitoria University, where it was carried out.

Nineteen young resistance-trained male took part in this study. A priori sample size calculation was performed by the G*Power 3.1.9.2 software using t-test family and the difference between 2 dependent means for matched pairs according to statistical tests of paired t-tests for related samples [21]. In addition, a one-tailed hypothesis, an α error probability of 0.05, a power (1-β error probability) of 0.80 and a large effect size [22] were considered. Thus, a total sample size of 12 participants was necessary to achieve an actual power of 0.828. Finally, considering a possible loss to follow-up, a sample size of 19 participants was recruited.

Inclusion criteria were male, age between 18-24 years, at least 2-years resistance training experience, to train strength at least twice per week currently, 1RM in bench press of at least 80% of body-weight, and not having any contraindication to perform physical activity.

We encouraged all participants to keep their usual lifestyle regarding physical exercise, hydration, and diet behaviour; but they should avoid training upper-limbs, at least, 72 hours before to visit our laboratory; as well as to avoid caffeine or any other stimulant substances or ergogenic aids, at least, 3 hours before measurements.

2.2. Training protocols

All participants visited our laboratory at three different times. During the first visit, we completed a maximal power (Pmax) test for bench press in a Smith machine (Evolution Deluxe Smith Machine and Rack, Titanium Strength, Spain) following the protocol described by others [23, 24], followed by a one-repetition maximum (1RM) test in vertical chest press (Compact C01, Bodytone, Spain). In addition, we explained to them the proposals of our study, the procedures and we collected demographic data from each participant. This session started with a 5-min cardiovascular activity at moderate intensity as a general warm-up, followed by joint mobility exercises for upper-limbs and 4-5 min of passive rest. Then, participants performed 1x10 for bench press in the Smith machine without any additional load (bar weight was 21 kg) at a controlled velocity of execution (2 sec for the concentric phase and 2 sec for the eccentric), followed by 4-5 min of passive rest; and after this set they achieved 1x3 at 20% 1RM estimated at maximal velocity for the concentric phase, followed by 4-5 min of passive rest.

Pmax test was developed performing 1x3 at maximal velocity for the concentric phase using 30, 40, 50, and 60% 1RM estimated, until we checked Pmax was achieved; with 4-5 min of passive rest between each set. Landmarks were used to ensure similar position of each subject for each training protocol. Once this test was concluded, we completed the 1RM test in vertical chest press to determine the load we would use during active interset rest protocol, where all subjects were able to complete between 2-5 repetitions until muscle failure and we calculated 1RM using the equation by Brzycki [25]. We used vertical chest press for active interset rest because a pilot study indicated that remaining in bench press during rest periods was very uncomfortable due to the supine position.

The next 2 sessions were separated by, unless 72 hours. We randomly selected during each visit the protocol every participant will perform: active or passive. During each protocol, warm-up was the same for the first day. For passive protocol (PAS), participants achieved 2x8 at maximal velocity using the optimal load for Pmax (OptLoad Pmax), and a 3rd set until muscle failure; resting between each set 2-min in a passive rest (Figure 1). For active interset rest (ACT), the protocol was the same but resting between each set 2-min in an active mode, where they were performing repetitions at vertical chest press with 5-10% 1RM at a controlled velocity by a metronome (2 sec for the concentric phase and 2 sec for the eccentric one; Metronome Beats 5.0.1) (Figure 1).

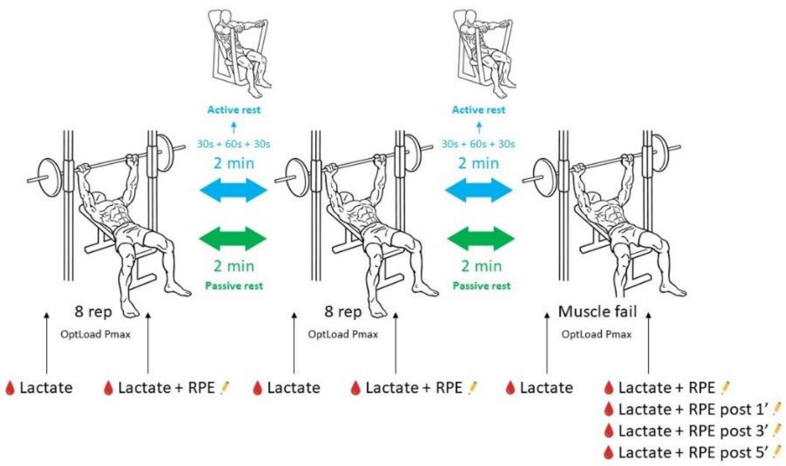

Figure 1 Experimental design.

(OptLoad Pmax, optimal load for maximal power; rep, repetitions; RPE, rate of perceived exertion)

2.3. Outcomes

Mean propulsive power (MPP) and mean propulsive velocity (MPV) for each repetition was registered of every repetition by a lineal encoder (Chronojump), with a frequency of 1000 Hz, and was measured with a specific software for data analysis (Chronojump 1.8.1-95). This device has been previously validated as a system to assess load displacement velocity in a resistance training machine [26]. Both intraset MPP and MPV loss was calculated using two different equations: (1) the difference between the first rep respected the last one for each set, according to the data published by Sánchez-Medina and González-Badillo [27] regarding the evaluation of velocity loss in resistance training (P_{Lost1} and V_{Lost1}); and (2) the difference between the mean values for the first 2 repetitions respected the last 2 repetitions for each set, according to the data published by Rial-Vázquez et al. [28] (P_{Lost2} and V_{Lost2}). Exploratory analysis based on the full longitudinal dataset revealed no influence of non-linear repetition (see "Supplementary File"). Thus, for simplicity we assumed linear relationship for the MPP and MPV across repetitions within series.

The maximal numbers of repetitions realised during the last set (nRM) was registered by the total number of repetitions completed by each subject until muscle failure.

Blood lactate levels (Lact) were obtained with a portable analyser (Lactate Pro 2, Busimedic, Spain) before and after each set (Lact Pre and Lact Post sets 1, 2, and 3; respectively), and 1, 3 and 5 minutes after the last set until muscle failure (Lact Post1, Lact Post3, and Lact Post5; respectively).

Rate of perceived exertion (RPE) was registered with a scale from 0 to 10 points adapted to resistance training, with 0.5 points accuracy allowed for volunteer's responses. We registered RPE at the end of each set (RPE 1, RPE 2, and RPE 3; respectively); and 1, 3 and 5 minutes after the last set (RPE Post1, RPE Post3, and RPE Post5; respectively).

2.4. Statistical analysis

All data were analysed using SPSS 20 (SPSS Inc., Chicago, IL, USA). Normality was confirmed for each outcome with Shapiro-Wilk test, and data homogeneity was checked with Levene's test. A t-test for repeated measures was used to compare related changes to each protocol (ACT vs. PAS) in dependent outcomes: mean propulsive power for each set (MPP), mean propulsive velocity for each set (MPV), intraset loss of MPP and MPV (P_{Lost1}, P_{Lost2}; and V_{Lost1}, V_{Lost2}; respectively), blood lactate levels (Lact), and rate of perceived exertion (RPE). Statically significance was fixed with a $P \leq 0.05$, with a confidence interval of 95%. Pearson's correlations analysis were used to examine the relationships between MPP intraset loss and blood lactate levels before the set, and the effect size of the correlations was interpreted as small

(<0.3), moderate (>0.3 and <0.5), and large (>0.5) according to the scale proposed by Cohen [22]. Values are expressed as mean ± SD in the text, as well as in tables and figures.

3. Results

All demographic data showed a normal distribution for age, height, weight, body mass index (BMI), training experience, Pmax, and 1RM for vertical bench press (Table 1).

Table 1 Participants demographic values.

	Total (n = 19)
Age (years)	22.21 ± 1.03
Height (cm)	176.89 ± 0.77
Weight (kg)	75.22 ± 10.10
BMI (kg/m^2)	23.89 ± 2.33
Experience (years)	4.01 ± 1.85
1RM vertical press (kg)	115 ± 33
Pmax (W)	654 ± 154

(BMI, body mass index; 1RM, one-repetition maximum; Pmax, maximal power)

There were not significant differences neither for the MPP nor for the MPV among both protocols between sets. However, intraset loss of MPP (P_{Lost}) was lower in ACT compared with PAS for almost all sets; being these differences statistically significant for the 1st set (P = 0.014 for P_{Lost1}, and P = 0.006 for P_{Lost2}) (Table 2).

Table 2 Mean propulsive power loss intraset (%) for both protocols.

	ACT		**PAS**	
	P_{Lost1}	**P_{Lost2}**	**P_{Lost1}**	**P_{Lost2}**
Set 1	11.53 ± 3.61*	9.15 ± 2.84*	15.96 ± 5.74*	12.71 ± 4.30*
Set 2	16.07 ± 5.85	12.87 ± 4.82	16.46 ± 7.15	12.85 ± 5.23
Set 3	13.04 ± 6.23	10.96 ± 5.52	14.64 ± 5.86	12.31 ± 5.11

*P < 0.05

(P_{Lost}, intraset power loss; ACT, active interset rest; PAS, passive interset rest)

In regard with intraset loss of MPV (V_{Lost}), it was lower in ACT compared with PAS for all sets; being these differences statistically significant for the 1st set (P = 0.016 for V_{Lost1}, and P = 0.007 for V_{Lost2}) (Table 3).

Table 3 Mean propulsive velocity loss intraset (%) for both protocols.

	ACT		**PAS**	
	V_{Lost1}	**V_{Lost2}**	**V_{Lost1}**	**V_{Lost2}**
Set 1	9.78 ± 3.23*	7.70 ± 2.55*	13.71 ± 6.54*	11.06 ± 5.24*
Set 2	12.81 ± 5.70	9.78 ± 4.33	13.51 ± 6.65	10.62 ± 4.67
Set 3	9.35 ± 5.50	7.52 ± 4.73	10.76 ± 4.97	8.72 ± 4.34

*P < 0.05

(V_{Lost}, intraset velocity loss; ACT, active interset rest; PAS, passive interset rest)

Participants were able to achieve a larger number of repetitions during the last set until muscle failure (nRM) with ACT protocol, but this difference was not significant (46.79±3.56 vs. 45.47±2.96, respectively; P = 0.281).

There was a significant increase in lactate before and after the last set for both protocols (P < 0.001). Furthermore, we found a significant increase only for the PAS protocol when comparing blood lactate levels at the end of the set and before starting the consecutive set (Table 4, Figure 2).

Table 4 Blood lactate levels (mmol/L) progression during 2 min interset rest intervals for both protocols.

	ACT	**PAS**
Lact $Post_{set1}$	2.432 ± 1.134	2.500 ± 0.760*
Lact Pre_{set2}	2.774 ± 0.713	3.068 ± 1.067*
Lact $Post_{set2}$	3.205 ± 1.867	3.063 ± 0.777*
Lact Pre_{set3}	3.084 ± 0.717	4.032 ± 1.515*

*P < 0.001

(Lact, lactate; ACT, active interset rest; PAS, passive interset rest)

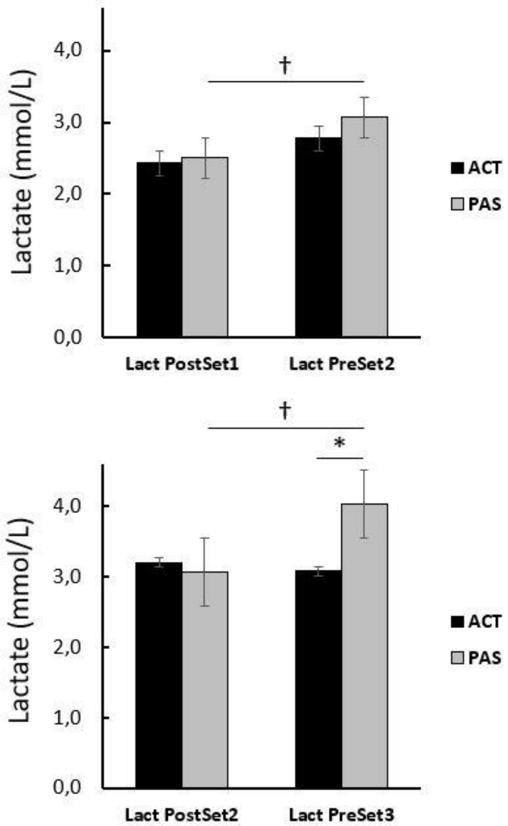

Figure 2 Blood lactate levels progression during 2 min interset rest intervals for both protocols.

(ACT, active interset rest; PAS, passive interset rest)

In addition, blood lactate levels were significantly higher in PAS comparing with ACT before starting the 3rd set (4.031±1.515 vs. 3.084±0.717, respectively; P = 0.003).

We also found a significant large correlation when comparing MPP intraset loss calculated with both equations with blood lactate levels before the set, but only for the ACT protocol and for the 3rd set (r = 0.53 for P_{Lost1}, P = 0.021; and r = 0.50 for P_{Lost2}, P = 0.029).

There were no significant differences for RPE between both protocols.

4. Discussion

Our major finding is that active interset rest decreased intraset power and velocity loss, enhanced blood lactate clearance, and it was well tolerated by all participants. These findings about active interset rest tolerance are in agreement with previous research where it has been analysed the effects of active rest between sets during a resistance training session where the muscles involved during rest periods were the same as those involved in the evaluated exercise [16-19, 29].

Scudese et al. [16] examined the effects of active and passive interset rest with the same duration (2 min) when performing 4x10RM in bench press, where the active protocol included the same movement as the exercise performed but without any additional load (only the own arms weight) at a controlled velocity of execution of 80 phases (concentric and eccentric) per minute. Their results showed that active interset rest did not decrease performance but elicited more fatigue as measured with RPE scale [16]. However, the fatigue increase with active interset rest protocol could be explained by the high velocity of execution used during interset rest, which could not facilitate phosphocreatine resynthesis for successive sets during resistance training, although they did not measure any physiological outcome, such as blood lactate levels or creatine phosphokinase (CPK).

In addition, Scudese et al. [17] analysed the effects of active and passive interset rest with an experimental design similar to the previous study but using a lower-limbs exercise (half squat), and they also concluded that active interset rest does not decrease performance but significantly increased fatigue. These results differ from the present study, probably, for several reasons: (i) the load used during the active interset rest protocol was equal to body-weight (half squat without additional load), which could entail a different internal load for each participant and it could impair recovery between sets; (ii) the velocity of execution of the active interset rest (60 phases, concentric and eccentric, per minute) could be too high and it probably involved the participation of the cytosolic glycolysis energy system to satisfy the synthesis of ATP demanded throughout the effort performed during recovery; and (iii) the experimental design used in which the subjects performed 5x10RM supposes a different physiological response to the one we propose in the present study, with an intervention based on muscle power training, where we use the optimal load for the maximum power output that was low- to moderate-load, corresponding to the optimal loads for maximum power production evidenced for resistance-trained subjects by previous literature [30].

In the same vein, Berlanga et al. [18] compared the effects of an active interset rest to passive during bench press exercise when using the optimal load for maximum muscle power and performing 2x8 followed by one last set until muscle failure. Active interset rest lasted 2 min, as well as passive rest, and it was developed in a vertical chest press with a 5-10% of 1RM load and performing each repetition with a controlled velocity of execution (2 sec for the concentric phase and 2 sec for the eccentric one). These authors demonstrated that active interset rest minimized intraset power loss compared to passive rest [18], like we showed in the present study for both power and velocity intraset loss and using two different equations to calculate it. Moreover, Timon et al. [19] also studied the effects of an active interset rest in bench press exercise using whole-body vibration applied to the same muscles that were recruited during the exercise for 30s before starting each consecutive set, and using an equivalent interset rest period of 2 min for both active and passive conditions. Their results showed that active interset rest increases velocity and bar acceleration during the first set in untrained subjects, but they could not find significant differences for the rest of the sets, neither for trained participants [19], probably because during active interset rest participants held on an isometric contraction while placing their hands on the vibration platform which might suppose the activation of many muscle groups that could increase excessively the metabolic responses and impair performance in consecutive sets during the exercise.

In regard with blood lactate levels, the greater elimination of this metabolite with active stimuli has been demonstrated by previous literature [29, 31]. Moreover, the most relevant of our findings was that during the interset rest, blood lactate levels even decreased through the interval from the 2^{nd} to the 3^{rd} set only for the ACT protocol, which could indicate a metabolic advantage for successive sets performance that characterised resistance training sequence organisation. For this reason, a lower intraset power and velocity loss could be explained in comparison with the PAS protocol, although we did not find differences neither for the MPP nor for the MPV for each set between protocols.

Additionally, active interset rest could increase excitability of the motor endplate, which may influence the afferent pathway related to the critical threshold of peripheral fatigue facilitating contractibility muscle in successive sets during resistance training [32], mechanism that may help to explain the lower intraset power and velocity loss found for ACT protocol in the present study.

Altogether, our data could help coaches and trainers to improve athlete's recovery during resistance training sessions, and including active interset rest, doing a similar movement that the one performed during training, may enhance performance in successive sets when using optimal load for maximal muscle power production.

Nevertheless, some limitations from our study are that we have just measured resistance-trained young male, we analysed an upper-body exercise, and we did not collect any biomarker directly related to phosphagen system (such as CPK, for example). Therefore, more research is needed in this lane to better understand the effects of active interset rest among kinematics, physiological and perceptual outcomes during resistance training sessions.

5. Conclusions

In conclusion, during resistance training sessions focused on maximal muscle power production, that is using low- to moderate-load and performing each repetition at the maximum possible velocity of execution, active interset rest based on the same exercise that the one which is executed during training session, reduce intraset power and velocity loss and enhance blood lactate clearance in young resistance-trained male in comparison to passive interset rest. However, to obtain these positive effects from active interset rest, the performed exercise during the rest period should use low load and it should be executed at a low velocity in order to enhance recovery.

Disclosure of interest

The authors declare that they have no competing interes.

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Supplementary File:

Linear and non-linear variation in MPP and MPV across repetitions: a longitudinal analysis

This appendix describes the results of longitudinal analyses of variation in mean propulsive power (MPP) and mean propulsive velocity (MPV) across repetitions within series.

For simplicity and comparison, as demonstrated by Iglesias-Soler et al. [1] for force-velocity relationship, we transformed longitudinal data obtained from repeated measurements across series to cross-sectional data by (i) the first repetition (rep) vs. the last one for each set, and (ii) the mean values for the first 2 reps vs. the last 2 reps for each set (see in main text for details). This simplification is based on the assumption that MPP and MVP change linearly across repetitions. To validate this assumption, we first examined the goodness of fit of candidate models testing for linear and curvilinear patterns of variation in each parameter. We used linear and nonlinear mixed-effects models (LMM) including MPP and MVP as dependent variables in separate models. The models included protocol (active vs. passive) as a fixed effect to account for the potential effect of interset rest, and linear and quadratic repetition as covariates. We fitted set identity nested within subject identity as a random effect. This accounted for the non-independence of repeated measurements within each set and also controlled for variation between subjects attributable to intrinsic factors of the individual, such as age or physical condition levels.

For the GLMMs, we used the package 'glmmTMB' [2] in the R environment, version 4.0.0 (http://cran.r-project.org). We carried out model validation based on QQ-plots and residuals vs. predicted values plots provided by the package DHARMa [3]. To assess the statistical support for each model, we used the Akaike Information Criterion (AIC) and compared the AIC values to ascertain the model that best described variation in MPP and MVP (i.e., the model having the lowest AIC value) [4]. Models that differed by less than 2 AIC units were considered to receive comparable support [4]. We also evaluated goodness-of-fit based on the conditional R^2, a parameter that estimates the fraction of variance in the response explained by fixed and random effects combined [5]. To compute the conditional R^2, we used the *r.squaredGLMM* function of the 'MuMIn' package [6].

Results

Based on the AIC values, the models including the nonlinear effect of repetition had the same (MPP) or less (MVP) support than those including linear repetition only (Table SF1). Both LMMs provided a good fit to the data according to the conditional R^2 values (Table SF1). The addition of nonlinear repetition to the models increased the proportion of variance explained by only 0.01% and 0.05% for MPP and MVP respectively (Table SF1). Overall, these results indicate that the nonlinear effect of repetition did not improve model fit, supporting the assumption that MPP and MVP change linearly across repetitions (see Figure SF1).

Table SF1 Comparison of the AIC values and conditional R^2 of the mixed-effect models analysing linear and nonlinear variation in MPP and MVP across repetitions (Rep).

Model structure	d.f.	AIC	**Δ**AIC	$R^2_{conditional}$
(a) MPP				
Protocol + Rep	7	8877.255	0	0.9501
Protocol + Rep + Rep^2	8	8877.550	0.295	0.9502
(b) MVP				
Protocol + Rep	7	-2440.680	0	0.9488
Protocol + Rep + Rep^2	8	-2446.417	5.737	0.9493

NOTE: All models included set identity nested within subject identity as a random effect (number of observations = 912; number of subjects = 19).

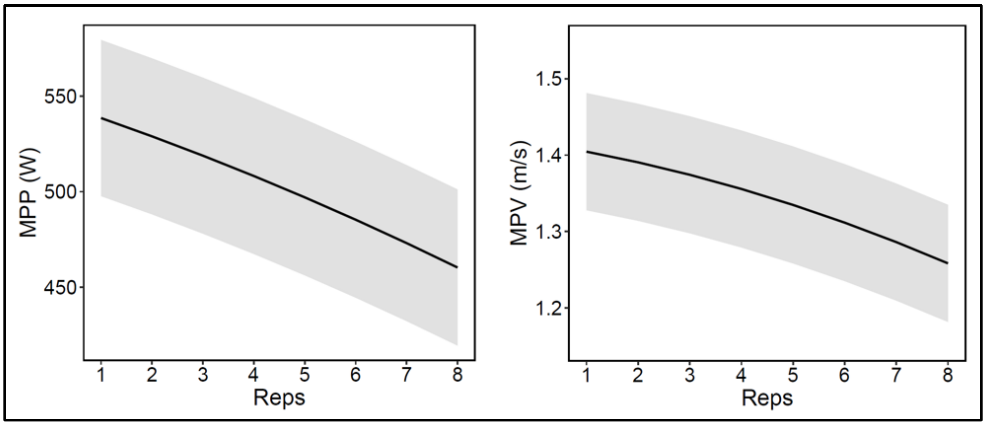

Figure SF1 Effect of repetition on MPP (left) and MVP (right). The shaded area is the 95% confidence interval of the regression model accounting for the effect of repetition, series and subject identity.

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