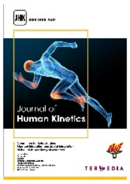

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Section III – Sports and Physical Activity

Acute Responses of Blood Lactate, the Countermovement Jump, and the Rating of Perceived Exertion after Flywheel Squats using Varied Power-Loss Thresholds

by

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This study examined acute responses of blood lactate concentration ([La]), the countermovement jump (CMJ) and the rating of perceived exertion (RPE) after performing flywheel exercise at different power-loss thresholds (10% vs. 15%). Fourteen senior male basketball players (mean ± SD; age: 24 ± 3 years; body height: 1.89 ± 0.06 m; body mass: 84.8 ± 10.1 kg) were recruited. Participants completed three sets with 2-min inter-set rest intervals using a squat flywheel device in counterbalanced and randomized order. [La] and the CMJ (jump height, peak force, and the reactive strength index modified (RSI_{mod})) were assessed before and after the exercise protocol at 1-, 3-, 5-, 7-, and 9-min time points. The level of significance was set at 0.05. Very-large time effects were present on [La] (mmol·L^{-1}), large-to-medium effects on jump height (cm), small-to-medium effects on peak force (N) and large effects on the RSI_{mod} (AU). There were differences between protocols only for [La] (medium effect). The 15% condition presented larger [La], greater jump height and RSI_{mod} reductions compared to the 10% condition. No differences were found for the rating of perceived exertion (AU), and delayed onset of muscle soreness (AU). In conclusion, high acute metabolic and neuromuscular stress was caused by both protocols, with greater detrimental effects following the 15% condition.

Keywords: *performance; jumping; sports; inertial; monitoring*

Introduction

Researchers and practitioners are always in the continuous process of finding new methods for improving athletic performance. Athletic training using flywheel devices has gained much interest recently, making them a commonly used technology to enhance strength and power (Petré et al., 2018). Although flywheel interventions seem not to provide better strength adaptations than gravity-dependent interventions (Vicens-Bordas et al., 2018), they have become one of the more relevant tools in strength and conditioning environments because of their unique advantages (e.g., variable resistance and eccentric overloading without third-party assistance) (De Keijzer et al., 2022a; Harden et al., 2020). Flywheel technology emphasizes eccentric actions by utilizing the energy stored in the flywheel system after a maximal concentric action. The flywheel's strap unwinds, creating kinetic energy that produces higher power production at the end of the eccentric phases. Eccentric overloading can be obtained if appropriate technique, familiarization, and equipment are utilized, and should be measured to be confirmed (Beato et al., 2024; Muñoz-López et al., 2022). Hence, exercise intensity can be adjusted by using flywheel wheels with different moments of inertia or adding and removing different masses integrated into the wheel. This technology has contributed to improved sports performance, resulting in greater muscle mass, force, and speed,

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as well as reduced injury risk (Beato et al., 2021a, 2021c; Carroll et al., 2019; Younes-Egana et al., 2023). Despite all this evidence, further knowledge on properly using these devices is needed to understand their physiological and neuromuscular effects, both acute and chronic, and to assist in practical applications (Beato et al., 2024).

In parallel, velocity-based training has gained traction for optimizing training efficiency and individualizing prescriptions, mainly using velocity-loss thresholds to monitor acute neuromuscular fatigue (Pareja-Blanco et al., 2017; Weakley et al., 2020, 2021). Velocity-based training allows practitioners to monitor loads and daily fluctuations in performance and readiness when using gravity-dependent interventions (Weakley et al., 2021). Therefore, using velocity and velocity-loss thresholds enables a better understanding of acute neuromuscular fatigue (Sánchez-Medina and González-Badillo, 2011). The relationship between velocity loss and metabolic responses underscores its relevance in structuring training volumes to elicit specific adaptations, with higher velocity loss favoring hypertrophy and lower velocity loss enhancing acute neuromuscular performance and reducing fatigue perception (Pareja-Blanco et al., 2017; Rodríguez-Rosell et al., 2021; Weakley et al., 2020). However, integrating velocity-based approaches into flywheel training remains a challenge, considering that the repetition to failure concept cannot be used (Maroto-Izquierdo et al., 2021).

When using flywheel devices, the linear velocity of the centre of mass could be obtained using a linear encoder or a kinematic analysis (Carroll et al., 2019; McErlain-Naylor and Beato, 2021); however, these approaches are not very practical. Instead, rotary encoders can reliably measure angular velocity, force and power production since they are included in almost all commercially available flywheel devices (Beato et al., 2021b, 2024). However, power is suggested to be monitored when using flywheel devices instead of force due to their reliability and also since it is the most common variable utilized by many practitioners (Beato et al., 2024; Maroto-Izquierdo et al., 2021). Although most of the interest in the literature has been focused on the differences in power production using diverse moments of inertia (ranging from 0.029 to 0.11 kg·m^2) (Beato et al., 2021a; Sabido et al., 2018, 2019), no studies so far have focused on the use of power loss thresholds to control the number of repetitions of a set efficiently, to end a set, or to prescribe the total training load.

Along the same line, any training stimulus could either provide reduced performance or a post-activation performance enhancement (PAPE) effect in a short period. In acute studies, flywheel training can induce PAPE in activities such as jumps, acceleration or change of direction tests (Beato et al., 2020). Most studies analyzing acute effects of flywheel exercise interventions have used pre-established sets and repetitions (from 2 x 6 to 4 x 8) (Beato et al., 2019, 2020; De Keijzer et al., 2020). Some provided PAPE effects at 3–6 min post-exercise using medium (0.029 kg·m^2) and high (0.061 kg·m^2) inertias, and resulted in improved long jump performance, countermovement jump (CMJ) height, CMJ peak power, and change of direction in a 5-m test (Beato et al., 2021a). Using the adequate rest interval between sets seems relevant then, affecting power production during the performed sets, as well as the acute blood lactate concentration ([La]) and perception of effort (Sabido et al., 2020). However, these effects can be exercise-dependent, expressing different inertia-power relationships depending on the exercise performed (De Keijzer et al., 2022b). However, inter-individual differences are generally present in exercise interventions, with some participants not reaching the desired PAPE effects (Boullosa et al., 2020), thus for them, the individualization of the exercise stimulus (total number of repetitions per set) using power-loss thresholds could be a promising tool. Hence, the relationship between power loss and acute effects using flywheel devices remains unexplored, presenting a notable gap in current knowledge (Buonsenso et al., 2023).

To address this gap, the present study aimed to explore the utilization of power-loss thresholds during flywheel resistance training, focusing on individualizing exercise doses based on power loss rather than predetermined set repetitions. By comparing the metabolic (blood lactate), neuromuscular (CMJ derived measures), and perceptual responses (RPE and DOMS) at different power loss thresholds (10% vs. 15%), this research aimed to elucidate the role of power loss as a marker for controlling acute fatigue during flywheel training and its implications for enhancing athletic performance. It was hypothesized that power loss would be a good marker to control acute fatigue when training with flywheel devices and that different thresholds would produce diverse metabolic, neuromuscular, and perceptual responses.

Methods

Participants

An *a priori* power analysis (G*Power version 3.1.9.6, Heinrich Heine University Düsseldorf, Germany) revealed that 20 participants (10 considering the cross-over design) would provide a >84% chance (actual power = 0.8418) of achieving $\alpha = 0.05$ in a frequentist 2 × 6 repeated measures analysis of variance, assuming an effect size of 0.25 and a correlation among repeated measures of 0.5. Considering sphericity assumption violation, 12–14 participants were assumed to be a conservative choice. In this study, we enrolled 14 senior male basketball players (mean ± SD; age: 24 ± 3 years; body height: 1.89 ± 0.06 m; body mass: 84.8 ± 10.1 kg) who competed in the Spanish 3rd and 4th tier (LEB Plata and EBA) during the 2021–2022 season. The basketball players had more than 5 years of competitive experience, with a standard of 3 to 5 days of training and one match per week. While all the players had more than 2 years of experience in resistance training in their respective teams, only few used flywheel devices before the intervention. The study followed the principles of the Declaration of Helsinki (Harriss and Atkinson, 2015). All players were informed about the procedures of the study and agreed to participate. After receiving information about the study aims, possible risks, benefits, and requirements, participants signed a written informed consent form before starting the intervention. Every subject could withdraw from the study at any moment. The study was approved by the Ethics Committee of the Universitat de Vic—Universitat Central de Catalunya, Barcelona, Spain (protocol code: 167/2021; approval date: 27 July 2021).

Design and Procedures

This study used a randomized crossover design to evaluate the acute effects induced by two different flywheel training conditions (10% vs. 15% power loss) on metabolic ([La]), neuromuscular (CMJ performance), and perceptual (subjective rating of perceived exertion (RPE) and delayed onset of muscle soreness (DOMS)) variables (Figure 1). The CONSORT guidelines were followed in this study (Moher et al., 2010). Participants were allocated to one of the interventions using a block randomization technique (ABBA sequencing, A = 10% and B = 15%) as they entered the study. Subject 1 started performing the 10% intervention on the first day and then completed the 15% intervention on the second day. Participants were informed about the order of the conditions on the first day of the intervention once the familiarization period was completed.

The study took part in May 2022, once the competitive period of the players was finished and before starting the transition period (holidays). Participants were required to maintain their habitual nutritional intake during the experimental period. Each participant attended the laboratory on four separate occasions. The first two visits served as familiarization sessions, where participants were introduced to the experimental protocol. During the remaining two visits, participants randomly performed both training interventions (10% or 15% power loss), with a four to seven-day recovery between sessions.

During the first familiarization session, players gave written consent to participate, and anthropometric measures (body mass and height) were taken. Then, during both familiarization sessions, participants performed the entire warm-up protocol (described in the following paragraph). Following the warm-up, they performed three CMJs on the force plates, then three to four sets of flywheel squats of 12–15 repetitions with self-selected recovery between sets, and finally three CMJs. Blood samples were not collected during the familiarization sessions, but the entire protocol was explained to the participants.

The standardized warm-up consisted of 5 min of jogging followed by dynamic mobility exercises (hamstring, quadriceps, calves, and adductors active stretching of three repetitions of 6 s) and bodyweight squats and hip hinges (6 repetitions of each exercise). The last part of the warm-up consisted of three CMJs and six repetitions of the flywheel squat. After 3 min of rest, participants performed three CMJs (baseline score), followed by the exercise protocol. Just after finishing the last set, participants proceeded to the

[La] analysis and the CMJ (one maximal attempt) at five time points (post 1, 3, 5, 7, and 9 min). Information about the subjective RPE was collected at the end of the session, and while data on DOMS were collected at 24 h, 48 h, and 72 h post-sessions.

Measures

The exercise protocol (Figure 1) consisted of 3 sets of the maximal number of repetitions (until pre-established power-loss was reached for the 10% or 15% condition) of a half-squat exercise using a flywheel device (RSP Squat, RSP Inercial Performance, Pontevedra, Spain). The concentric power production was monitored using a rotary encoder (Chronojump Boscosystem v2.2.1, Barcelona, Spain) (Beato et al., 2024), and the maximum power production from each set was used to calculate either the 10% or the 15% power-loss threshold. Participants were instructed to stop each set when two repetitions reached a 10% or 15% power loss of the maximum concentric power output reached in each set (usually, this maximum was attained in the first three repetitions, without accounting for the first two repetitions needed to initiate the exercise). Two minutes of passive recovery were allowed between sets. The inertial load used for the exercise protocol was 0.0514 kg·m^2. All sessions were evaluated qualitatively by an investigator to ensure appropriate technique. Participants were instructed to perform the concentric phase with maximal velocity and to achieve approximately 90º of knee flexion during the eccentric phase, breaking the movement in the last third of the movement as recommended (Beato et al., 2024).

Blood lactate concentration [La] was analyzed before the start of the warm-up at rest and after the exercise protocol (post: 1, 3, 5, 7, and 9 min) using Lactate Plus (L+, Nova Biomedical, USA). After sterilizing the ring finger, a puncture was made with a spring-loaded single use disposable lancet. The first drop of blood was wiped away to avoid contamination, and the participant's blood was then collected into the strip. The samples were then immediately analyzed for [La]. The device was calibrated before each session using two samples of known concentrations.

The CMJ was assessed using two portable force plates (37 cm x 37 cm, PASCO, Passport PS-2142, Roseville, USA), collecting the data at a sample rate of 1,000 Hz with the PASCO Capstone software v2.5.1 (PASCO, Roseville, USA). Each CMJ was performed with each foot on each force plate. Force plates were powered on 30 min before data collection and tared before each session. Participants were instructed to remain as still as possible (at least 1 s), with hands on the hips, until given the command to "jump". They were instructed to use a self-selected countermovement depth to perform a maximal effort vertical jump "as quickly and explosively as possible", landing back onto the force plates and returning to the starting position. For each jump, verbal encouragement was provided to ensure maximal effort was given during each attempt. Force-time data were not filtered and was processed using a customized spreadsheet. Previous research supports the analyses of raw over-filtered CMJ force-time data (Harry et al., 2022). Three CMJ variables (jump height [cm], peak force [N], and RSI$_{\text{mod}}$ [AU]) were chosen as outcomes of interest. The best baseline jump height was used as the baseline score.

The subjective rating of perceived exertion (RPE) (Robertson et al., 2003) was used to monitor the subjective perception of effort after each protocol. This information was collected after the last CMJ, about 10 min after the previous set of squats. Participants were required to answer the question "How hard was the exercise?" with the following anchor points: "0 = extremely easy" and "10 = extremely hard".

Perceived delayed onset of muscle soreness (DOMS) (Sabido et al., 2020) was reported at 24 h, 48 h, and 72 h after each exercise protocol for different muscle groups (quadriceps, hamstrings, adductors, calves, and quadratus lumborum). Participants were invited to answer five questions (one for each muscle group) via an online questionnaire: "How painful does your "respective muscle" feel?" rating their subjective feeling on a 0–10 scale (0 = no pain; 10 = a lot of pain).

Statistical Analysis

Data were summarized as mean ± SD and 95% confidence intervals (CIs). The within-subject reliability of test measures (intersession repeated efforts) was analyzed using a two-way random intraclass correlation coefficient (ICC) with the 95% CI and a coefficient of variation (CV). For interpretation, ICC values >0.9 were considered excellent, 0.9–0.75 good, 0.75–0.5 moderate, and <0.5 poor (Koo and Li, 2016), and CV values were considered acceptable if <10% (Cormack et al., 2008). The authors followed the CHAMP checklist for assessing the statistics used in the study (Mansournia et al., 2021).

Data were analyzed using repeated measures ANOVA (RMANOVA), comparing the effects of condition (10% or 15%), time (baseline, 1, 3, 5, 7 and 9 min post exercise) and their interaction on [La] ($mmol·L^{-1}$) and CMJ output (jump height [cm], peak force [N] and RSI_{mod} [AU]). All assumptions were assessed, the residuals' normality was evaluated checking the Q-Q plot, the Levene's test was applied to check the homogeneity, and the Mauchly's test was used when sphericity was violated. When significant effects were found in the RMANOVA, post hoc tests were performed using Bonferroni correction for multiple comparisons. Cohen's *d* effect sizes were used to report the magnitude of the differences and were interpreted as: <0.20 = trivial; 0.20–0.59 = small; 0.60–1.19 = moderate; 1.20–1.99 = large; and >2.00 = very large (Hopkins et al., 2009). Unless otherwise stated, significance was set at $p < 0.05$ for all tests. Analyses were conducted using the JASP package (Version 0.16.4, JASP Team (2022) [Computer software]).

Results

The results are summarized in Tables 1–3, Figure 2, and supplementary material. Intra-session reliability was excellent for all the CMJ variables, with the specific SEM, CV, and SWC of each variable reported in Table 1. Two participants could not complete the study; one was ill during one of the study sessions, and the other could not attend the two familiarization sessions, and thus, they were excluded.

The power production and the number of repetitions for each condition (10% and 15%) are reported in Table 2. Participants performed more repetitions per set ($p < 0.001$) during the 15% condition while producing the same amount of power (average, $p = 0.47$; and maximum, $p = 0.90$).

Blood Lactate Concentration

Blood lactate concentration showed a significant time (F = 136.43, $p < 0.001$) and condition (F = 6.05, $p = 0.023$), but no interaction (F = 2.09, $p = 0.073$) effect. Post hoc tests (Figure 2 and Table 3) showed very large effects of [La] from the 1st to the 9th min post-exercise compared to baseline ($p < 0.001$, *very large*). [La] differed between conditions ($p = 0.023$, *medium*). The 10% condition resulted in faster [La] clearance, showing reduced [La] values at the 7th min post-exercise (–2.58 $mmol·L^{-1}$, $p = 0.001$, *large*) using the 1-min value as a reference. On the other hand, the 15% condition resulted in clearing [La] at the 9th min (–2.35 $mmol·L^{-1}$, $p = 0.007$, Table 3) using the 1-min post-exercise value as a reference.

CMJ Jump Height, Peak Force, and RSImod

Jump height showed a significant time (F = 23.19, $p < 0.001$) and interaction (F = 2.64, $p = 0.027$), but no condition (F = 0.39, $p = 0.539$) effect. Post hoc tests (Figure 2 and Table 3) showed a jump height reduction at the 1st min post exercise (–4.54 cm, $p < 0.001$, *large*) without returning to baseline levels during the whole 9-min period of recovery (–2.83 cm, $p < 0.001$, *medium*).

Peak force showed a significant time effect (F = 4.32, $p = 0.001$), but no condition (F = 0.059, $p = 0.810$) or interaction effect (F = 1.10, $p = 0.364$). Post hoc tests (Figure 2 and supplementary material), showed a reduction in peak force production only at the 1st min post-exercise (–88.8 N, $p < 0.001$, *medium*).

The RSI_{mod} showed a significant time (F = 12.96, $p < 0.001$), but no condition (F = 0.19, $p = 0.666$) or interaction (F = 2.03, $p = 0.081$) effects. Post hoc tests (Figure 2 and supplementary material) showed an RSI_{mod} reduction from the 1st to the 9th min post exercise compared to baseline ($p < 0.001$, *medium* to *large*).

Subjective RPE and DOMS

The reported subjective rating of perceived exertion (RPE) in arbitrary units (AU) was the same in both conditions ($p = 0.72$), with 6.9 ± 1 AU and 7.2 ± 1 AU for the 10% and 15% conditions, respectively. Delayed onset muscle soreness (DOMS) was observed in all muscle groups, with a time effect showing peak DOMS at 24–48 h and reduced DOMS at 72 h. There were no significant differences ($p > 0.05$) in DOMS between the 10% and 15% conditions (supplementary material for more details).

Table 1. Reliability measures for CMJ variables (jump height, peak force and RSI_{mod}).

	Jump height (cm)	Peak force (N)	RSI_{mod} (au)
ICC [95% CI]	0.91 [0.78–0.97]	0.90 [0.75–0.97]	0.87 [0.69–0.96]

	Trial 1	Trial 2	Trial 3	Mean	SEM (95% CL)	CV % (95% CL)	$SWC_{0.2}$
CMJ (cm)	39.6 ± 4.1	39.6 ± 4.1	40.3 ± 3.9	39.8 ± 4.1	1.2 (0.9–1.9)	3.1% (2.3–4.7)	0.8 cm (2.0%)
Peak force (N)	1229 ± 227	1316 ± 279	1293 ± 218	1279 ± 243	86 (65–130)	6.7% (5.1–10.1)	49 N (3.8%)
RSI_{mod} (AU)	0.50 ± 0.08	0.52 ± 0.09	0.53 ± 0.08	0.52 ± 0.08	0.03 (0.02–0.04)	5.4% (4.1–8.1)	0.02 au (3.1%)

Abbreviations: CMJ, countermovement jump; CV, coefficient of variation; SEM, standard error of measurement; SWC, smallest worthwhile change

Table 2. Average and maximum power production (per set) and the number of repetitions for 10% and 15% conditions.

Condition	Average Power (W)	Maximum Power (W)	Repetitions (nº)
10%	3130.1 ± 301.4	3451.8 ± 319.4	14.3 ± 2
15%	3077.5 ± 307.0	3440.8 ± 319.0	19.7 ± 2

Table 3. Physiological and physical outcomes following each training intervention (10% and 15% condition). Data are presented as means (95%CI).

Moment	Condition	Lactate (mmol·L)	Jump height (cm)	Peak force (N)	RSI$_{mod}$ (AU)
Baseline	10%	1.3 (0.8; 1.8)	40.5 (37.9; 43.2)	1214 (1093; 1335)	0.52 (0.47; 0.57)
	15%	1.6 (0.9; 2.2)	40.1 (37.4; 42.8)	1206 (1134; 1278)	0.52 (0.46; 0.57)
	Pooled	1.4 (0.6; 2.3)	40.3 (38.3; 42.3)	1210 (1153; 1266)	0.52 (0.48; 0.56)
1st min	10%	10.2 (8.2; 12.2) *	37.0 (34.5; 39.6) *	1154 (1078; 1229)	0.48 (0.42; 0.53) *
	15%	11.4 (10.4; 12.5) *	34.8 (30.9; 38.6) *	1089 (1019; 1159)	0.43 (0.36; 0.50) *
	Pooled	10.8 (9.9; 11.7) *	35.8 (33.8; 37.8) *	1121 (1064; 1177)	0.45 (0.41; 0.49) *
3rd min	10%	8.8 (7.4; 10.2) *	38.3 (35.2; 41.3) *	1171 (1085; 1258)	0.48 (0.43; 0.54)
	15%	10.9 (9.4; 12.4) *	35.6 (32.4; 38.9) *	1149 (1051; 1247)	0.46 (0.39; 0.52) *
	Pooled	9.8 (9.0; 10.7) *	37.0 (35.0; 38.9) *	1160 (1103; 1216)	0.47 (0.43; 0.51) *
5th min	10%	8.7 (7.0; 10.4) *	37.7 (35.1; 40.3) *	1172 (1066; 1278)	0.48 (0.42; 0.55)
	15%	10.4 (9.1; 11.8) *	37.2 (33.7; 40.7) * #	1194 (1151; 1275)	0.48 (0.40; 0.55)
	Pooled	9.6 (8.7; 10.4) * #	37.5 (35.5; 39.4) * #	1182 (1126; 1239)	0.48 (0.44; 0.52) *
7th min	10%	7.6 (6.2; 8.9) * #	37.6 (35.3; 40.0) *	1164 (1080; 1248)	0.47 (0.42; 0.52) *
	15%	10.0 (8.5; 11.4) *	36.6 (33.4; 39.8) *	1165 (1094; 1236)	0.46 (0.41; 0.52) *
	Pooled	8.8 (7.9; 9.6) * #	37.2 (35.2; 39.2) * #	1164 (1108; 1220)	0.47 (0.43; 0.51) *
9th min	10%	6.7 (5.4; 7.9) * #	37.8 (34.9; 40.6) *	1162 (1069; 1255)	0.48 (0.42; 0.53) *
	15%	9.1 (7.6; 10.6) * #	37.2 (34.2; 40.6) * #	1163 (1091; 1235)	0.47 (0.41; 0.53) *
	Pooled	7.9 (7.0; 8.7) * #	37.5 (35.5; 39.5) * #	1162 (1106; 1219)	0.48 (0.44; 0.52) *

*Notes: * statistically different from baseline; # statistically different from 1 min*

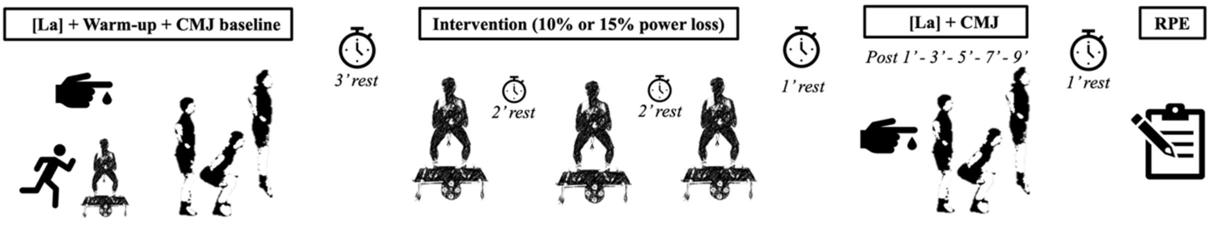

Figure 1. Schematic representation of the intervention protocol.

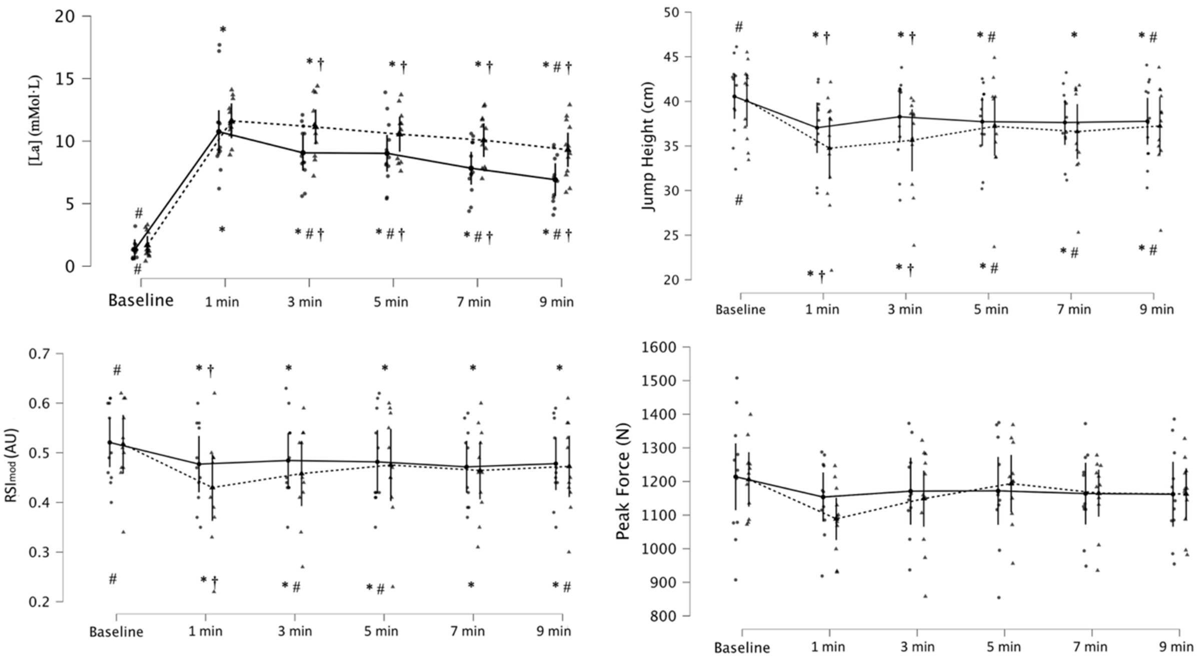

Figure 2. Baseline and post-exercise effects on lactate (top left), jump height (top right), RSI$_{mod}$ (bottom left) and peak force (bottom right), for 10% and 15% conditions (white and black circles, respectively).

Discussion

The present study aimed to compare the metabolic, neuromuscular, and perceptual fatigue after performing three sets of flywheel squats at different power loss thresholds (10% vs. 15%). Blood lactate concentration, jump height, peak force and the RSI$_{mod}$ were negatively affected by post-flywheel conditions (Figure 2 and Table 3). The 15% exercise condition resulted in larger [La] than the 10% condition (Figure 2 and Table 3). Finally, no differences between conditions were present for jump height, peak force and the RSI$_{mod}$, nor the perceptual measures of the subjective RPE and DOMS (Table 2 and supplementary material).

Blood Lactate Concentration

The present investigation showed greater [La] (1.69mmol·L, d = 0.83) following the 15% power loss, which was the more demanding protocol. These results align with the literature, where higher lactate concentration was present with greater volume (total repetitions) of resistance exercises (Sánchez-Medina and González-Badillo, 2011; Weakley et al., 2020). Although [La] at different time points post-protocols was not different ($p > 0.05$), the 10% condition resulted in clearing lactate more rapidly (beginning at the 7th min) compared to the 15% condition. These results align with previous literature, showing a strong linear relationship between [La] and velocity-loss when using free weights (Sánchez-Medina and

González-Badillo, 2011). The peak [La] presented in the study for the 10% (10.2 mmol·L) and 15% (11.4 mmol·L) conditions are similar to [La] from previous research that used a protocol consisting of three sets of 8 repetitions (8RM) (10.4 mmol·l) and 3 sets of 10 repetitions (10 RM) (11.7 mmol·L), respectively (Sánchez-Medina and González-Badillo, 2011). While our participants completed a greater number of repetitions per set (but using a flywheel resistance device), those two different protocols exhibited similar metabolic stress ([La]).

In a study of Sabido and colleagues (2020), participants performed flywheel squats (4 sets of 8 repetitions with low and high inertias) and the applied protocol resulted in [La] between 4 and 5.5 mmol·L, which shows that it was much less metabolic demanding than in the present study. Despite experiencing a 20–25% power loss (non-individualized) during the sets, the total number of repetitions was lower than in the present study. Interestingly, participants reported a rate of perceived exertion of 7 AU, which is similar to the that from the present study. Even though our study participants did not reach muscle failure, the complex relationship among total work, intensity and volume, as studied by Iannetta and colleagues (2022), and the related metabolic and peripheral fatigue mechanisms should be considered. Hence, the characteristics of the flywheel devices (i.e., their mass, radius and shape) and not the power-loss thresholds need to be taken into account when attempting to control the loading variables, the stimulus and subsequent effects. The device used by Sabido and colleagues (2020) probably displayed a narrower shaft, and even using lower inertias, the mechanical effort was higher (greater power loss with fewer repetitions). It is important to note that, when using flywheel devices, the participants' effort from the first repetitions must be the highest, and the volume of that high-intensity effort provides higher metabolic stress. At this point, practitioners need to consider which loading characteristics will result in greater mechanical (greater inertias) or metabolic stress (greater volumes).

Regarding [La] kinetics, we found that the peak [La] was reached 1 min post-exercise following a flywheel resistance exercise protocol consisting of three sets. Usually, the lactate peak is found between 2 and 7 min post exercise (Chatel et al., 2016; Wirtz et al., 2014), with some [La] increases already after the first set of squats at 10%, 20%, or 30% velocity-loss thresholds (Weakley et al., 2020). In our case, we recorded this peak lactate 1 min after the end of the entire exercise protocol, which was between 6 to 8 min after completing the first flywheel exercise set, and this aligns with previous literature (Wirtz et al., 2014). It is the authors’ opinion that using only one single time point to assess [La] may not provide sufficient information about [La] kinetics since the more fatiguing protocol produced greater [La] at the following time points and a more plateaued [La] clearance. Similarly to our results, [La] kinetics after three sets of a free-weight resistance exercise showed an increase in [La] after each set, with no lactate clearance after the 6th min post-exercise (Wirtz et al., 2014). Therefore, several time points, such as at 1, 5, and 9 min post-exercise, and even further (considering [La] was not cleared) may be needed to gather sufficient information on lactate kinematics to compare particular training protocols.

CMJ Jump Height, Peak Force, and RSImod

The two protocols used in the present study did produce a reduction in jump performance at the 1st min post-exercise (4.54 cm for jump height; 88.8 N for peak force and 0.07 AU for the RSI_{mod}), with jump height and the RSI_{mod} being hampered in the following time points. Hence, none of the protocols produced any PAPE effect during the 9-min period post-exercise. The 15% group presented a non-significant but larger jump height reduction at the 1st (5.5 cm) and the 3rd (4.5 cm) min post-exercise than the 10% group (3.6 and 2.3 cm, respectively), probably due to higher mechanical stress generated by the greater number of repetitions completed (19 vs. 14 reps/set, respectively). Although several studies have found a decrement in performance or a lack of PAPE 1 min after the completion of the potentiation protocol (Beato et al., 2021a, 2021d), it has usually been seen that flywheel resistance exercise is capable of generating a PAPE effect 3 min post exercise (till around 10 min) (Beato et al., 2020). This could be due to the fatigue’s dominant effect on PAPE in the early stage of the recovery period. However, as previously reported, the fatigue inhibition dissipates over time, and participants can acutely improve their performance (e.g., jump height) for the following minutes (Beato aet al., 2021a). The amount of fatigue caused by exercise cannot be too high as it would undermine the benefits of the PAPE protocol (Beato et al., 2020). In the current study, since we used two protocols that required participants to perform many repetitions (e.g., >14 reps/set), we believe that the acute fatigue generated was the cause of the lack of PAPE found following this protocol. It could be speculated that some potentiation effect might be present after the 9th min post-exercise, which was the time point examined in the study; however, this cannot be confirmed. While the volume of the stimulus seems to be important to drive PAPE effects, only one set did not elicit PAPE effects in jumping performance, but two to three sets did (De Keijzer et al., 2020). It could be hypothesized that an inverted U-shaped relationship exists among volume, fatigue, and PAPE, which could also be specific to each person, exercise, intensities, and the loading paradigm.

Previous research using flywheel resistance exercise used repetitions per set, an exercise volume much lower than what was used in our study (Beato et al., 2021a). While the authors did not control for a power-loss during the exercise, it could be hypothesized that power-loss was not present in those conditions, considering the results from the present study where a 10% power-loss was equivalent to more than 14 repetitions performed (depending on the subject). Although not using power-loss but velocity-loss thresholds, Yuan and colleagues (2023) similarly determined 5% to be the optimal velocity-loss threshold compared to 10%, 15%, and 20% velocity-loss thresholds for an optimal PAPE response in the CMJ. The present results could also confirm that a 10% power-loss threshold may not be recommended when looking at PAPE effects and using a medium or a low moment of inertia in flywheel devices. Instead, 10% or 15% protocols could be used when considering greater training stimulus and more delayed performance effects, probably during non-competitive periods. In line with these results, Pérez-Castilla and colleagues (2018) showed that a 10% velocity loss largely exceeded the number of repetitions per set commonly recommended to enhance muscular power. Those conclusions could probably be drawn when using low loads (below 60%RM) or low inertias, where the velocity-loss will be present lately during the set, and more repetitions will be accumulated before such velocity or power losses. While not studied, it could be interesting to see whether the same total volume using different power-loss thresholds or settings (i.e., 1 x 12 vs. 2 x 6 or 2 x 12 vs. 4 x 6) would produce the same physiological and neuromuscular effects. Therefore, it seems possible that lower volume protocols (such as three sets of 6 repetitions with high loads; Beato et al., 2021a) would be more beneficial than a power-loss-based protocol including more than 14 repetitions for PAPE purposes, considering the inertia and the number of sets used in the present study.

Related to the previous point, Sabido and colleagues (2018) found that 5 to 12 repetitions produced the greatest power output repetitions with a range of inertias (0.025 to 0.100 kg·m^2). Again, this justifies using less than 12 repetitions to optimize power production without accumulating fatigue. In the present study, 10% power-loss was inappropriate for those repetition ranges. While having the same inertia (0.0514 km·m^2) as the study of Sabido and colleagues (2018), the utilization of different machines (different shaft and flywheel diameters) may have allowed the participants to produce an additional amount of power. It could be argued that a 5% power loss should be used as the threshold to finish the training protocol. However, such small power-loss thresholds (5%) may not be suitable since the athlete must produce very low between-repetition variability (<5%). This is not the case with flywheel devices, where 7.7% to 20% of concentric peak power decrements were the minimum to be detected during a set (Sabido et al., 2018). Hence, the variability in the exercise may not allow practitioners to monitor small changes in a multi-joint exercise such as a half squat, which may limit the usefulness of power-loss thresholds when using medium to low inertias (0.0514 km·m^2).

RPE and DOMS

In this study, we found that both protocols were highly demanding regarding metabolic and neuromuscular effects, but surprisingly, the perceived effort (RPE) was not excessively high. In both the 10% and 15% conditions, the RPE was the same (6.9 and 7.2, respectively), despite the 15% protocol achieving 5 more repetitions per set on average (Table 2). This effect could be attributed to the small power-loss thresholds used. A higher power-loss threshold of 20% or 30% would have resulted in greater volume and a higher RPE (Weakley et al., 2020). Again, the complex relationship among total work, intensity and volume, as studied by Iannetta and colleagues (2022), and the related acute metabolic, neuromuscular mechanisms and perceptual responses need to be further investigated with flywheel devices, using different moments of inertia and volumes. Regarding DOMS, both protocols led to increased DOMS at 24–48 h, with no differences between protocols. Such results may suggest that both interventions were similarly demanding, which aligns with previous research emphasizing the high intensity of the exercises performed during the early repetitions (Norrbrand et al., 2011). In addition, such an aggressive approach may not be suitable during a competitive period, but applicable during a preparatory period considering the high acute metabolic and neuromuscular stress (reduced CMJ performance 9 min post-intervention and increased DOMS at 24–48 h) caused to the athletes.

Our study highlights some limitations regarding using specific power and velocity loss thresholds. The commonly used 10% power loss threshold may not be appropriate for all exercise intensities (%1RM for gravity-dependent exercises or inertias kg·m^2 for inertial flywheel exercises). Our findings suggest that a 10% power-loss threshold in the squat exercise, with an inertia of 0.0514 kg·m^2 was too demanding to elicit a PAPE effect. Therefore, relying solely on the 10% power-loss threshold may underestimate the fatigue accumulated during high-repetition sets. Additionally, our study indicates the need to consider the relationship among different power-loss thresholds, inertias, shaft types, and radius to accurately examine the effects of using such technology. Future research should incorporate these measures to better understand current thresholds' limitations and improve training programs. We only assessed one exercise in the study, and the athletes who participated focused on a particular discipline that caused specific body adaptations. It is important to note that any changes to these conditions can affect the results.

Conclusions

This study highlights the importance of designing resistance training protocols carefully to achieve optimal adaptations while minimizing fatigue-induced performance decrements. Setting a power loss threshold of 10% during flywheel squat training with inertia of 0.0514 kg·m^2 is too demanding to elicit PAPE effects. Using a power-loss threshold of 10–15%, combined with this inertia setup, may result in excessive metabolite accumulation and neuromuscular fatigue, reducing jumping ability for up to 9 min after the sets. Furthermore, relying on a single lactate extraction post-exercise may not provide sufficient information about [La] kinetics. Therefore, strength and conditioning coaches should consider using several lactate extractions to assess [La] kinetics accurately. Coaches should be cautious when using flywheel resistance exercise protocols that require many repetitions, as they can cause acute fatigue and hinder the benefits of PAPE. In particular, this approach may not be suitable before a competition but is more appropriate for training purposes. Indeed, flywheel training based on those power losses can be helpful during a preparatory phase as it may cause high metabolic and neuromuscular stress to athletes, resulting in reduced CMJ performance for up to 9 min after the exercise protocol completion and increased DOMS at 24–48 hours. Lastly, coaches should critically assess velocity or power loss thresholds to determine whether the information obtained using flywheel devices can help achieve the desired training goals.

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Supplementary Material

Table S1. Lactate (mmol·L), main condition effect.

	Mean difference	SE	df	95% CI Lower	95% CI Upper	t	*p*	*d*	
10% vs. 15%	1.69	0.69	11	0.26	3.12	2.46	0.03	0.83	*medium*

Table S2. Lactate (mmol·L), main time effect (pooled groups); baseline as the reference value.

	Mean difference	SE	95% CI Lower	95% CI Upper	t	*p*	*d*	
baseline vs. 1 min	−9.36	0.55	−1116	−7.56	−17.18	< 0.001	−4.61	*very large*
baseline vs. 3 min	−8.39	0.55	−10.20	−6.58	−15.36	< 0.001	−4.13	*very large*
baseline vs. 5 min	−8.12	0.53	−9.87	−6.36	−15.32	< 0.001	−4.00	*very large*
baseline vs. 7 min	−7.34	0.53	−9.09	−5.58	−13.85	< 0.001	−3.61	*very large*
baseline vs. 9 min	−6.44	0.53	−8.20	−4.68	−12.11	< 0.001	−3.17	*very large*

Table S3. Lactate (mmol·L), main time effect (pooled groups); 1-min value as the reference.

	Mean difference	SE	95% CI Lower	95% CI Upper	t	*p*	*d*	
1 vs. 3 min	0.97	0.49	−0.65	2.58	1.98	0.906	0.48	*small*
1 vs. 5 min	1.24	0.28	0.33	2.16	4.49	3.00×10^{-3}	2.21	*very large*
1 vs. 7 min	2.02	0.49	0.39	3.66	4.10	7.80×10^{-3}	2.41	*very large*
1 vs. 9 min	2.92	0.51	1.24	4.60	5.76	< 0.001	3.42	*very large*

Table S4. Jump height (cm), main time effect (pooled groups); baseline as the reference value.

	Mean difference	SE	95% CI Lower	95% CI Upper	t	*p*	*d*	
baseline vs. 1 min	−4.42	0.61	−6.40	−2.42	−7.29	< 0.001	−0.93	*large*
baseline vs. 3 min	−3.36	0.49	−4.98	−1.74	−6.81	< 0.001	−0.71	*medium*
baseline vs. 5 min	−2.86	0.47	−4.38	−1.33	−6.13	< 0.001	−0.61	*medium*
baseline vs. 7 min	−3.2	0.47	−4.73	−1.66	−6.80	< 0.001	−0.68	*medium*
baseline vs. 9 min	−2.82	0.41	−4.17	−1.47	−6.85	< 0.001	−0.60	*medium*

Table S5. Jump height (cm), between-group (10% vs. 15%) interaction effect.

			95% CI	95% CI				
	Mean difference	SE	Lower	Upper	t	*p*	*d*	
baseline	0.45	1.93	−6.89	7.79	0.23	1	0.10	*trivial*
1 min	2.29	1.93	−5.04	9.63	1.19	1	0.49	*small*
3 min	2.63	1.93	−4.71	9.97	1.37	1	0.56	*moderate*
5 min	0.52	1.93	−6.81	7.86	0.27	1	0.11	*trivial*
7 min	1.01	1.93	−6.33	8.35	0.53	1	0.21	*small*
9 min	0.53	1.93	−6.81	7.87	0.28	1	0.11	*trivial*

Table S6. Jump height (cm), within-group interaction effect.

			95% CI	95% CI				
	Mean difference	SE	Lower	Upper	t	*p*	*d*	
10%, 1 min	−3.50	0.62	−5.66	−1.35	5.63	< 0.001	0.74	*moderate*
10%, 3 min	−2.27	0.62	−4.43	−0.12	3.66	0.026	0.48	*small*
10%, 5 min	−2.82	0.62	−4.97	−0.67	4.54	< 0.001	0.60	*moderate*
10%, 7 min	−2.92	0.62	−5.07	−0.76	4.69	< 0.001	0.62	*moderate*
10%, 9 min	−2.78	0.62	−4.93	−0.62	4.47	0.001	0.59	*moderate*
15%, 1 min	−5.35	0.62	−7.50	−3.19	8.60	< 0.001	1.13	*large*
15%, 3 min	−4.46	0.62	−6.61	−2.30	7.17	< 0.001	0.94	*large*
15%, 5 min	−2.90	0.62	−5.05	−0.74	4.66	< 0.001	0.61	*moderate*
15%, 7 min	−3.48	0.62	−5.63	−1.32	5.59	< 0.001	0.74	*moderate*
15%, 9 min	−2.86	0.62	−5.01	−0.71	4.60	< 0.001	0.61	*moderate*

Table S7. Peak force (N), main time effect (pooled groups); baseline as the reference value.

			95% CI	95% CI				
	Mean difference	SE	Lower	Upper	t	*p*	*d*	
baseline vs. 1 min	88.83	24.27	8.50	169.16	3.66	0.022	0.68	*medium*
baseline vs. 3 min	50.01	23.81	−28.80	128.82	2.10	0.545	0.38	*small*
baseline vs. 5 min	27.20	22.69	−47.88	102.28	1.20	1	0.21	*small*
baseline vs. 7 min	45.51	21.04	−24.11	115.13	2.16	0.545	0.35	*small*
baseline vs. 9 min	47.63	24.36	−33.00	128.26	1.96	0.640	0.37	*small*

Table S8. Peak force (N), main time effect (pooled groups); 1-min value as the reference.

			95% CI	95% CI				
	Mean difference	SE	Lower	Upper	t	*p*	*d*	
1 vs. 3 min	−38.82	20.04	−105.14	27.50	−1.94	0.6399	−0.30	*small*
1 vs. 5 min	−61.63	23.30	−138.74	15.48	−2.65	0.2119	−0.47	*small*
1 vs. 7 min	−43.32	20.00	−109.51	22.87	−2.17	0.5455	−0.33	*small*
1 vs. 9 min	−41.19	21.93	−113.79	31.40	−1.88	0.6399	−0.32	*small*

Table S9. RSI$_{mod}$ (AU), main time effect (pooled groups); baseline as the reference value.

	Mean difference	SE	95% CI Lower	95% CI Upper	t	*p*	*d*	
baseline vs. 1 min	−0.07	0.01	−0.10	−0.03	−6.5	< 0.001	−1.59	*large*
baseline vs. 3 min	−0.05	0.01	−0.08	−0.02	−5.63	< 0.001	−1.36	*large*
baseline vs. 5 min	−0.04	0.01	−0.07	−0.01	−4.60	0.002	−1.44	*large*
baseline vs. 7 min	−0.05	0.01	−0.08	−0.02	−5.50	< 0.001	−1.79	*large*
baseline vs. 9 min	−0.04	0.01	−0.06	−0.02	−7.25	< 0.001	−1.61	*large*

Table S10. RSI$_{mod}$ (AU), main time effect (pooled groups); 1-min value as the reference.

	Mean difference	SE	95% CI Lower	95% CI Upper	t	*p*	*d*	
1 vs. 3 min	0.02	0.01	−0.01	0.04	2.58	0.26	0.13	*trivial*
1 vs. 5 min	0.02	0.01	−0.01	0.06	2.56	0.27	0.06	*trivial*
1 vs. 7 min	0.01	0.01	−0.01	0.05	1.39	1	0.16	*trivial*
1 vs. 9 min	0.02	0.01	−0.01	0.06	2.06	0.77	0.10	*trivial*

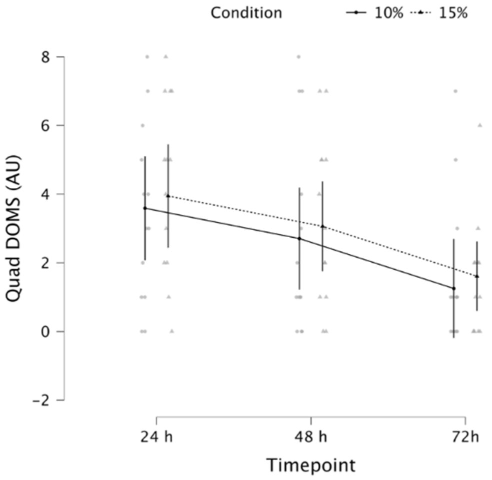

Figure S1. Time effect (24 h to 72 h) of DOMS in the quadriceps muscle group for each condition (10% vs. 15%).

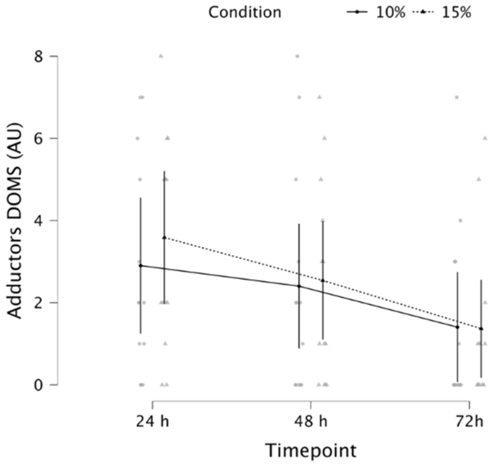

Figure S2. Time effect (24 h to 72 h) of DOMS in the adductors muscle group for each condition (10% vs. 15%).

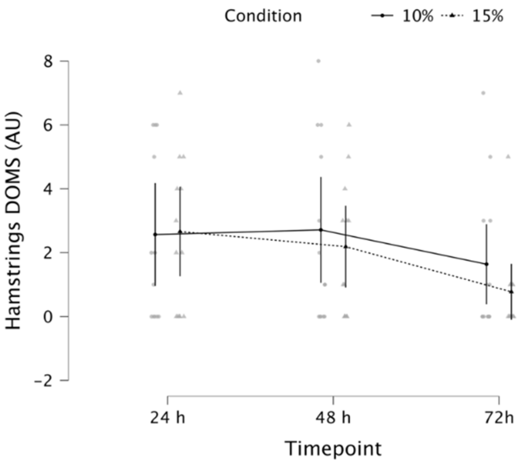

Figure S3. Time effect (24 h to 72 h) of DOMS in the hamstrings muscle group for each condition (10% vs. 15%).

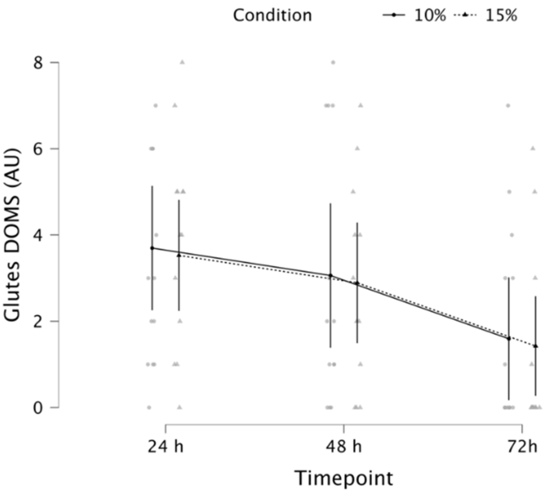

Figure S4. Time effect (24 h to 72 h) of DOMS in the glutes muscle group for each condition (10% vs. 15%).

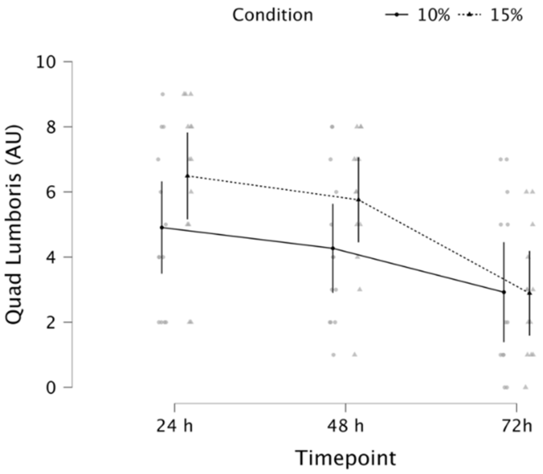

Figure S5. Time effect (24 h to 72 h) of DOMS in the quadratus lumborums muscle group for each condition (10% vs. 15%).