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EFFECTS OF TWO DIFFERENT FLYWHEEL RESISTANCE TRAINING PROTOCOLS ON EXPLOSIVE KNEE EXTENSION STRENGTH: A PILOT RANDOMIZED STUDY

PRIMERJAVA UČINKOV DVEH RAZLIČNIH PROTOKOLOV INERCIJSKE VADBE ZA MOČ NOG NA EKSPLOZIVNO MOČ IZTEGOVALK KOLENA: RANDOMIZIRANA PILOTNA ŠTUDIJA

ABSTRACT

The aim of our study was to evaluate differences in explosive isometric knee extension strength adaptations after a flywheel squat resistance training programs performed under low- and high-load conditions. Twenty physically active adults were randomly assigned to an individually allocated high- or low-load eight-week training intervention. Isometric knee extension rate of torque development (RTD) and rate of electromyography signal rise (RER) variables were assessed pre and post eight-week intervention. Statistically significant improvements in the RTD slope variables (100 and 200 ms time intervals after the onset of torque rise; $p < 0,05$) were observed, regardless of the training load used. Normalized averaged vastus lateralis and rectus femoris electromyography (EMG) amplitude decreased in the intervals 80 ms before, and 75, 100 and 200 ms after the onset of activation (all $p < 0,05$), regardless of the training group. Our results suggest that high- and low-load resistance flywheel training interventions induce similar increases in explosive knee extension strength, accompanied with a decrease in time-analog normalized EMG signal amplitude.

Keywords: isoinertial, torque, explosive, moment, muscle adaptation, EMG

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IZVLEČEK

Namen raziskave je bil primerjati učinke dveh protokolov počepanja na inercijski napravi na eksplozivno moč iztegovalk kolena. Protokola sta se razlikovala v velikosti inercijskega bremena, ki je bilo za vsakega posameznika individualno določeno pred začetkom vadbe. Dvajset redno telesno aktivnih odraslih je bilo naključno razdeljenih v dve skupini, eno, ki je vadila z velikim inercijskim bremenom, in drugo, ki je vadila z majhnim inercijskim bremenom. Spremenljivke hitrosti prirastka navora in amplitude elektromiografskega signala (EMG) pri eksplozivnem iztegu kolena v izometrični upornici so bile izmerjene pred in po 8-tedenskem obdobju vadbe. V obeh skupinah smo odkrili statistično značilno izboljšanje spremenljivk hitrosti prirastka navora (100 in 200 ms po začetku prirastka navora; $p < 0,05$). Normalizirana amplituda EMG signala mišic *vastus lateralis* in *rectus femoris* v intervalih 80 ms pred začetkom prirastka navora in 75, 100 ter 200 ms po začetku prirastka navora pa se je statistično značilno zmanjšala v obeh skupinah (vse $p < 0,05$). Rezultati kažejo, da inercijska vadba za moč nog z majhnim in velikim bremenom povzroči podoben napredek v hitrosti prirastka navora pri eksplozivnem iztegu kolena kljub zmanjšanju normalizirane amplitude EMG signala.

Ključne besede: izoinercija, navor, eksplozivna kontrakcija, mišična prilagoditev, EMG

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INTRODUCTION

The rate of force development (RFD) refers to the ability of the neuromuscular system to increase contractile force from a low or resting level when muscle activation is performed as quickly as possible. It is considered an important parameter of muscular performance, especially for athletes competing in sports that require high-speed actions (Rodríguez-Rosell et al., 2018). Therefore, the RFD is commonly assessed to monitor the effects of training interventions. The evaluation of RFD in human skeletal muscle is complex, as it is influenced by numerous distinct methodological factors including mode of contraction, type of instruction, variable type and time interval used to quantify RFD, measurement device and ambient temperature (Maffiuletti et al., 2016).

Neuromuscular components that influence the expression of RFD can be assessed along with their corresponding mechanical variables by quantifying the electromyography (EMG) signal in the time-analog intervals. Motor unit (MU) discharge rate, doublet discharge, MU recruitment threshold and MU synchronization may play a critical role in the ability to achieve rapid force development during the initial phase of muscle contraction. As maximal RFD can only be obtained during electrical muscle stimulation with very high pulse rates (de Haan, 1998) (approximately double those needed to elicit maximal isometric force production in vivo [Sale, 1988]) it was concluded in the past that such supramaximal MU discharge rates in the initial phase of a muscle contraction serve to maximize RFD rather than to influence maximal muscle strength. Moreover, concurrently active MUs may optimize the rate of force generation via increased superposition of MU force twitches (Rodríguez-Rosell et al., 2018). Also, an interesting mechanism responsible for high force generation from the onset of muscle contraction is the premovement silent period or premotor silence (PMS). The first detection of EMG activity in an agonist muscle may be a decrease that occurs prior to the first agonist EMG activity (Conrad et al., 1983), before the rapid increase in the signal that indicates agonist action. This mechanism could serve to increase the synchrony of the MU pool, which may be functionally related to contractile rate (Walter, 1989). It was previously found that the increase in amplitude of EMG signal at the beginning of muscle contraction reflects the MU discharge rate and the MU recruitement threshold (Del Vecchio et al., 2019), therefore EMG amplitude measures could be used to quantify differences in MU behaviour over time (Elgueta-Cancino et al., 2022) (Duchateau & Baudry, 2014).

Increases in RFD, accompanied with increases in efferent motoneuron output (as evidenced by changes in EMG signal amplitude) have been reported after slow concentric heavy-resistance strength training and explosive or power-type resistance training (Maffiuletti et al., 2016). Results in the previous literature indicate that slow concentric, high load, low volume (90% 1RM, 3x5 reps) resistance training is more advantageous than slow concentric, moderate load, high volume (70%, 3x12 reps) for improving RFD characteristics in closed kinetic chain exercises (Mangine et al., 2016). And, it was also found in the recent study of Rodriguez-Lopez et al. (2022) that the improvement in RFD variables did not differ between heavy load (80% 1RM, 6x6 reps) and low load (40% 1RM, 6x12 reps) explosive-type leg press training groups. These results confirm a thirty-year-old finding by Behm & Sale (1993), that intended ballistic (explosive) effort is thought to be a more important factor in increasing RFD than the type of contraction performed and the actual movement velocity defined by the loading condition (Behm, 1995).

Flywheel (FW) inertial resistance training is an emerging training mode that is gaining research interest due to the variety of positive effects of FW interventions observed in strength- and power-related variables (González, de Keijzer, bishop, & Beato, 2020; Maroto-Izquierdo et al., 2017; Nuñez Sanchez & Villarreal, 2017; Petré, Wernstål, & Mattsson, 2018), and the functional abilities of athletes (Beato, Fleming, Coates, & Dello Iacono, 2020; Cabanillas, Serna, Muñoz-Arroyave, & Ramos, 2020; Raya-González, Castillo, & Beato, 2020). Moreover, FW devices are also frequently used in clinical settings (Gual, Fort-Vanmeerhaeghe, Romero-Rodriguez, & Tesch, 2015; Romero-rodriguez, Gual, & Tesch, 2010; Tesch, Fernandez-Gonzalo, & Lundberg, 2017). A key limitation of existing research regarding FW resistance training is the lack of intervention studies. Consequently, the specificity of FW-based training methods is poorly understood, which represents a limitation in designing an appropriate program for developing the strength or power abilities of athletes. While FW resistance training has been shown as a useful tool to increase RFD in squat and countermovement jump tests (Weng et al., 2022), to date, no study has investigated the knee extensor's RFD or the rate of EMG rise (RER) adaptations to an FW training intervention under different loading conditions.

Increases in maximal strength following training with heavy loads results in a concurrent improvement in RFD (Aagaard et al., 2002). The prescription of heavy loads is related to the size principle for MU recruitment. The type 2 muscle fibres, which are considered predominately responsible for powerful and explosive athletic performances (Duchateau &

Baudry, 2014) are theorized to be more fully recruited and thus trained when training involves heavy loads (Cormie et al., 2011; Kamen & Knight, 2004). In FW squats, heavier loads result in increased ground reaction forces during both the concentric and eccentric phases, as well as during the transition between the two. However, they lead to reduced velocity and power generation (McErlain-Naylor & Beato, 2021; Spudić et al., 2020b, 2021). Eccentric overload (the difference between peak force produced in the eccentric and concentric parts of the squat) increases with greater FW loads (Spudić et al., 2021) and the transition from the eccentric to the concentric part of the squat lengthens with increased FW loads (Martinez-Aranda & Fernandez-Gonzalo, 2017). In proportion to force production, the EMG amplitude of leg extensor muscles also increases with rising FW loads (Spudić et al., 2020a). The variations in FW squat kinetics resulting from different loading conditions could potentially induce distinct RFD and accompanying RER training adaptations in knee extensor muscles.

The aim of this study was to evaluate the differences in explosive isometric knee extension strength adaptations after a FW squat resistance training program performed under low and high loading conditions. We hypothesized greater increases in the knee extension rate of torque development (RTD) and accompanied vastus lateralis and rectus femoris RER variables to be observed in the HL group. The results could help finding the optimal load for explosive strength improvement using FW devices which serve as the foundation for future comparisons of the magnitude of improvement with gravity-based resistance exercises.

METHODS

Study design

The study was designed as a randomized parallel-group trial to investigate the effects of eight weeks of FW squat resistance training under high-load (HL) and low-load (LL) conditions. Testing of explosive isometric knee extension strength was performed 3-5 days both before and after the 8-week training period.

Participants

Twenty physically-active volunteers were randomly assigned to HL (*n* = 10) or LL (*n* = 10) training group. Participant characteristics are shown in Table 1. The inclusion criterion was strength-training experience, defined by a training history that included strength exercises at least two times per week for the previous year. Exclusion criteria included knee injuries (e.g.

ligament, meniscus or cartilage damage), chronic diseases (systemic, cardiac and/or respiratory diseases or neuromuscular disorders), history of lower back pain or acute injuries in the past six months that could negatively influence squatting performance. Participants assigned to the experimental groups participated in an eight-week FW resistance training program. Stratified random sampling was used to allocate participants to the LL or HL FW training group. The stratification variable was the slope of the linear regression Force-Velocity curve, assessed using FW squats with incremental load conditions. Randomization was performed by a member of the research team who was not directly involved in the recruitment or assessment of participants, using a computer-generated random allocation program and a 1:1 ratio (LL:HL). Five to three weeks before the initial explosive knee extension testing and testing on the FW device, participants underwent familiarization sessions. This process aimed to ensure participants were comfortable and proficient with the testing and squat execution techniques before the actual testing sessions. These sessions consisted of one explosive knee extension strength testing session and between eight to ten FW squat familiarization sessions. During the familiarization sessions, an experienced investigator verbally described and demonstrated the correct procedure for explosive knee extension strength testing and the FW squat technique. After the demonstration, participants performed explosive knee extensions and completed two or three sets of FW squats with different FW loads, respectively. The study was approved by the National Medical Ethics Committee (no. 0120-690/2017/8) and adhered to the tenets of the Oviedo Convention and the Declaration of Helsinki. Participants were informed about the testing procedures and provided written informed consent prior to their participation.

Table 1. Participant characteristics.

Group	**Sex**	**Age (y)**	**Height (m)**	**Body mass (kg)**		**BMI (kg/m^2)**		**IPAQ (MET-min/week)**		**Peak KET (Nm/kg)**	
				Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
HL	**M**	24,8 (2,4)	1,78 (0,7)	73,1 (11,9)	75,4 (11,6)	22,9 (2,8)	23,6 (2,5)	6338 (4241)	6096 (5099)	3,35 (0,68)	3,91 (0,58)
	F	24,6 (2,7)	1,65 (0,4)	59,2 (4,2)	59,6 (4,1)	21,7 (1,1)	21,9 (0,9)	4256 (3986)	3729 (1446)	3,25 (0,25)	3,60 (0,69)
	M+F	24,7 (2,4)	1,72 (0,9)	66,2 (11,2)	67,5 (11,7)	22,3 (2,1)	22,7 (2,0)	5297 (4032)	4912 (3747)	3,30 (0,42)	3,76 (0,63)
LL	**M**	24,2 (2,8)	1,82 (0,7)	80,8 (12,5)	81,1 (10,7)	24,2 (2,5)	24,3 (2,1)	3588 (1063)	4174 (560)	3,60 (0,51)	4,26 (0,52)
	F	23,2 (2,8)	1,68 (0,6)	65,4 (10,5)	66,5 (10,3)	23,0 (2,6)	23,4 (2,5)	3695 (3935)	3035 (2733)	2,84 (0,65)	3,38 (0,65)
	M+F	23,7 (2,7)	1,75 (1,0)	73,1 (13,6)	73,8 (12,6)	23,6 (2,5)	23,9 (2,2)	3641 (2718)	3604 (1955)	3,22 (0,68)	3,82 (0,72)
Combined		24,2 (2,5)	1,74 (0,9)	69,6 (12,6)	70,6 (12,2)	23,0 (2,3)	23,3 (2,1)	4469 (3453)	4258 (2985)	3,30 (0,42)	3,75 (0,63)

Notes: Data are mean (SD). Physical activity data represent a retrospective recall of the seven days prior to each testing session. Abbreviations: BMI, body mass index; F, female (n = 5 in each group); HL, high-load (70% P_{max}); IPAQ, international physical activity questionnaire (Hagströmer, Oja & Sjöström, 2006); KET, knee extension torque; LL, low-load (P_{max}) ; M, male.

Training sessions

The training intervention consisted of FW squats using an allocated load depending on condition (HL vs. LL). The volume of the exercise intervention progressed throughout the eight weeks. The number of sets increased from three (week 1, 2), through four (week 3, 4, 5), to five (week 6, 7, 8) per training session. Each set consisted of ten repetitions, and there was a five-minute rest between sets. The first two repetitions of each set were used to attain proper squat execution (tempo and amplitude) and the last repetition was used to decelerate the spinning FW safely. From repetitions three to nine (7 repetitions), the participants were instructed to perform the concentric phase as fast as possible, and delay braking during the first third of the eccentric phase while making the transition from the eccentric to the concentric phase as short as possible (»all-out« execution). Squat amplitude was determined from the lowest point (approximatelly 90° knee angle) to full knee extension (approximatelly 0° knee angle). Participants crossed their arms and placed their hands on opposing shoulders. Lifting heels of the ground was not allowed. Participants received verbal encouragement and feedback from the researcher during all training sessions.

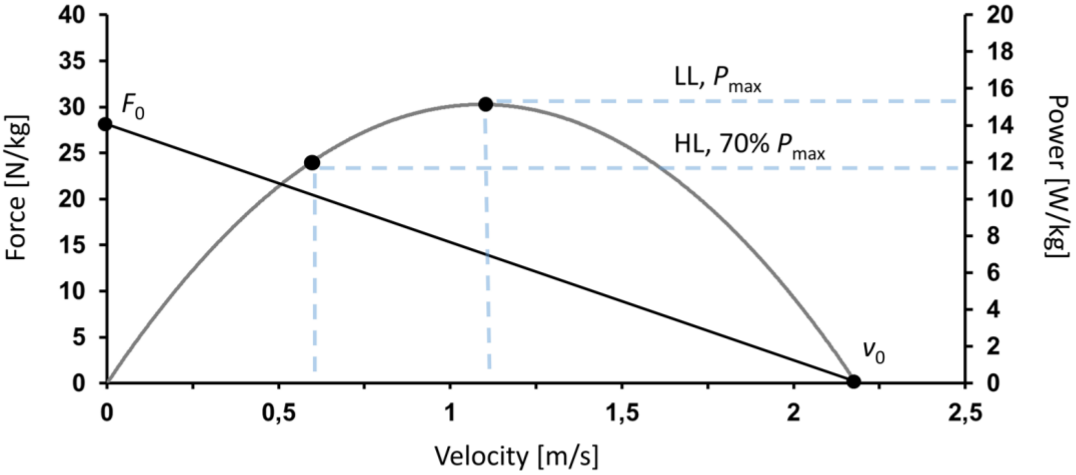
Figure 1. Testing and training setup.

Notes. The flywheel (FW) exercise device utilized the inertia of a spinning FW (A) to produce resistance. The FW standing platform (B) with force plates (C) size was 1.1 x 0,6 m, rotary shaft diameter was 3 cm and pulling rope diameter was 6 mm. A harness (D) was used to aid in performing FW squats. For the load allocation testing, a draw-wire sensor was installed under the device. The wire originated directly above the center of the axis - to avoid diagonal vertical displacement (E). The distal part of the wire was attached to the harness rope attachment (between the legs) (F). Sensory information was not captured during training sessions.

Load allocation

Load allocation was individually defined, based on the initial Force-Velocity-Power (*F-v-P*) testing in FW squats, following a previously-reported testing procedure, data aquisition and statistical analysis approach (Spudić et al., 2020b). Briefly, two sets of 10 consecutive squats were performed at four FW loading conditions (0,025, 0,075, 0,225 and 0,25 kg·m^2). The first two repetitions were used to attain proper squat execution and the last two were used to decelerate the spinning FW safely. Repetitions two to eight (6 repetitions) were performed »all-out« and included in the further analyses. Participants received verbal encouragement from the researchers during all testing sessions. To standardize squat depth, vertical displacement was monitored and provided as real-time feedback on a screen in front of the participants. Rest periods between the different loading conditions were two minutes to allow participants to adequately recover from the previous load (Sabido et al., 2020). Four *F-v-P* outcome measures were determined based on linear regression analyses between mean concentric ground reaction force and mean concentric vertical velocity. Maximal theoretical force (F_0), which represents the force-intercept, and the slope (k) of the *F-v* relationship, which in turn enabled the calculation of maximal theoretical velocity (velocity-intercept; $V_0 = F_0/k$) and maximal theoretical power ($P_{\max}=(F_0 \cdot V_0)/4$) (Samozino et al., 2010). Based on individual *F-v-P* characteristics, LL were allocated to the closest FW load at which the vertical velocity corresponded to the calculated $P_{\max}$, while HL were allocated to the closest FW load at which the vertical velocity corresponded to 70% $P_{\max}$ (Figure 2). Loads were determined with the accuracy of 0,025 kg·m^2. Prior to the load allocation session, participants performed the standardized 10-min warm-up procedure, as well as seven submaximal FW squats using a medium FW load (0,125 kg·m^2).

Figure 2. Representative individual Force-velocity-Power characteristics graph assessed with flywheel squats.



Notes. The black line represents the linear regression between the mean force and velocity variables. The y-intercept represents maximal theoretical force and the x-intercept indicates maximal theoretical velocity. The grey curve is the hyperbolic relationship between power and velocity during FW squats using incremental loading conditions. 70% P_{max} corresponds to the high load group (HL) and P_{max} to the low load group (LL) load allocation. *Abbreviations*: P_{max}, maximal theoretical power; v_0, maximal theoretical velocity, F_0, maximal theoretical force.

Testing procedures

Participants were instructed to avoid any strenuous exercise for at least two days prior to each testing session. Physical activity levels for the seven days leading up to each test were determined retrospectively upon arrival to the laboratory using the International Physical Activity Questionnaire (Hagströmer, Oja, & Sjöström, 2006). Before the testing and training sessions, participants performed a standardized 10-min warm-up procedure. This consisted of two minutes of alternating step-ups on a 25-cm high bench (80 repetitions per minute); arm, hip, knee and ankle mobility exercises (10 repetitions each); dynamic stretches of hip flexors, knee extensors, knee flexors and ankle extensors (10 repetitions each); and heel raise, squat, crunches resistance exercises (10 repetitions each). After the general warm-up, each participant performed five maximal squat jumps, counter-movement jumps and jump push-ups.

Isometric knee extension testing

Figure 3 shows the experimental setup for the knee extension tests. These were performed on a rigid chair (custom design), equipped with a strain-gauge force sensor (MES, Maribor, Slovenia) with a constant lever to the chair (knee) axis which provided torque-time data. Participants were in a seated position (90° hip and 60° knee flexion angle, 0° represents full knee and hip extension), and were securely strapped to the chair at the hip. The rotational axis of the lever arm was aligned to the lateral femoral epicondyle by visual inspection, and the lower leg was attached to the lever arm above the medial malleolus. The individual positioning of the seat and lever arm for each participant was replicated for their pre- and post-intervention tests. During the tests, participants were instructed to hold onto the arm supports on either side of the chair. All measurements were performed in the push-off preferred leg. Feedback was provided on a screen in the front of the subject.

Figure 3. Static knee dynamometer setup for the maximal isometric contraction and rate of force development testing protocols.

After three submaximal preconditioning trials, each participant performed three knee extensions at maximal voluntary contraction (MVC) effort, separated by at least 60 s rest. Participants were instructed to contract as forcefully as possible and to sustain maximal effort for at least three seconds. Visual feedback of the instantaneous dynamometer torque was provided to the participants on a computer screen.

After five minutes of passive rest, explosive knee extension measures were performed in the same testing position as MVC. To obtain a valid measure of the ability to produce torque quickly, a pre-tension was defined as 5% of MVC torque. Before initiating a fast contraction, participants were instructed to obtain the target pre-tension utilizing a computerized digital readout for at least one second. Participants were instructed to contract as fast and as forcefully as possible, and to sustain the contraction for at least two seconds. Three valid trials were required for the analysis. To ensure adequate PMS, trials with an initial countermovement (identified by a visible drop in the torque signal) were excluded, and a replacement trial was performed.

During MVCs and explosive knee extensions, EMG activity was assessed using a Trigno Delsys Wireless System (Delsys Inc., Massachusetts, USA), with pre-amplified self-adhesive wireless electrodes (dimensions: 27 x 37 x 15 mm; mass: 14.7 g; electrode material: silver; contact dimension: 5 x 1 mm). After skin preparation (shaving, light abrasion, and cleaning with alcohol; < 5 kΩ), the electrodes were placed over the vastus lateralis (*vl*) and rectus femoris (*rf*) of the preferred leg, according to SENIAM recommendations (Hermens et al., 2000).

Data processing

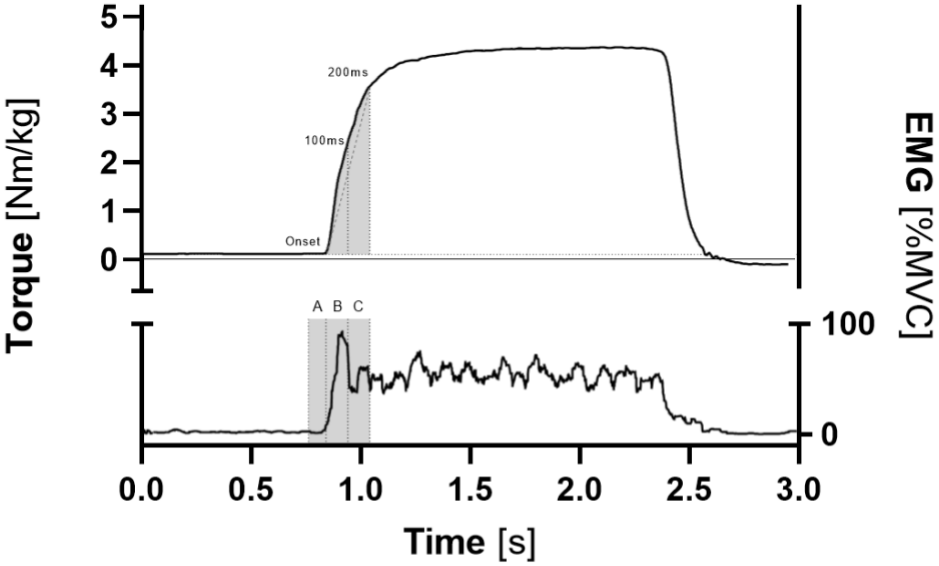
Signals were processed according to previous research (Maffiuletti et al., 2016). Torque and EMG data were simultaneously sampled at 1000 Hz using a USB Data Acquisition System (Power Lab, National Instruments, Austin, USA) and visualized using LabChart 8 (ADInstruments, Bella Vista, Australia). Torque data were subsequently adjusted to account for the effect of gravity on the lower limb and normalized to indivdual's body mass – separately for pre and post measurements, respectively. The onset of muscle contraction was defined as the time point at which the torque curve exceeded baseline torque value by five standard deviations. Baseline torque time interval was set from 1 s to 0,5 s before the time-point of peak RTD (defined as the maximal instantaneous slope of the torque-time curve at one ms interval) to avoid mistakes in the onset threshold calculation due to signal disturbance (vibrations, countermovement, anticipation, etc.). The rate of torque increase, defined as the slope of the torque-time curve at 100 and 200 ms time points relative to the onset of contraction (Slope_{100}, Slope_{200}) were identified in each trial (Figure 4).

The EMG data were bandpass-filtered using a Butterworth fourth-order filter (20–500 Hz), and then rectified using a root mean square (RMS) function (50 ms window length). The onset of EMG activation was defined as the time point at which the EMG amplitude curve exceeded baseline EMG amplitude value by five standard deviations. Baseline EMG time interval was set from 1 s to 0,5 s before the time-point of peak RER (defined as the maximal instantaneous slope of the EMG amplitude-time curve at one ms interval). The following EMG variables were identified in each trial: (a) average EMG amplitude in the 75, 100 and 200 ms time intervals relative to the onset of EMG activation (EMG_{75}, EMG_{100}, EMG_{200}) and, (b) average EMG amplitude during 80 ms time interval before the onset of muscle activation (EMG_{-80}). This final variable was identified to control for the potential enhancement of performance without an adequate PMS (Conrad et al., 1983). Time intervals of 75 ms was used due to a decrease in EMG signal amplitude after 80-100 ms of neural activity after the onset of explosive contraction

– as reported in previous studies (Aagaard et al., 2002). EMG amplitude variables were expressed as a percentage of the average EMG activity during the MVC trial with the highest torque produced (%MVC). EMG value during MVC was calculated as a peak value of MVC_{RMS} signal on a one-second moving window, separately for pre and post measurements (Figure 4).

Signal processing was performed in LabChart 8. The data were then copied into custom-written Excel spreadsheets (Microsoft Corporations, Redmond, Washington, USA) where the RTD and RER variables were calculated.

Figure 4. Representative curve of the torque (above) and EMG_{RMS} (below) signal.



Notes. The onset of contraction was separately determined for torque and EMG signal. Area A corresponds to 80 ms before the activation onset, area B for first 100 ms and area C for the first 200 ms, relative to the onset of contraction or EMG activation. Pretension of 5% of MVC is presented with a horizontal dotted line on the torque-time curve.

Statistical analyses

All data are presented as mean (standard deviations - SD). An average value of three trials results (RFD and EMG amplitude) were entered into the analyses. The Shapiro-Wilk test confirmed that all data were adequately normally-distributed ($p > 0,05$) for parametric tests to be conducted. Differences between groups were checked before the start of the intervention using an independent-samples t-test. Then, a two-way mixed-effects ANOVA (Time [pre, post] * Group [LL, HL]) was used to compare the changes in the variables across the intervention and between groups. Equality of variances between groups were confirmed using Levene's test ($p > 0,05$). In the event that the assumption of sphericity was violated (Mauchly's Test of Sphericity < 0,05), the Greenhouse–Geisser correction was applied. The reported effect size

(ES) from the univariate model for the comparisons was Partial eta squared (η^2), where the criteria for ES were small (ES = 0,010), medium (ES = 0,059) and large (ES = 0,138) (Kotrlik & Williams, 2003). Intra-session reliability of the results was assessed using intraclass correlation coefficients ($ICC_{2.1}$) (Koo & Li, 2016) and coefficients of variation (CVs) (Hopkins, 2000). $ICC_{2.1}$ values were interpreted according to guidelines (< 0,50: poor reliability, 0,50–0,75: moderate reliability, 0,75–0,90: good reliability, > 0,90: excellent reliability) (Koo & Li, 2016). All statistical analyses were performed using SPSS (IBM SPSS Statistics for Windows, Version 28.0. Armonk, NY: IBM Corp, USA). An alpha value of 0,05 was accepted as the level of statistical significance.

RESULTS

No statistically significant differences were found for any of the RTD and RER variables before the intervention (all *p*-values > 0.05).

Training adaptations

Table 2 reports the changes in the RTD parameters for each group across the interventions. A main effect of time was observed for all variables. Each of these main effects of time reflected an increase in the respective variable across the intervention. There were however no main effects of group (*p* = 0,507–0,654) or time*group interaction effects (*p* = 0,718–0,993).

Table 2. Changes in the rate of torque development variables across the intervention in each group.

Variable	Group	Pre	Post	Δ (Post – Pre)	ANOVA								
					Main Effect of Time			Main Effect of Group			Time*Group Interaction		
					F-ratio	*p*-value	η^2	F-ratio	*p*-value	η^2	F-ratio	*p*-value	η^2
$Slope_{100}$ ([Nm/kg]/s)	**HL**	18,127 (2,494)	19,946 (3,446)	1,38 (3,21)	70,143	0,016*	0,284	0,208	0,654	0,011	0,135	0,718	0,007
	LL	17,706 (4,827)	19,086 (2,297)	1,819 (2,004)									
$Slope_{200}$ ([Nm/kg]/s)	**HL**	24,371 (3,674)	27,892 (4,88)	3,509 (3,598)	260,545	<0,001*	0,596	0,458	0,507	0,025	0,021	0,993	<0,001
	LL	22,919 (5,060)	26,428 (3,878)	3,520 (2,380)									

Note: Data are mean (SD). Abbreviations: ANOVA, analysis of variance; HL, high-load (70% P_{max}); LL, low-load (P_{max}); MVC, maximal voluntary contraction; η^2 - eta squared; * - $p < 0,05$.

Changes in the mean EMG variables for each group across their respective interventions are presented in Table 3. Main effects of time were observed for all variables. Each of these main effects of time reflected a decrease in the respective variable across the intervention. There were no significant main effects of group (p = 0,101–0,607) or time*group interaction effects (p = 0,357–0,878) in any of the EMG variables.

Table 3. Changes in the observed vastus lateralis and rectus femoris EMG variables across the intervention in each group.

Muscle	Variable	Group	Pre	Post	Δ (Post – Pre)	ANOVA								
						Main Effect of Time			Main Effect of Group			Time*Group Interaction		
						F-ratio	*p*-value	η^2	F-ratio	*p*-value	η^2	F-ratio	*p*-value	η^2
VL	**EMG$_{75}$ (%MVC)**	**HL**	47,7 (22,7)	46,3 (24,2)	-3,6 (22,8)	0,257	0,616	0,008	1,547	0,223	0,046	0,052	0,821	0,002
		LL	42,6 (18,3)	39,0 (12,7)	-1,4 (33,6)									
	EMG$_{100}$ (%MVC)	**HL**	90,6 (22,8)	66,3 (36,8)	-24,3 (29,3)	13,303	0,002*	0,425	0,862	0,365	0,046	0,030	0,865	0,002
		LL	80,1 (28,4)	58,0 (12,8)	-22,1 (27,6)									
	EMG$_{200}$ (%MVC)	**HL**	91,2 (21,1)	73,3 (25,9)	-17,9 (22,9)	13,801	0,002*	0,434	2,439	0,136	0,119	0,024	0,878	0,001
		LL	79,9 (22,2)	60,4 (9,5)	-19,4 (21,9)									
	EMG$_{-80}$ (%MVC)	**HL**	10,3 (3,9)	7,0 (5,5)	-3,3 (5,7)	9,240	0,007*	0,339	0,794	0,385	0,042	0,030	0,863	0,002
		LL	9,1 (3,8)	5,4 (4,0)	-3,7 (4,5)									
RF	**EMG$_{75}$ (%MVC)**	**HL**	6,1 (2,9)	5,7 (2,7)	-0,4 (3,1)	1,951	0,172	0,057	0,269	0,607	0,008	0,546	0,465	0,017
		LL	7,1 (4,9)	5,9 (3,0)	-1,2 (3,4)									
	EMG$_{100}$ (%MVC)	**HL**	67,6 (21,4)	54,1 (30,0)	-13,5 (33,8)	5,504	0,032*	0,256	0,509	0,486	0,031	0,031	0,864	0,002
		LL	63,3 (17,0)	47,6 (8,7)	-15,7 (15,8)									
	EMG$_{200}$ (%MVC)	**HL**	77,5 (19,7)	67,8 (24,4)	-9,6 (28,0)	5,790	0,029*	0,226	1,218	0,286	0,071	0,190	0,669	0,012
		LL	72,4 (12,6)	58,5 (7,5)	-3,9 (8,7)									
	EMG$_{-80}$ (%MVC)	**HL**	13,2 (6,2)	8,3 (6,3)	-4,9 (7,0)	7,214	0,018*	0,340	3,086	0,101	0,181	0,909	0,357	0,061
		LL	8,6 (2,5)	6,2 (3,0)	-2,3 (3,6)									

Note: Data are mean (SD). Abbreviations: ANOVA, analysis of variance; EMG, electromyography; HL, high-load (70% P_{max}); LL, low-load (P_{max}); MVC, maximal voluntary contraction; η^2 - eta squared; * - p < 0,05.

Intra-session reliability

The CV results for RTD variables ranged from 4,5 (3,2)% (post Slope$_{200}$) to 14,1 (12,8)% (pre Slope$_{100}$). On the contrary, EMG variables demonstrated unacceptable CVs (>10%). The CV results for *vl* EMG variables ranged from 11,4 (6,5)% (pre EMG$_{200}$) to 31,1 (16,8)% (pre EMG$_{-80}$). The CV results for *rf* EMG variables ranged from 12,3 (9,1)% (post EMG$_{200}$) to 29,3 (21,5)% (post EMG$_{75}$). Moreover, ICC values ranged from moderate (ICC = 0,649 for post Slope$_{100}$) to excellent (ICC = 0,92 for pre Slope$_{200}$) for RTD variables; from moderate (ICC = 0,52 for pre EMG$_{-80}$) to good (ICC = 0,82 for post EMG$_{75}$) for *vl* EMG variables and from moderate (ICC = 0,57 for pre EMG$_{200}$) to good (ICC = 0,890 for post EMG$_{75}$) for *rf* EMG variables.

DISCUSSION

The aim of this study was to compare the effects of HL vs. LL FW squat resistance training programmes on explosive isometric knee extension strength. Improvements in RTD variables were observed, whereas *vl* and *rf* normalized EMG amplitude variables displayed a decrease across the interventions. In contrast to the hypothesis, no significant differences in adaptations were observed between the HL and LL groups.

The most important outcome of this study is the discovery that similar improvements in RFD were observed after HL and LL FW resistance squat training. In general, there is a lack of studies in the literature comparing the influence of LL and HL explosive or power type training on RFD adaptations. Considering the association between the use of heavy loads and the size principle for MU recruitment, as well as the engagement of type 2 muscle fibers — predominantly responsible for powerful and explosive athletic performances (Duchateau & Baudry, 2014) — we initially hypothesized that different FW loading conditions would lead to varying RFD and neural adaptations. However, the current data demonstrate no significant differences between the HL and LL groups in RTD and RER variables. On the other hand, the use of an intended ballistic effort is thought to be a more important factor in increasing RFD than the type of contraction performed and the actual movement velocity (D. G. Behm & Sale, 1993). This seems to be also valid for FW resistance training conditions. The intention to rotate the FW load as quickly and forcefully as possible appears to be more relevant to improving explosive knee extension strength than the magnitude of the FW load.

Notably, normalized EMG amplitudes in the early intervals (75 and 100 ms) and the late interval (200 ms) after the onset of contraction were reduced following the intervention, regardless of the training group. This contradicts other studies but supports the notion that certain latent factors, unassessable using the RER measurement technique, protocol, and variables employed in this study, led to increased associated mechanical variables. The lower EMG burst along with the observed improvements in RFD in this study could be attributed to several explanations: (a) predominance of morphological adaptations over neural changes (e.g., pennation angle alterations (Oliveira et al., 2016) or changes in the relative proportion of fast-twitch muscle fibers – IIx decrease over IIa); (b) potential antagonist relaxation contributing to increased net torque without agonist adaptations; and (c) RER variables normalization to corresponding EMG values during MVC. We noted an average increase of 16,5% in MVC knee extension torque values, accompanied by an 80,5% increase in non-normalized EMG amplitude. Conversely, a

11% increase was observed in Slope$_{200}$, accompanied by a mere 1% increase in non-normalized amplitude and, subsequently, a 19% decrease in normalized *vl* EMG$_{200}$ amplitude. This suggests that participants made greater gains in maximal strength compared to explosive isometric strength and that neural adaptations were more pronounced during maximal strength testing (Del Vecchio et al., 2022). To further confirm this assumption, activation level methods (Strojnik & Komi, 1998) could have been utilized, while the non-normalized voltage potential of the surface electromyographic signal detected by the electrodes depends strongly on several factors that vary between individuals and also over time within an individual (Sousa & Tavares, 2012). It appears that RTD variables increased due to gains in maximal strength, consistent with the findings of Aagaard et al. (2002), where increases in maximal strength following heavy load training lead to concomitant improvements in RTD. This conclusion is further supported by the absence of discernible neural adaptations during the explosive strength test. Additionally, we cannot dismiss the likelihood that morphological muscle-tendon adaptations influenced the RTD increase, particularly because typical neural adaptations during explosive strength tests encompass PSP, higher muscle firing frequency, MU synchronization, earlier recruitment of large MUs, and an increased number of doublet discharges. These adaptations usually result in amplified EMG amplitude during explosive strength tests (Del Vecchio et al., 2022), but were not evident in our study.

Rapid force generation and underlying neural mechanisms could have been altered, presumably due to specific squat execution with FW load. Due to the »all-out« eccentric-concentric nature of repetitions in FW squats, it can be challenging to precisely control muscle tension right before the onset of the explosive concentric effort, in contrast to gravity-based resistance, where the load can be supported before the start of the movement. An inverse linear relationship was previouly observed between %MVC and RFD (Viitasalo, 1982). And, it was found that higher muscle pretension negatively influences fast MUs firing frequency, double discharges and MU synchronization at the initiation of the contraction (Ricard et al., 2005; Van Cutsem & Duchateau, 2005). Moreover, it could be speculated that eccentric muscle contraction during the braking phase of the FW squat provides an initial condition (i.e., high muscle pretention) for the concentric part of the squat that negatively affects the capacity of the MU discharge rate and thus the performance of an explosive voluntary contraction. It appears that not only HL, but also LL has exhibited the initial pretension to such as extend to negatively influence relative RER adaptations. Furthermore, when performing a FW squat with delaying the braking action in the first third of the eccentric phase, eccentric overload can be achieved (Tesch et al., 2004).

Eccentric forces and eccentric overload were found to be higher when squatting with higer FW loads (Spudić et al., 2021). Neuromuscular activation of the quadriceps femoris muscle was found to be inhibited during slow and fast eccentric contractions despite full voluntary effort (Aagaard et al., 2000), which is attributed to a tension-limiting mechanism specific to eccentric exercise action (Alcazar et al., 2019; Amiridis & et al., 1996). Therefore, especially in HL group, high eccentric force demands in FW squats might have caused neuronal inhibition, limiting the recruitment and/or discharge of MUs and therefore representing unfavorable neuronal conditions for rapid force generation and consequently RER adaptations over an 8-week period.

Peñailillo et al. (2015) concluded that $RFD_{100–200}$ is a more specific and sensitive indirect marker of eccentric exercise-induced muscle damage than peak torque during MVC. It could be speculated that the improvement of RTD and concurrent EMG variables were affected by the prolonged loss of muscle function after the last training session before the final testing – especially in the HL group. This could have been mitigated by conducting the final testing more than 5 days after the last training session. However, studies on the repeated bout effect after eccentric exercises (Nosaka et al., 2001) and FW squat exercises (Coratella et al., 2016) have shown a muscle protective role of previous eccentric exercise in subsequent bouts, lasting up to 6 or 9 months (Nosaka et al., 2001). The possibility of muscle damage affecting differences in RTD and EMG variables between groups in our study is therefore less likely (Warren et al., 2002). Moreover, different stability requirements and uneven training volumes (total ground reaction force impulse was 55% higher in HL group) between the groups may have impacted the extent of adaptations within each group. Based on our unpublished data, lower posture stability is evident when squatting with lower FW loads. Additionally, it is possible that a higher number of repetitions or sets in the LL group were needed to maximize RTD adaptations. Conversely, fewer than seven "all-out" repetitions could have been enough to maximize RTD adaptations and minimize the effect of fatigue accumulation throughout the weeks of training.

This study included a relatively small sample and, therefore, may not have been sufficiently powered to detect statistically significant differences between groups. Due to the lack of studies analyzing RTD variables after FW training, an adequate a priori estimate of the sample size was not possible. Based on other studies (Aagaard et al., 2002; Oliveira et al., 2016; Šarabon et al., 2020), it can be reasonably speculated that a larger sample size might reveal statistically significant differences in adaptations between groups. Moreover, the isometric knee extension test has been performed due to its high reliability of results (Hernández-Davó & Sabido, 2014) but, there is considerable controversy regarding the external validity of the isometric assessment, particularly the ability of the tests to monitor changes in dynamic performance, for example eccentric RFD (Wilson & Murphy, 1996). We have also calculated relative and absolute reliability coefficients for RTD and RER variables. RTD variables revealed acceptable reliability across three test repetitions, while RER variables revealed unacceptable reliability (CV > 10%). Therefore, it could be speculated that the RER results of our study lack credibility, and that averaging more than three repetitions should be considered to lower the noise-to-signal ratio. Improving the quality of the results by averaging more than three repetitions can be frequently observed when analyzing evoked muscle contractions (Suter & Herzog, 2001) or dynamic voluntary actions (Spudić et al., 2020a), but not typically when analyzing RFD or RER variables (Maffiuletti et al., 2016).

CONCLUSION

In summary, FW inertial resistance training has received increasing attention in recent years due to the many positive effects observed on athletic performance variables such as change of direction (Hoyo et al., 2015), jumping (Raya-González et al., 2021), and sprinting (Sagelv et al., 2020). However, the underlying neural mechanisms responsible for these beneficial effects remain unknown. This was the first study to investigate the adaptations of explosive knee extension strength adaptations following FW squat resistance training with different training loads. Contrary to our hypothesis, no differences in RTD adaptations were found between LL and HL groups. Both groups significantly improved their explosive isometric knee extension strength during the intervention, and the improvement was accompanied by a decrease in *vl* and *rf* EMG signal amplitude, regardless of the training load (HL vs. LL). Based on the results, the improvement in RTD cannot be attributed to neural mechanisms. The results of this study may provide valuable data for sports practitioners using FW resistance equipment, and for researchers seeking to investigate the use of this technique further.

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Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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