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DIFFERENCES IN POST-ACTIVATION POTENTIATION AND POST-ACTIVATION PERFORMANCE ENHANCEMENT BETWEEN FLYWHEEL AND BARBELL SQUAT PROTOCOLS

RAZLIKE V POAKTIVACIJSKI POTENCIACIJI IN POAKTIVACIJSKEM IZBOLJŠANJU MED PROTOKOLOMA POČEPANJA NA INERCIJSKI NAPRAVI IN Z OLIMPIJSKO ROČKO

ABSTRACT

This study aimed to compare the post-activation potentiation (PAP) and post-activation potentiation performance enhancement (PAPE) response following the flywheel (FW) and barbell resistance protocols on subsequent evoked knee extensor muscle characteristics and countermovement jump (CMJ) height. The study used a randomized crossover design including nineteen physical education students (24.9 [2.6] years, 171.1 [6.9] cm, 66.9 [8.6] kg). The participants were divided into experienced (EX) and unexperienced (unEX) groups. They visited the laboratory eight times and in randomized order performed the following tests: I) optimal FW load determination, II) optimal barbell load determination, III) control visit to determine twitch characteristics, IV) control visit to determine CMJ characteristics, V and VI) evoked contractions of the quadriceps femoris muscle after FW squat and barbell protocols, VII and VIII) CMJ testing after FW squat and barbell squat protocols. A mixed model ANOVA (factors load condition [control, FW, barbell], time [1-10 min] and experience) revealed changes in jump height, twitch amplitude, contraction time and half-relaxation time as a factor of time. Only minor differences in variables analyzed were found between EX and unEX participants and between load conditions. The prevalent observation is that the two loading conditions (FW vs. barbell) induced no different PAP/E responses. Presumably, because the intensity and tempo of the two resistance exercise protocols were matched by the peak power load selection, coupled eccentric-concentric contractions, and while only a single set of squats was performed.

Keywords: isoinertial, countermovement jump, eccentric overload, power-load profile, twitch

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IZVLEČEK

Namen raziskave je bil preveriti razlike v poaktivacijski potenciaciji (PAP) in poaktivacijskem izboljšanju (PAPE) med protokoloma počepanja na inercijski napravi (FW) in z olimpijsko ročko. Spremljane so bile lastnosti skrčka in višina skoka z nasprotnim gibanjem (CMJ). Izvedena je bila navzkrižna študija, v kateri je sodelovalo devetnajst študentov Fakultete za šport (24.9 [2.6] let, 171.1 [6.9] cm, 66.9 [8.6] kg). Preiskovanci so bili glede na izkušnje z inercijsko vadbo za moč razdeljeni v bolj (EX) in manj (unEX) izkušeni skupini. Meritve so bile izvedene v osmih terminih v naključnem vrstnem redu, in sicer: I) določitev optimalnega inercijskega bremena, II) določitev optimalnega masnega bremena z olimpijsko ročko, III) kontrolni obisk za določitev lastnosti skrčka, IV) kontrolni obisk za določitev višine CMJ, V in VI) lastnosti skrčka po protokolih počepanja na inercijski napravi in z olimpijsko ročko, VII in VIII) višina CMJ po protokolih počepanja na inercijski napravi in z olimpijsko ročko. Z analizo variance z mešanim načrtom (faktorji protokol [kontrolni, FW, ročka], čas [1-10 min] in izkušnje) smo ugotovili razlike v višini skoka, amplitudi skrčka, kontrakcijskem času skrčka in polovičnem relaksacijskem času skrčka med različnimi časovnimi intervali (1-10 min). Med protokoloma (FW in ročka) ter med EX in unEX preiskovanci so se nakazovale razlike, vendar v večini primerov niso bile statistično značilne. Glavna ugotovitev naše raziskave je, da protokola počepanja (FW in ročka) ne povzročita različnih sprememb v PAP in PAPE. Predvidevamo, da do razlik ni prišlo, ker sta bila protokola izenačena po intenzivnosti in tempu izvedbe ponovitev z bremenom, pri katerem so preiskovanci proizvedli največjo moč z ekscentrično-koncentričnim tipom izvedbe ponovitev, in zato, ker je protokol zajemal samo eno serijo počepov.

Ključne besede: inercija, skok z nasprotnim gibanjem, ekscentrična preobremenitev, odnos breme-moč, skrček

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INTRODUCTION

Skeletal muscle performance is affected by its contraction history (Sale, 2002). The most obvious effects of contraction history are fatigue, which deteriorates performance, and post-activation potentiation (PAP), which helps improve performance. PAP can be induced by evoked twitches, an evoked tetanic contraction or maximal voluntary contraction (MVC) (Sale, 2002). PAP compensates for fatigue in endurance sports (it serves to compensate for low-frequency fatigue) (Rassier & MacIntosh, 2000), increase rate of force development (RFD), and, thus, improve speed and power performance (Sale, 2002). The principal mechanism of PAP is considered to be phosphorylation of myosin regulatory light chains, which renders actin-myosin interaction more sensitive to Ca^{2+} released from the sarcoplasmic reticulum. The increased sensitivity has its greatest effect at low myoplasmic levels of Ca^{2+} (twitch, low-frequency tetanic contractions, RFD) and little or no effect at saturating Ca^{2+} levels (high-frequency tetanic contractions and MVCs). On the basis of frequency domain, different contraction types and fiber types (Hamada et al., 2000) react differently to a conditioning contraction. For example, higher frequencies are needed to evoke a given percentage of maximum force in concentric contractions in comparison to isometric contractions (Abbate et al., 2000). Moreover, greater phosphorylation of myosin regulatory light chains in response to a conditioning activity is observed in faster muscle fibers (Type II), therefore certain muscles and people with higher percentage of fast muscle fibers may exhibit greater PAP response. Besides fiber type, rest time, intensity, volume, training status, type of exercise and type of muscle contraction also impact the magnitude of the potentiation because all these factors can influence the amount of fatigue (Sale, 2002).

PAP is a well-described phenomenon with a short half-life (~28 s) (Blazevich & Babault, 2019). Despite the claim that PAP was the object of the previous research in using flywheel (FW) conditions, it is obvious that other delayed potentiation responses were assessed (muscle temperature, muscle/cellular water content, and muscle activation) while no study included measurements of evoked muscle contractions (twitch force) in a short time after conditioning activity. Recently, post-activation performance enhancement (PAPE) term was introduced to distinguish it from “classical” PAP (Blazevich & Babault, 2019). Both phenomena may theoretically benefit voluntary muscle function, while it stays in question if PAP due to its short duration is of any significant practical importance (Boullosa, 2021). From the other perspective, eccentric overload in barbell front squats with the help of eccentric hooks enhanced subsequent concentric velocity and power (Munger et al., 2017) and it was suggested to be used by strength coaches and athletes during the power phase of a training program. While eccentric overload is the main premise of the FW training and muscles are stronger, require less energy and selectively recruit type II muscle fibers eccentric contractions (Enoka, 1996; Herzog, 2018; Hessel et al., 2017), this might be an advantage of the FW loading in electing PAP and PAPE (PAP/E) responses. Thus, it could be hypothesized that eccentric overload might result in post-activation muscle function enhancement but the mechanism is theoretical at this point. Moreover, the reduction of eccentric strength due to inhibitory mechanisms was found to be higher in sedentary subjects in comparison to strength-trained athletes (Aagaard et al., 2000; Amiridis & et al., 1996), suggesting that the underlying mechanisms may be modulated by training experience.

Over the last decade, there has been increasing interest in the use of FW resistance training devices. In gravity-based resistance exercises the resistance is determined by a means of a mass of a load (kg). In contrary, the FW resistance exercises utilizes the inertia (kg·m^2) of a spinning FW to produce resistance. Previous studies have found improvements in performance after an acute bout of FW squats (Beato, de Keijzer, et al., 2020; de Keijzer et al., 2020; Maroto-Izquierdo et al., 2020; McErlain Naylor et al., 2021) but there is a lack of research investigating differences in performance enhancement between FW and gravity-based resistance (Beato et al., 2019; Sañudo et al., 2020) because of absence of the common relative load intensity denominator (Muñoz-López et al., 2021). Therefore, comparisons between loading condition and subsequent performance enhancement effects might have led to misinterpretation of the results. To determine the loading training intensity zone in gravity dependent load exercises, trainers typically use an incremental load test which was also previously presented in FW squat conditions (Spudić et al., 2020; Spudić, Cvitkovič, et al., 2021). Recently, a maximum FW load index was presented as a solution to relativize load intensity in the leg extension exercise (Muñoz-López et al., 2021). It is also possible to normalize the loads by using maximum peak power with reference to the optimal power zone concept using incremental load test (Kawamori & Haff, 2004; Loturco et al., 2022). This seems to be the most functional approach, while peak power production is positively correlated to sprinting (Morin et al., 2010; Samozino et al., 2016) and vertical jump performance (Jaric & Markovic, 2009, 2013; Pazin et al., 2013; Suzovic et al., 2013).

It was found that broad range of FW load intensities enhances sport-specific performance (Beato, Mcerlain-Naylor, et al., 2020) and that there is no difference between the effect of small versus large (McErlain Naylor et al., 2021), and medium versus large FW load (Beato, de

Keijzer, et al., 2021) on subsequent athletic performances (e.g., vertical and horizontal jumps, sprints, changes of direction, swimming kick start) and corresponding kinetic outputs (Beato, Mcerlain-Naylor, et al., 2020). Although multiple sets are suggested, it seems that single and multiple sets can induce similar PAPE responses (de Keijzer et al., 2020). Early part of the recovery period (up to 30 s) deteriorates performance and PAPE come to the fore after 3-6 min, and lasts up to 20 minutes (Maroto-Izquierdo et al., 2020)). Moreover, ground reaction force orientation profiles (Beato, de Keijzer, et al., 2021; Beato, Stiff, et al., 2021; Zacca et al., 2018) or task specificity seems to have the highest impact, while tasks execution (coupled eccentric-concentric movements in FW squats and transfer to concentric squat jump [SJ] conditions) seems to play a negligible role (Timon et al., 2019). In addition, familiarization with FW resistance exercises might positively influence PAPE response (Beato, Mcerlain-Naylor, et al., 2020). The research findings regarding the superiority of FW resistance PAPE protocols in comparison to gravity-based resistance ones remain superficial. The main shortcoming of the current literature appears to be the lack of studies comparing the PAP/E effects between FW and gravity-based load conditions by matching load intensities between the conditions.

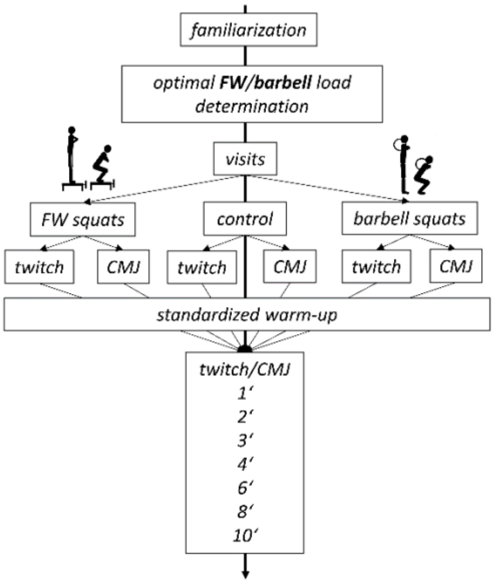
FW devices have the advantage of being easily transportable compared with barbells, supporting their utilization in field-based sports. Previous investigations have found improvements in performance after an acute bout of FW squats (Beato, de Keijzer, et al., 2020; de Keijzer et al., 2020; Maroto-Izquierdo et al., 2020; McErlain Naylor et al., 2021). Nevertheless, there is less research investigating differences in performance enhancement between FW and gravity-based resistance (Beato et al., 2019; Sañudo et al., 2020) due to absence of the common relative load intensity denominator (Muñoz-López et al., 2021). Recent research had focused on the PAPE and to the authors knowledge, there is no study examining differences in the PAP response between FW and gravity-based resistance exercise protocols, and what is of importance, to the control (warm-up) protocol. Therefore, the mechanisms electing acute performance enhancement are fairly unknown. The first aim of our study was to compare PAP and PAPE responses between a set of optimal power load FW squats and barbell squats and, additionally, to a control protocol. Our second aim was to determine if responses induced are related to participants' experience with FW resistance training. Because of intensity and tempo matched squat protocols we hypothesized no differences in positive PAP and PAPE responses. Moreover, based on current findings (Beato et al., 2019; Seitz et al., 2014) we hypothesized more positive PAP and PAPE responses in a group of FW resistance exercise experienced participants.

METHODS

Study design

To determine the impact of loading conditions on PAP and PAPE variables we used a crossover within-participants randomized controlled study design. Each participant attended the laboratory on eight separate occasions, separated by at least 48 h of recovery to avoid any possible transient fatigue (Strojnik & Komi, 1998) due to repeated efforts, long-term potentiation effect due to hormonal changes (Cook et al., 2014), corticospinal tact excitability, spinal reflex excitability and intracortical inhibition (Peterson, 2009) - all mentioned being significant up to 24 hours after different potentiation protocols, including strength exercises. Moreover, testing sessions were assigned randomly to avoid any inter-session effect (Figure 1).

Figure 1. Block diagram of the study procedures.



Notes. FW – flywheel. CMJ – countermovement jump.

Participants

Nineteen physically active volunteers experienced in strength training participated in the study (see Table 1 for details). The inclusion criterion was strength training experience defined by a training history that included strength exercises at least twice per week in the past year. The exclusion criteria were: knee injuries (e.g., ligament, meniscus, or cartilage damage), chronic medical conditions (systemic, cardiac, and/or respiratory diseases, and neuromuscular disorders), a history of low back pain, or an acute injury in the past six months that could negatively affect squat performance. The sample size was estimated using the data from previous studies (Maroto-Izquierdo et al., 2020; Sañudo et al., 2020; Vargas-Molina et al., 2021) in which the FW and barbell conditioning activities were investigated for the twitch characteristics changes and countermovement jump (CMJ) height performance enhancement effect. An a priori power analysis (repeated-measures, within factors design, three groups by six measurements, correlation among repeated measures: r = 0.9) using G*power (version 3.1., Düsseldorf, Germany; http://www.gpower.hhu.de/) indicated that a sample of twelve participants was required to detect an effect size of 0.4 with 80% power and an alpha of 0.05. The study was approved by the National Medical Ethics Committee (No. 0120-690/2017/8) and adhered to the principles of Oviedo Convention and the Declaration of Helsinki. Participants were informed of the possible harmful risks of the experiment and provided written informed consent agreeing to the conditions of the study. They were instructed to avoid any strenuous exercise at least two days before the first testing session. While training status directly impacts the response to PAP and/or PAPE (Chiu et al., 2003) it is worth mentioning that ten out of nineteen participants were previously a part of a bigger study which included squats on a FW device (EX; experienced participants) and the other half completed only one familiarization session (unEX; unexperienced participants). EX participants performed eight weeks of progressive FW squat training (2-3 times a week, 3-5 times per 10 consecutive FW squats). In total they performed 22 training sessions preceded by one familiarization session. The last training session was performed approximately 6-8 weeks before the start of this study.

Table 1. Participants characteristics.

Group	Subgroup	n	Age (years)	Height (cm)	Mass (kg)	BMI (kg/m^2)	FW optimal load power (W/kg)	Barbell optimal load power (W/kg)
Experienced	Female	6	23.2 (2.2)	166.5 (5.1)	67.5 (9.0)	24.3 (2.4)	30.1 (6.8)	20.0 (2.2)
	Male	4	25.5 (2.4)	175.5 (5.3)	68.7 (8.2)	22.3 (2.5)	38.4 (8.9)	25.2 (4.2)
	All	10	24.1 (2.5)	170.1 (6.7)	68.0 (8.2)	23.5 (2.5)	33.4 (8.4)	22.1 (4.0)
Unexperienced	Female	5	26.6 (2.1)	166.6 (2.1)	72.4 (6.8)	21.8 (2.7)	24.1 (5.2)	19.1 (2.6)
	Male	4	24.8 (2.9)	179.3 (3.9)	60.5 (7.8)	22.5 (1.4)	30.3 (3.5)	25.3 (2.9)
	All	9	25.8 (2.5)	172.2 (7.2)	65.8 (9.3)	22.1 (2.1)	26.9 (5.4)	21.8 (4.1)
Together	Total	19	24.9 (2.6)	171.1 (6.9)	66.9 (8.6)	22.8 (2.4)	30.3 (7.7)	22.0 (3.9)

Notes. n - number of participants in the group. all - male and female. Data are presented as means (standard deviations). Optimal load power is expressed for the concentric part of the FW/barbell squat.

Testing procedures

One week prior to experiment familiarization protocol was conducted. It included standardized warm-up procedure (described below) and two sets of ten submaximal FW squats using a medium FW inertia (0.05 kg·m^2) and two sets of ten submaximal barbell squats using a barbell (20 kg) for female and barbell + 10 kg (30 kg) for male participants, respectively. Tempo of exercise execution (FW and barbell squats) was described in detail (Spudić, Cvitkovič, et al., 2021) and controlled by an experienced researcher as described in detail bellow. Moreover, shortened procedure (up to five electrical stimuluses) of evoked contractions of the quadriceps femoris muscle with percutaneous electrical stimulation of the femoral nerve were performed to familiarize participants.

Testing procedures included a) optimal FW load determination, b) optimal barbell load determination, c) control visit to determine twitch characteristics, d) control visit to determine CMJ characteristics. Moreover, PAP/E visits included e) evoked contractions of the quadriceps femoris muscle and FW squat PAP/E protocol, f) CMJ testing and FW squat PAP/E protocol, g) evoked contractions of the quadriceps femoris muscle and barbell squat PAP/E protocol, and h) CMJ testing and barbell squat PAP/E protocol. Testing procedures (apart from a and b) and PAP/E protocols (e-g) were performed on separate visits in a randomized order.

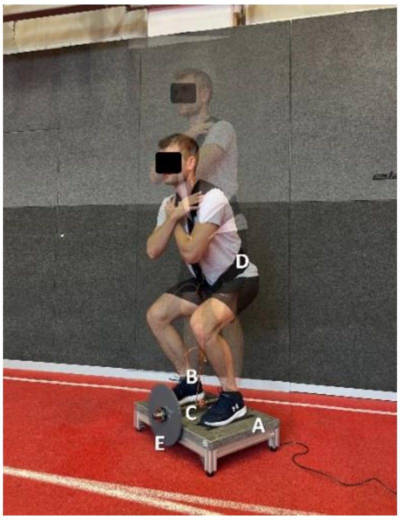
Standardized-warm up procedure included two minutes of stepping on a 25 cm high bench at 60 RPM, alternately with right and left foot followed by dynamic stretches of hip flexors, knee extensors, knee flexors, and ankle extensors (10 slow repetitions each), and heel raise and squat exercises (8 slow repetitions each). No specific warm-up procedures were performed to avoid any post-activation potentiation effect.

Optimal FW and barbell load determination

Loading condition for PAP/E protocol was previously defined using an incremental loading test procedure, separately for FW (Spudić et al., 2020) and barbell squats (Armstrong et al., 2022). During each squat execution average power produced in the concentric part of the movement was measured. Consequently, *P-load* spectrum was calculated. FW and barbell load at which the highest mean concentric power was produced were used in PAP/E protocols. The experiment was performed on a custom-made FW device (Figure 2) (Spudić, Cvitkovič, et al., 2021) and using a 10 kg barbell with additional weight plates. To increase reliability, power was calculated as the average of six consecutive squat repetitions, as previously suggested (Spudić et al., 2020). Rest periods between different loading conditions were three minutes and between sets two minutes to allow participants to adequately recover from the previous load and/or set (Sabido et al., 2020). Participants received verbal encouragement from the researchers during all testing sessions.

In FW squats, two sets of 10 consecutive squats were performed at five FW loading conditions (0.025, 0.05, 0,75, 0.1 and 0,125 $kg \cdot m^2$), where the first two repetitions were used to attain proper squat execution (tempo and amplitude) and the last two were used to decelerate the spinning FW safely. The set with higher mean power produced for the six maximal effort repetitions was addressed in load determination. Number of loads used was determined based on authors' previous experience and real-time feedback of concentric power output during incremental test loading conditions. Generally, maximal mean concentric power was produced up to the 0.1 $kg \cdot m^2$ FW load ($\leq$ 0.125 $kg \cdot m^2$). None out of participants produced maximal power at the highest FW loading condition (0.125 $kg \cdot m^2$). From repetitions two to eight, 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. Squat execution was determined from the lowest point (approximately 90° knee angle) to full knee extension (approximately 0° knee angle). Participants crossed their arms and placed their hands on opposing shoulders. The heels were not permitted to lift from the floor. Testing procedure and data acquisition were previously validated (Spudić, Cvitkovič, et al., 2021). Rotary encoder data were collected using the shaft rotation sensor (slot type Optocoupler Module Speed Measuring Sensor for Arduino/51/AVR/PICCG, JingJiang, China), which records FW angular frequency data based on angular displacement. The sensor detects the holes in a sprocket-wheel mounted on the FW axis at a rate of 1 pulse per 7.5°. This method of data acquisition allows for greater data sampling at high speeds. Variables from the shaft rotation were calculated from the angular frequency of the shaft using basic Newton's laws (known as the inverse dynamic approach), as described in detail by Spudić and coworkers (Spudić, Cvitkovič, et al., 2021). Mean power output was calculated as a product of vertical velocity and estimated ground reaction force in each time interval of 1 ms. Concentric part of the repetitions was determined from the vertical position data: from the lowest squat position (approximately 90° knee flexion) to the standing position (approximately 0° knee flexion).

Figure 2. Flywheel (FW) squat setup.



Notes. The characteristics of the custom-made device were: a platform (A) (size 0.65 × 0.4 m), a pulling rope (B) (diameter of 0.006 m), a rotating shaft (C) (diameter of 0.03 m), a harness (D) and a FW load (E).

In barbell squats, two sets of 10 consecutive squats were performed at five loading conditions (Figure 3). The first loading condition was body mass [BM] + 10 kg barbell. Then, progressively additional 5 kg were added for female and 10 kg for male participants. This resulted in additional 17% (2%), 25% (3%), 33% (5%), 41% (6%) and 49% (7%) of BM for women and additional 16% (2%), 30% (3%), 44% (5%), 59% (6%) and 73% (8%) of BM for man, respectively. Number of loads was determined based on and real-time feedback of concentric power output during the incremental test. In general, maximal mean concentric power was produced up to the forth load (i.e. additional 41% of BM for women and 59% of BM for man). None out of participants produced maximal power at the highest loading condition. The first two repetitions were used to attain proper squat execution (tempo and amplitude) and the last two were used to safely stop the movement. The set with higher mean power produced for the six maximal effort repetitions was addressed in load determination. 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. Squat execution was determined from the lowest point (90° knee angle) to full knee extension (0° knee angle). Their arms were placed on the barbell. The heels were not permitted to lift from the floor. Ground reaction force data was acquired from the force plate (model 9287A, Kistler, Winterthur, Switzerland) at a frequency of 1000 Hz. Then signals were filtered using a 50 ms moving average filter (Spudić et al., 2020). Mean power output was calculated as a product of vertical velocity and vertical ground reaction force data in each 1 ms time interval. Moreover, concentric part of the repetitions was determined from the vertical position data. All the variables required were calculated from ground reaction force data following inverse dynamic approach.

Figure 3. Barbell squat test.

Quadriceps femoris evoked contractions

Evoked knee extensions were performed for the left leg sitting in the chair of an isometric knee dynamometer (Figure 4) (S2P, Science to Practice, ltd., Ljubljana, Slovenia) (Šarabon et al., 2013). The knee angle was set to 60° flexion (full knee extension is 0°) and the hip angle to 90° flexion. The flexion-extension knee axis was aligned with the axis of the dynamometer's lever arm, while the shank was supported at the level 2 cm proximal from the lateral malleolus. Rigid straps tightened over the pelvis ensured good hip fixation. The optimal position for percutaneous electrical stimulation of the femoral nerve and the required intensity were determined while sitting. Stimulation was performed with single square pulses (1 ms) delivered from a constant current stimulator (DS7A; Digitimer, Hertfordshire, UK) to the left femoral nerve via a surface cathode (30 × 24 mm; Kendall, Covidien, Mansfield, TX, USA) manually pressed into the femoral triangle and a 50 × 90 mm anode (Axelgaard Manufacturing Co, LTD, Fallbrook, CA, USA) placed slightly above the gluteal fold. To determine the maximum stimulation intensity individual stimuli were delivered in 30 s intervals gradually in 5–10 mA increments until a plateau was reached in the quadriceps twitch torque. Intensity was then increased by 50% to confirm supramaximal stimulation. Resting twitch was measured two minutes after supramaximal intensity stimulation determination to avoid any post-activation depression response (Xenofondos et al., 2015). Evoked contractions were also performed 1, 2, 3, 4, 6, 8 and 10 minutes after the PAP/E protocols following abovementioned protocol. Knee extension torque, corrected for gravity, was captured using the PowerLab system (16/30-ML880/P, ADInstruments) with a sampling frequency of 1000 Hz. Twitch characteristics were recorded and analyzed using LabChart8 software (ADInstruments, Bella Vista, Australia). The following twitch variables were analyzed from raw torque-time signal: a) the peak twitch amplitude (the highest value of the twitch torque curve), b) the twitch contraction time (the time from the increase of the initial torque above 5% of the peak twitch torque to the time point at the peak twitch torque), and c) twitch half relaxation time (the time from the time point at the peak twitch torque to the 50% of the peak twitch torque in the descending part of the twitch signal).

Figure 4. Placement of the participant into isometric dynamometer for evoked knee extensor contraction test.

Countermovement jump

Before each jump, participants were instructed to stand up straight and still on the centre of the force plate with their hands akimbo. This hand position remained the same during the entire movement. From this position, participants initiated a fast-downward movement until a crouching position with a knee angle of about 90°, followed by a jump for maximal height as quickly and explosively as possible. Test execution was supervised from the experienced researcher to improve proficiency in jumping technique (Mandic et al., 2015). A force plate system (model 9287A, Kistler, Winterthur, Switzerland) with Analysis and Reporting Software for Force Plates software (S2P Ltd., Ljubljana, Slovenia) was used to acquire ground reaction force. Data were sampled at 1000 Hz, filtered using a moving average filter with 50-ms window and analysed using the built-in module for CMJ. Jump height from push-off force impulse was used in the analysis (Linthorne, 2001).

PAP and PAPE protocols

Protocols were performed after initial twitch or CMJ measurements followed by standardized warm-up procedure (Figure 1). In FW and barbell squats protocols consisted of one set of 11 consecutive squats at peak power load condition. The two repetitions were used to attain proper squat execution (tempo and amplitude) and the last two were used to decelerate the spinning FW safely or to safely stop the vertical movement of the barbell. The same exercise equipment and exercise execution were used as for optimal FW and barbell load determination (described above). Briefly, from repetitions two to nine, 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. Moreover, the heels were not permitted to lift from the floor. Within one minute after the protocol, participants were directed to the evoked quadriceps contractions or CMJ measurements. Steps of the protocol were beforehand carefully explained to the participants to avoid any delays in the sequential measurements.

Statistical Analyses

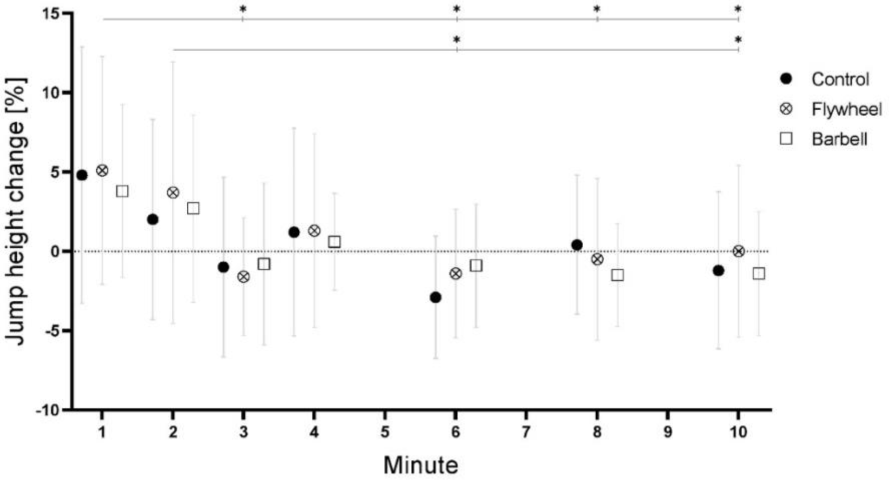
Firstly, relative changes (in percent) of the CMJ jump height and twitch characteristics were calculated in relation to the results of the initial measurements at each visit (before warm-up). Data are presented as means (standard deviations). Normal distribution was confirmed using the Shapiro–Wilk test ($p > 0.05$). A mixed model ANOVA was performed to assess the influence of load condition (control, flywheel, barbell), time (1, 2, 3, 4, 6, 8 and 10 min) and participants' experience (EX, unEX) over jump height, twitch amplitude, twitch contraction time and twitch half-relaxation time and, moreover, to assess the influence of participants' experience (EX, unEX) and load condition (FW, barbell) over optimal load squat power production. In the case that the sphericity assumption was not met, degrees of freedom were corrected using Greenhouse-Geisser estimation. The reported effect size for aforementioned comparisons was partial eta-squared ($p\eta^2$) where the criteria for effect size were small ($p\eta^2 = 0.010$), medium ($p\eta^2 = 0.059$), and large ($p\eta^2 = 0.138$), as suggested by previous papers (Kotrlik & Williams, 2003). Post hoc analysis was performed using t-test with Bonferroni adjustment. Statistical analyses were performed in SPSS (Version 26, IBM, Armonk, NY, USA). For all analyses, the level of significance was set at $p < 0.05$.

RESULTS

The mixed model ANOVA testing the effect of participants' experience (EX, unEX) and load condition (FW, barbell) over optimal load squat power production revealed significant experience*load condition interaction ($F = 6.624$, $p = 0.020$, $p\eta^2 = 0.280$), main effect of load condition ($F = 45.356$, $p < 0.001$, $p\eta^2 = 0.727$) and main effect of participants' experience ($F = 45.356$, $p < 0.001$, $p\eta^2 = 0.727$) (Table 1).

The mixed model ANOVA testing the effect of the load condition (control, flywheel, barbell), time (1, 2, 3, 4, 6, 8 and 10 min) and participants experience over CMJ jump height (Figure 5) showed no time*load condition*experience interaction ($F = 0.923$, $p = 0.525$, $p\eta^2 = 0.051$), time*load condition interaction ($F = 0.341$, $p = 0.980$, $p\eta^2 = 0.020$) nor load condition*experience interaction ($F = 0.802$, $p = 0.457$, $p\eta^2 = 0.045$). On the contrary, the analysis revealed significant time*experience interaction ($F = 2.790$, $p = 0.015$, $p\eta^2 = 0.141$). We found a significant main effect of time ($F = 9.180$, $p < 0.001$, $p\eta^2 = 0.351$) and experience ($F = 9.087$, $p = 0.008$, $p\eta^2 = 0.348$) and no significant main effect of load condition ($F = 2.234$, $p = 0.123$, $p\eta^2 = 0.116$). Pairwise comparison revealed significant decrease in the jump height between minutes 1 and 3 (-5,7%, $p < 0.001$), 1 and 6 (-6.2%, $p < 0.001$), 1 and 8 (-5.0%, $p = 0,005$), 1 and 10 (-5.3%, $p = 0,015$), 2 and 6 (-4.6%, $p = 0.019$), and finally, 2 and 10 (-3.7%, $p = 0.11$). Pairwise comparison at a second minute revealed significantly larger jump height increase among unEX participants in comparison to EX participants (4.4%, $p = 0.034$).

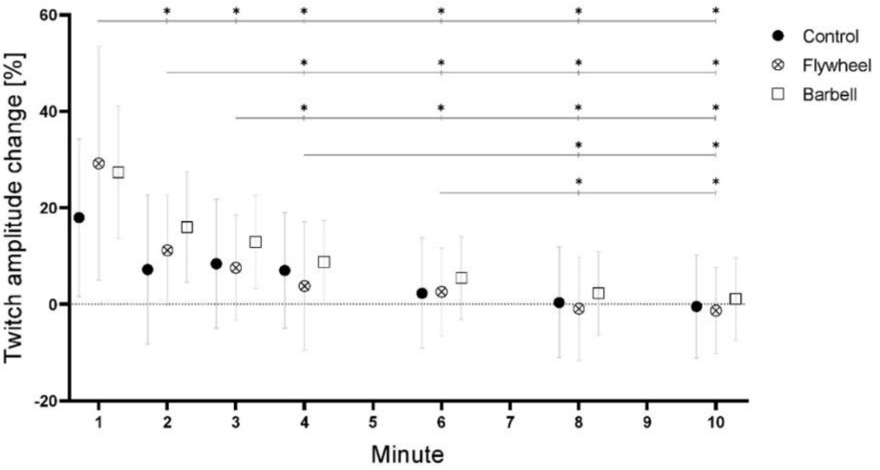
Figure 5. Changes in countermovement jump height over time after a control, flywheel and barbell protocols.



Notes. Standard deviations are presented as vertical lines. * - statistically significantly lower jump height between two time points, regardless of the loading condition.

The mixed model ANOVA testing the effect of the load condition, time, and participants experience over twitch amplitude (Figure 6) showed no time*load condition*experience interaction (F = 0.560, p = 0.872, $p\eta^2 = 0.032$), time*experience interaction (F = 0.139, p = 0.991, $p\eta^2 = 0.008$) nor load condition*experience interaction (F = 1.406, p = 0.259, $p\eta^2 = 0.076$). On the contrary, the analysis revealed significant time*load condition interaction (F = 2.554, p = 0.004, $p\eta^2 = 0.131$). Moreover, we found a significant main effect of time (F = 50.651, p < 0.001, $p\eta^2 = 0.794$), while the main effects of load condition (F = 1.347, p = 0.274, $p\eta^2 = 0.073$) and experience (F = 0.859, p = 0.367, $p\eta^2 = 0.048$) were not significant. Pairwise comparison revealed significant decrease in the twitch amplitude between minutes 1 and 2 (-13.4%, p < 0.001), 1 and 3 (-15.2%, p < 0.001), 1 and 4 (-18.4%, p < 0.001), 1 and 6 (-21.4%, p < 0.001), 1 and 8 (-24.3%, p < 0.001), 1 and 10 (-25.1%, p < 0.001), 2 and 4 (-5.0%, p = 0.002), 2 and 6 (-8.0%, p = 0.003), 2 and 8 (-10.9%, p < 0.000), 2 and 10 (-11.7%, p < 0.000), 3 and 4 (-3.2%, p < 0.001), 3 and 6 (-6.1%, p < 0.001), 3 and 8 (-9.1%, p < 0.000), 3 and 10 (-9.8%, p < 0.001), 4 and 8 (-5,9%, p < 0.001), 4 and 10 (-6.7%, p = 0.004), 6 and 8 (-2.9%, p = 0.004), and finally, 6 and 10 (-3.7%, p = 0.005). Moreover, pairwise comparison revealed significantly larger twitch amplitude increase at a second minute after barbell in comparison to control protocol (8.7%, p = 0.023).

Figure 6. Changes in twitch amplitude over time after a control, flywheel and barbell protocols



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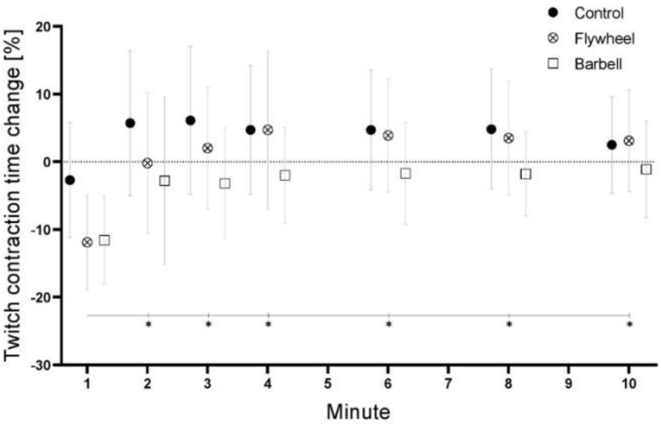
Notes. Standard deviations are presented as vertical lines. * - statistically significantly lower twitch amplitude between two time points, regardless of the loading condition

The mixed model ANOVA testing the effect of the load condition, time and participants' experience over twitch contraction time (Figure 7) showed no time*load condition*experience interaction (F = 1.018, p = 0.433, $p\eta^2 = 0.057$), load condition*experience interaction (F =

2.963, p = 0.065, pη^2 = 0.148) and time*experience interaction (F = 1.591, p = 0.157, pη^2 = 0.086). On the contrary, the analysis revealed significant time*load condition interaction (F = 4.119, p < 0.001, pη^2 = 0.195). Moreover, we found a significant main effect of load condition (F = 5.170, p = 0.011, pη^2 = 0.233) and time (F = 34.615, p < 0.001, pη^2 = 0.7671) and no main effect of experience (F = 2.119, p = 0.164, pη^2 = 0.111). The pairwise comparison with Bonferroni adjustment revealed significant differences in the twitch contraction times between the control and barbell load conditions (6.9%, p = 0.003). Moreover, pairwise comparison revealed significant increase in the twitch contraction time between minutes 1 and 2 (9,8%, p < 0.001), 1 and 3 (10.4%, p < 0.001), 1 and 4 (11.3%, p < 0.001), 1 and 6 (11.1%, p < 0.001), 1 and 8 (11.0%, p < 0.001), and minutes 1 and 10 (10.3%, p < 0.001). Additionally, pairwise comparisons revealed significantly larger twitch contraction time decrease at first minute after FW (-8.8%, p = 0.006) and barbell (-8.5%, p = 0.001) protocols in comparison to control protocol; contradictory twitch contraction time change at second minute after barbell protocol in comparison to control protocol (8.2%, p = 0.038); contradictory twitch contraction time changes at third minute after barbell protocol in comparison to control protocol (9%, p = 0.004); contradictory twitch contraction time changes at fourth minute after barbell protocol in comparison to control protocol (6.5%, p = 0.010) and in comparison to FW protocol (6.9%, p = 0.039); contradictory twitch contraction time changes at fifth minute after barbell protocol in comparison to control protocol (6.2%, p = 0.017) and finally; contradictory twitch contraction time changes at sixth minute after barbell protocol in comparison to control protocol (6.5%, p = 0.007).

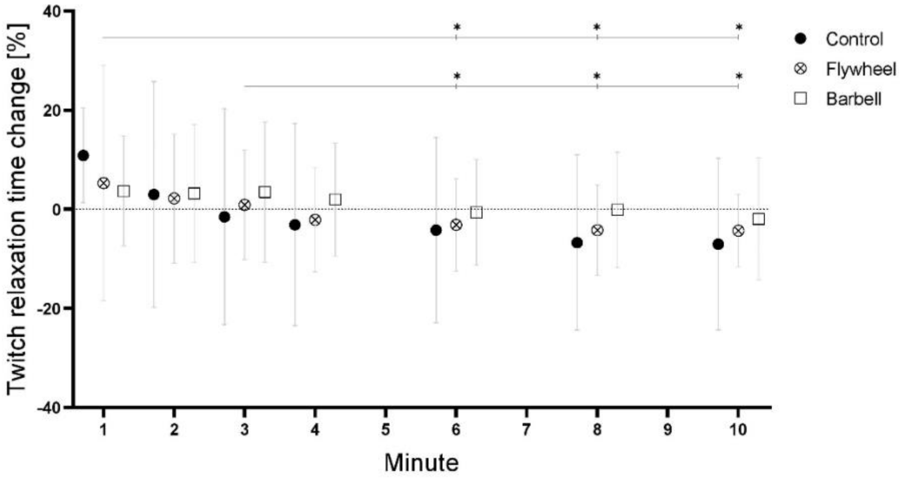
Figure 7. Changes in twitch contraction time over time after a control, flywheel and barbell protocols.



Notes. Standard deviations are presented as vertical lines. * - statistically significantly longer twitch contraction time between two time points

The mixed model ANOVA testing the effect of the load condition, time and participants experience over twitch half-relaxation time (Figure 8) showed significant time*load condition*experience interaction ($F = 2.321$, $p = 0.008$, $p\eta^2 = 0.120$) and no time*experience ($F = 0.630$, $p = 0.706$, $p\eta^2 = 0.036$), time*load condition ($F = 1.509$, $p = 0.123$, $p\eta^2 = 0.082$) nor load condition*experience ($F = 1.826$, $p = 0.177$, $p\eta^2 = 0.097$) interactions. We found a significant main effect of time ($F = 10.688$, $p < 0.001$, $p\eta^2 = 0.386$) and no significant main effects of load condition ($F = 0.214$, $p = 0.809$, $p\eta^2 = 0.012$) and experience ($F = 0.257$, $p = 0.619$, $p\eta^2 = 0.015$). Pairwise comparison revealed significant decrease in the twitch half-relaxation time between minutes 1 and 6 (-9,4%, $p = 0.020$), 1 and 8 (-10.4%, $p = 0.013$), 1 and 10 (-11.2%, $p = 0.006$), 3 and 8 (4.7%, $p = 0.030$), and finally, 3 and 10 (5.4%, $p = 0.029$). Moreover, pairwise comparisons in unEX participants revealed significantly lower increase in twitch half-relaxation time at a first minute after a barbell in comparison to a control protocol (9.7%, $p = 0.046$). Moreover, in EX participants after a control protocol half-relaxation time decreased significantly between minutes 1 and 4 (-18.8%, $p = 0.048$), 1 and 6 (-18,5%, $p = 0.043$), 1 and 8 (-21.3%, $p = 0.019$), and 1 and 10 (-22%, $p = 0.012$).

Figure 8. Changes in twitch half-relaxation time over time after a control, flywheel and barbell protocols.



Notes. Standard deviations are presented as vertical lines. * - statistically significantly shorter twitch half-relaxation time between two time points.

DISCUSSION

The first aim of our study was to compare PAP/E responses between a set of optimal power load FW squats and barbell squats and, additionally, to a control protocol. We hypothesized no differences in PAP and PAPE responses, while the relative intensity and the tempo of the two resistance exercise protocols were matched by the peak power load selection. We found out that jump height changed as a factor of time (the highest response at the first minute) and experience of the participants (higher jump in the unEX group at the second minute) but regardless of the PAP/E protocol. Twitch amplitude changed as a factor of time and load condition. A larger twitch amplitude increase was found at a second minute after the barbell in comparison to the control protocol. Twitch contraction time changed as a factor of time and load condition, but differences were only found between one of the PAP/E and control protocols. Finally, twitch half-relaxation time changed as a factor of time, PAPE/E protocol and experience. We found a lower increase in the twitch half-relaxation time at the first minute after a barbell in comparison to a control protocol among unEX participants and a faster decrease of the half-relaxation time among EX participants. Our first hypothesis can therefore be confirmed. Despite minor differences between unEX and EX participants, we can also partly confirm our second hypothesis that PAP/E responses are related to participants' experience with FW resistance training. Only jump height and half-relaxation time variables revealed some differences between EX and unEX participants. At the second minute after the conditioning activity higher jump height increase was found among unEX participants. Lower increase of half-relaxation time was found after first minute following barbell in comparison to control protocol. Moreover, half-relaxation time returned to the initial value faster among EX participants.

In general, we found no differences in the PAP/E responses between FW and Barbell protocols. What is more, PAP/E protocols elicited better results than the control only for twitch amplitude. The protocols used (1 set of 7 all out coupled eccentric-concentric squat repetitions) provided us with not much better results than a standardized warm-up alone, regardless of the type of resistance used (FW or gravity-based). Our results are contrary to the results in the previous literature, exploring the effect of FW squats on jumping performance (Beato et al., 2019; Beato, de Keijzer, et al., 2021; de Keijzer et al., 2020; Maroto-Izquierdo et al., 2020; McErlain Naylor et al., 2021; Sañudo et al., 2020; Timon et al., 2019; Zacca et al., 2018). The CMJ test was selected because the force orientation vector, joint and muscle actions are similar to the preceding conditioning activity (Beato, de Keijzer, et al., 2021; Seitz & Haff, 2016). It is worth mentioning, that in our study only one set of FW and barbell squats were performed in comparison to other studies where multiple sets were performed (Beato, Mcerlain-Naylor, et al., 2020). Moreover, our study explored the time (1-10 min) of PAP/E response in comparison to a control visit, not only compared to visit initial value of the jump height at familiarization visit (de Keijzer et al., 2020) or baseline value of the testing visit (Beato, de Keijzer, et al., 2021) as used in some other studies. The barbell and FW intensities were standardised by using the load that produced the elicited peak concentric power. However, the peak concentric power itself was not matched between the two exercises. Even if the peak powers were matched, there would likely still be differences in power, force, velocity, eccentric overload, muscle force length, and force-velocity characteristics during the rest of the concentric phase. Many of these factors could have influenced our results, nevertheless we attempted to standardise intensity in a practical way that could be implemented in practise.

A detailed investigation of twitch contractile properties could provide further insight into muscular response to preceding activity and reflect peripheral physiological mechanisms (beyond sarcolemma) that take place in the muscle (e.g. the Ca^{2+} cycle at different sites of excitation-contraction-relaxation coupling). To our knowledge, there are no studies that had examined muscle contractility responses following FW and barbell protocols. PAP response is associated with increase in twitch amplitude and reduction in twitch contraction time (Ereline et al., 2011) and, vice versa, classical signs of peripheral fatigue are normally associated with reduction in twitch amplitude, an increase in contraction time and half-relaxation time (Alway et al., 1987; Booth et al., 1997; Gollnick et al., 1991). Two main factors have been described as responsible for the changes in twitch properties: sarcoplasmic reticulum Ca^{2+} release/uptake and its concentration in the interfibrillar area and rate of cross-bridge kinetics (Booth et al., 1997; Ereline et al., 2011). All protocols (including control) elicited PAP effect, while twitch amplitude and contraction time increased as a factor of time and the load condition. Twitch half-relaxation time changed as a factor of time, PAPE/E protocol and experience. It is interesting finding that half-relaxation time returned to the initial value faster among EX participants, which could indicate a faster regeneration. On the contrary, it was previously explained that training experience may cause an adaptation in the sarcoplasmic reticulum leading to slower uptake of calcium ions during the relaxation phase of the twitch, thereby causing a longer relaxation time. The functional advantage of such an adaptation is that the torque-time integral in response to a nerve impulse (and muscle action potential) would be increased (Kitai & Sale, 1989). Overall, we have found no differences between the two loading conditions, and only several differences in comparison to control protocol, therefore the practical usefulness of the PAP/E protocols used remains questionable.

Regarding the participants' experience, we have found differences in the peak power production during squats on FW device and using a barbell. While there were only minor differences between barbell squats power production (EX vs. unEX: 22.1 vs. 21.8 W/kg), higher differences were found in FW loading conditions (EX vs. unEX: 33.4 vs. 26.9 W/kg) which clearly indicates experience in performing a specific resistance exercise using gravity-independent load. It was previously revealed that the PAP effect is larger among stronger individuals and those with more resistance training experience and after shallower squat conditioning activities, longer recovery intervals, multiple-set protocols, and higher intensity exercises (repetition maximum and especially plyometrics). Moreover, the PAP effect may occur earlier after completion of a plyometric exercise than after high or moderate intensity lifting. When considering strength status, the PAP effect is larger after shorter recovery intervals and single-set and maximum intensity among stronger individuals, while longer recovery intervals, multiple-sets, and sub-maximal intensity are more effective at inducing PAP in weaker individuals (Seitz & Haff, 2016). The results of our research are therefore contrary to traditional gravity-based resistance PAP studies (Seitz & Haff, 2016) since at a second minute after the conditioning activity, higher jump height increase was found among unEX participants. Moreover, half-relaxation time returned to the initial value faster among EX participants, what could be potentially explained by a faster regeneration (Gollnick et al., 1991) among more resistance trained participants, regardless of the type of resistance. While the eccentric contractions may have some advantages in eliciting PAP/E response, there are also some disadvantages to address. During eccentric overload, high forces are produced in the eccentric part of the squat – this is especially true using FW devices (Spudić, Cvitkovič, et al., 2021). High eccentric force demands could have caused neural inhibition (Aagaard et al., 2000) due to tension-limiting mechanism specific to eccentric action (Alcazar et al., 2019; Amiridis & et al., 1996). While the existence of a neural regulatory mechanisms may be modulated by training experience (Amiridis & et al., 1996), some differences between PAP/E responses were expected.

The main strengths of our study are load individualization in both loading conditions, matching the type of exercise tempo execution (coupled eccentric-concentric actions) and adding a control visits to get insight into CMJ and twitch contractile properties without PAP/E protocol. The latter extended the time of the study but the results are more trustworthy while the control condition was compared with the PAP/E results during the time of the testing protocol. Moreover, this is the first study to assess PAP response (i.e. evoked quadriceps muscle contractions) following the FW resistance exercise. In the present study, loading conditions were matched by peak power load. In the barbell conditions, ground reaction force and velocity of the center of mass obtained from force plates were used to calculate power. In contrary, in FW conditions, the data from rotational encoder was used to estimate ground reaction force, velocity and consequently power. It was previously found that rotary encoder overestimates the force plates and linear encoder force, velocity and power variables, and that the differences are dependent on the level of FW load (Spudić, Cvitkovič, et al., 2021). Therefore, direct comparison of the absolute results between loading conditions is questionable, nevertheless, the discrepancies between the sensory systems used should not influence relative load selection within each of the loading conditions. Blazevich (2019) suggested a study design consideration to stick with when preparing PAP/E studies. According to these suggestions, we did not blind a researcher or participant + researcher. We did compare between at least two conditions and control, familiarization and randomization were performed, and we controlled for time of day, diet and hydration, physical activity performed in the days prior to testing, and potential use of ergogenic aids, but not for muscle temperature.

Moreover, optimal muscle-force sequencing during push-off affect ground reaction force application and jumping performance (Pandy & Zajac, 1991). The lowest FW load follows the proximal-to-distal principle of muscle activation, while higher FW loads require a specific and stable muscle coordination pattern, which is not proximal-to-distal (Spudić, Smajla, et al., 2021). These findings are not in the line with the previous literature (Giroux et al., 2014; van den Tillaar et al., 2019) which suggested that muscle coordination was not influenced by the external load during a ballistic SJ and squats performed with maximal movement velocity, respectively. It could be speculated that the differences occur due to use of the harness in FW squats. Harness sits across the shoulders, chest, and lower back, stressing the muscles crossing the hip joint and the spine erectors and could influence movement dynamics in the transition from the eccentric to the concentric part of the squat. The CMJ test was selected because of the task-specificity to the conditioning activity (FW and barbell squats). It is clear that CMJ follows the same ground reaction force orientation profile as squatting (Beato, de Keijzer, et al., 2021; Beato, Stiff, et al., 2021; Zacca et al., 2018), but on the basis of aforementioned results regarding the intra-muscular coordination during FW squats, intra-muscular coordination and therefore CMJ jump height might have been impaired by a preceding FW squats activity.

CONCLUSION

FW load, barbell load and control protocol (warm-up) enhanced jumping performance and evoked quadriceps muscle functioning. Only minor differences between loading conditions were found, which are, to the authors opinion, practically irrelevant. There was no benefit of including a set of FW squats or barbell squats to the standard warm-up protocol in order to elicit PAP response of the quadriceps femoris muscle and consequently enhance CMJ jump height. Our results are contrary to the existing literature, reporting favorable effects of FW loading on PAPE response, probably because executing only one set of squats, matching the tempo of the exercise execution and relative load selection in both, FW and barbell load conditions. A previous study had shown that more than one set is required for a PAPE effect of FW squats (Beato, Mcerlain-Naylor, et al., 2020). Therefore, we can speculate that a single set of FW squats is not sufficient to distinguish PAP(E) effects between flywheel and barbell squats. Moreover, we found only few, practically irrelevant, differences in the jump height and twitch characteristics between FW, barbell and control protocols. Therefore, we conclude that practical experience with FW resistance training does not influence PAP/E response, what is also contrary to the body of research using gravity-based resistance. In the future, more studies are needed to confirm our findings. Based on our results and experience, we believe that, firstly, the most efficient PAP/E protocol using FW equipment should be explored, and secondly, the protocol should be compared to the most efficient gravity-based or even isometric loading condition, to get the most trustworthy information regarding the practical applicability of the two loading conditions. PAP/E response should therefore be studied for different muscle groups, recovery intervals, performance parameters and force vectors orientations, training background, age, sex, and protocol variables, such as number of repetitions, sets, between sets rest intervals and magnitude of FW load inertia.

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Declaration of Conflicting Interests

The authors report there are no competing interests to declare.

REFERENCES

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, S. P., Halkjær-Kristensen, J., & Dyhre-Poulsen, P. (2000). Neural inhibition during maximal eccentric and concentric quadriceps contraction: Effects of resistance training. *Journal of Applied Physiology*, *89*(6), 2249–2257. https://doi.org/10.1152/jappl.2000.89.6.2249

Abbate, F., Sargeant, A. J., Verdijk, P. W. L., & De Haan, A. (2000). Effects of high-frequency initial pulses and posttetanic potentiation on power output of skeletal muscle. *Journal of Applied Physiology*, *88*(1), 35–40. https://doi.org/10.1152/jappl.2000.88.1.35

Alcazar, J., Csapo, R., Ara, I., & Alegre, L. M. (2019). On the shape of the force-velocity relationship in skeletal muscles: The linear, the hyperbolic, and the double-hyperbolic. *Frontiers in Physiology*, *10*, 769. https://doi.org/10.3389/fphys.2019.00769

Alway, S. E., Hughson, R. L., Green, H. J., Patla, A. E., & Frank, J. S. (1987). Twitch potentiation after fatiguing exercise in man. *European Journal of Applied Physiology and Occupational Physiology*, *56*(4), 461–466. https://doi.org/10.1007/BF00417776

Amiridis, L. G., & et al. (1996). Co-activation & tension-regulating phenomena during isokinetic knee ext in sedentary & highly skilled humans. *Eur. J. Appl. Physiol.*, *73*, 149–156.

Armstrong, R., Baltzopoulos, V., Langan-Evans, C., Clark, D., Jarvis, J., Stewart, C., O'Brien, T. D., & O'Brien, T. D. (2022). Determining concentric and eccentric force – velocity profiles during squatting. *European Journal of Applied Physiology*, *122*(3), 769–779. https://doi.org/10.1007/s00421-021-04875-2

Beato, M., Bigby, A. E. J., De Keijzer, K. L., Nakamura, F. Y., Coratella, G., & McErlain-Naylor, S. A. (2019). Post-activation potentiation effect of eccentric overload and traditional weightlifting exercise on jumping and sprinting performance in male athletes. *PLoS ONE*, *14*(9), 1–13. https://doi.org/10.1371/journal.pone.0222466

Beato, M., de Keijzer, K. L., Fleming, A., Coates, A., La Spina, O., Coratella, G., & McErlain-Naylor, S. A. (2020). Post flywheel squat vs. flywheel deadlift potentiation of lower limb isokinetic peak torques in male athletes. *Sports Biomechanics*, *August*. https://doi.org/10.1080/14763141.2020.1810750

Beato, M., de Keijzer, K. L., Leskauskas, Z., Allen, W. J., Dello Iacono, A., & McErlain-Naylor, S. A. (2021). Effect of postactivation potentiation after medium vs. high inertia eccentric overload exercise on standing long jump, countermovement jump, and change of direction performance. *Journal of Strength and Conditioning Research*, *35*(9), 2616–2621. https://doi.org/10.1519/JSC.0000000000003214

Beato, M., Mcerlain-Naylor, S. A., Halperin, I., & Iacono, A. D. (2020). Current Evidence and Practical Applications of Flywheel Eccentric Overload Exercises as Postactivation Potentiation Protocols: A Brief Review. *International Journal of Sports Physiology and Performance*, *15*(2), 154–161. https://doi.org/10.1123/ijspp.2019-0476

Beato, M., Stiff, A., & Coratella, G. (2021). Effects of Postactivation Potentiation After an Eccentric Overload Bout on Countermovement Jump and Lower-Limb Muscle Strength. *Journal of Strength and Conditioning Research*, *35*(7), 1825–1832. https://doi.org/10.1519/JSC.0000000000003005

Blazevich, A. J., & Babault, N. (2019). Post-activation Potentiation Versus Post-activation Performance Enhancement in Humans: Historical Perspective, Underlying Mechanisms, and Current Issues. *Frontiers in Physiology*, *10*(Nov). https://doi.org/10.3389/fphys.2019.01359

Booth, J., McKenna, M. J., Ruell, P. A., Gwinn, T. H., Davis, G. M., Thompson, M. W., Harmer, A. R., Hunter, S. K., & Sutton, J. R. (1997). Impaired calcium pump function does not slow relaxation in human skeletal muscle after prolonged exercise. *Journal of Applied Physiology*, *83*(2), 511–521. https://doi.org/10.1152/jappl.1997.83.2.511

Boullosa, D. (2021). Post-activation performance enhancement strategies in sport: A brief review for practitioners. *Human Movement*, *22*(3), 101–109. https://doi.org/10.5114/hm.2021.103280

Chiu, L. Z. F., Fry, A. C., Weiss, L. W., Schilling, B. K., Brown, L. E., & Smith, S. L. (2003). Postactivation Potentiation Response in Athletic and Recreationally Trained Individuals. *Journal of Strength and Conditioning Research*, *17*(4), 671–677. https://doi.org/10.1519/00124278-200311000-00008

Cook, C. J., Kilduff, L. P., Crewther, B. T., Beaven, M., & West, D. J. (2014). Morning based strength training improves afternoon physical performance in rugby union players. *Journal of Science and Medicine in Sport*, *17*(3), 317–321. https://doi.org/10.1016/j.jsams.2013.04.016

de Keijzer, K. L., McErlain-Naylor, S. A., & Beato, M. (2020). Effect of Volume on Eccentric Overload–Induced Postactivation Potentiation of Jumps. *International Journal of Sports Physiology and Performance*, *October*, 1–6. https://doi.org/10.1123/ijspp.2019-0411

Enoka, R. M. (1996). Eccentric contractions require unique activation strategies by the nervous system. *Journal of Applied Physiology*, *81*(6), 2339–2346. https://doi.org/10.1152/jappl.1996.81.6.2339

Ereline, J., Gapeyeva, H., & Pääsuke, M. (2011). Comparison of twitch contractile properties of plantarflexor muscles in nordic combined athletes, cross-country skiers, and sedentary men. *European Journal of Sport Science*, *11*(1), 61–67. https://doi.org/10.1080/17461391.2010.481335

Giroux, C., Guilhem, G., Chollet, D., & Rabita, G. (2014). Muscle coordination in loaded squat jump. *Computer Methods in Biomechanics and Biomedical Engineering*, *17*, 158–159. https://doi.org/10.1080/10255842.2014.931621

Gollnick, P. D., Korge, P., Karpakka, J., & Saltin, B. (1991). Elongation of skeletal muscle relaxation during exercise is linked to reduced calcium uptake by the sarcoplasmic reticulum in man. *Acta Physiologica Scandinavica*, *142*(1), 135–136. https://doi.org/10.1111/j.1748-1716.1991.tb09139.x

Hamada, T., Sale, D. G., MacDougall, J. D., & Tarnopolsky, M. A. (2000). Postactivation potentiation, fiber type, and twitch contraction time in human knee extensor muscles. *Journal of Applied Physiology*, *88*(6), 2131–2137. https://doi.org/10.1152/jappl.2000.88.6.2131

Herzog, W. (2018). Why are muscles strong, and why do they require little energy in eccentric action? *Journal of Sport and Health Science*, *7*(3), 255–264. https://doi.org/10.1016/j.jshs.2018.05.005

Hessel, A. L., Lindstedt, S. L., & Nishikawa, K. C. (2017). Physiological mechanisms of eccentric contraction and its applications: A role for the giant titin protein. *Frontiers in Physiology*, *8*, 70. https://doi.org/10.3389/fphys.2017.00070

Jaric, S., & Markovic, G. (2009). Leg muscles design: The maximum dynamic output hypothesis. *Medicine and Science in Sports and Exercise*, *41*(4), 780–787. https://doi.org/10.1249/MSS.0b013e31818f2bfa

Jaric, S., & Markovic, G. (2013). Body mass maximizes power output in human jumping: A strength-independent optimum loading behavior. *European Journal of Applied Physiology*, *113*(12), 2913–2923. https://doi.org/10.1007/s00421-013-2707-7

Kawamori, N., & Haff, G. G. (2004). The optimal training load for the development of muscular power. *Journal of Strength and Conditioning Research*, *18*(3), 675–684. https://doi.org/10.1519/1533-4287(2004)18<675:TOTLFT>2.0.CO;2

Kitai, T. A., & Sale, D. G. (1989). Specificity of joint angle in isometric training. *European Journal of Applied Physiology and Occupational Physiology*, *58*(7), 744–748. https://doi.org/10.1007/BF00637386

Kotrlik, J. W., & Williams, H. A. (2003). The Incorporation of Effect Size. *Information Technology, Learning, and Performance Journal*, *21*(1), 1–7.

Linthorne, N. P. (2001). Analysis of standing vertical jumps using a force platform. *American Journal of Physiology*, *69*(11), 1198–1204. https://doi.org/10.1119/1.1397460

Loturco, I., Iacono, A. D., Nakamura, F. Y., Freitas, T. T., & Boullosa, D. (2022). The Optimum Power Load: A Simple and Powerful Tool for Testing and Training. *International Journal of Sports Physiology and Performance*, *17*(2), 151–159. https://doi.org/10.1123/ijspp.2021-0288

Mandic, R., Jakovljevic, S., & Jaric, S. (2015). Effects of countermovement depth on kinematic and kinetic patterns of maximum vertical jumps. *J Electromyogr Kinesiol*, *25*(2), 265–272. https://doi.org/10.1002/cncr.27633.Percutaneous

Maroto-Izquierdo, S., Bautista, I. J., & Rivera, F. M. (2020). Post-activation performance enhancement (PAPE) after a single bout of high-intensity flywheel resistance training. *Biol Sport*, *37*(4), 343–350. https://doi.org/10.5114/biolsport.2020.96318

McErlain Naylor, S. A., Beato, M., Mcerlain-naylor, S. A., & Beato, M. (2021). Post flywheel squat potentiation of vertical and horizontal ground reaction force parameters during jumps and changes of direction. *Sports*, *9*(5), 1–9. https://doi.org/10.3390/sports9010005

Morin, J. B., Samozino, P., Bonnefoy, R., Edouard, P., & Belli, A. (2010). Direct measurement of power during one single sprint on treadmill. *Journal of Biomechanics*, *43*(10), 1970–1975. https://doi.org/10.1016/j.jbiomech.2010.03.012

Munger, C. N., Archer, D. C., Leyva, W. D., Wong, M. A., Coburn, J. W., Costa, P. B., & Brown, L. E. (2017). Acute Effects of Eccentric Overload on Concentric Front Squat Performance. *Journal of Strength and Conditioning Research*, *31*(5), 1192–1197.

Muñoz-López, A., Flor, P., Sañudo, B., Pecci, J., Carmona, J., & Pozzo, M. (2021). The Maximum Flywheel Load: A Novel Index to Monitor Loading Intensity of Flywheel Devices. *Sensors*, *21*, 8124. https://doi.org/doi.org/10.3390/s21238124

Pandy, M. G., & Zajac, F. E. (1991). Optimal muscular coordination strategies for jumping. *Journal of Biomechanics*, *24*(1), 1–10. https://doi.org/10.1016/0021-9290(91)90321-D

Pazin, N., Berjan, B., Nedeljkovic, A., Markovic, G., & Jaric, S. (2013). Power output in vertical jumps: Does optimum loading depend on activity profiles? *European Journal of Applied Physiology*, *113*(3), 577–589. https://doi.org/10.1007/s00421-012-2464-z

Peterson, C. R. (2009). Acute neural adaptations to resistance training performed with low and high rates of muscle activation. *Dissertation Abstracts International: Section B: The Sciences and Engineering*, *70*(5-B), 2746. http://gateway.proquest.com/openurl?url_ver=Z39.88-2004&rft_val_fmt=info:ofi/fmt:kev:mtx:dissertation&res_dat=xri:pqdiss&rft_dat=xri:pqdiss:3356271%5Cnhttp://ovidsp.ovid.com/ovidweb.cgi?T=JS&PAGE=reference&D=psyc6&NEWS=N&AN=2009-99220-001

Rassier, D. E., & MacIntosh, B. R. (2000). Coexistence of potentiation and fatigue in skeletal muscle. *Brazilian Journal of Medical and Biological Research*, *33*(5), 499–508. https://doi.org/10.1590/S0100-879X2000000500003

Sabido, R., Hernández-davó, J. L., Capdepon, L., & Tous-fajardo, J. (2020). How Are Mechanical, Physiological, and Perceptual Variables Affected by the Rest Interval Between Sets During a Flywheel Resistance Session? *Frontiers in Physiology*, *11*(663), 1–8. https://doi.org/10.3389/fphys.2020.00663

Sale, D. G. (2002). Postactivation potentiation: role in human performance. *Exercise and Sport Sciences Reviews*, *30*(3), 138–143. https://doi.org/10.1136/bjsm.2004.003392

Samozino, P., Rabita, G., Dorel, S., Slawinski, J., Peyrot, N., Saez de Villarreal, E., & Morin, J. B. (2016). A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. *Scandinavian Journal of Medicine and Science in Sports*, *26*(6), 648–658. https://doi.org/10.1111/sms.12490

Sañudo, B., de Hoyo, M., Haff, G. G., & Muñoz-López, A. (2020). Article influence of strength level on the acute post-activation performance enhancement following flywheel and free weight resistance training. *Sensors (Switzerland)*, *20*(24), 1–11. https://doi.org/10.3390/s20247156

Šarabon, N., Rosker, J., Fruhmann, H., Burggraf, S., Loefler, S., & Kern, H. (2013). Reliability of maximal voluntary contraction related parameters measured by a novel portable isometric knee dynamometer. *Physikalische Medizin Rehabilitationsmedizin Kurortmedizin, 23*(1), 22–27. https://doi.org/10.1055/s-0032-1331190

Seitz, L. B., de Villarreal, E. S., & Haff, G. G. (2014). The temporal profile of postactivation potentiation is related to strength level. *Journal of Strength and Conditioning Research, 28*(3), 706–715. https://doi.org/https://doi.org/10.1519/JSC.0b013e3182a73ea3

Seitz, L. B., & Haff, G. G. (2016). Factors Modulating Post-Activation Potentiation of Jump, Sprint, Throw, and Upper-Body Ballistic Performances: A Systematic Review with Meta-Analysis. *Sports Medicine, 46*(2), 231–240. https://doi.org/10.1007/s40279-015-0415-7

Spudić, D., Cvitkovič, R., & Šarabon, N. (2021). Assessment and Evaluation of Force – Velocity Variables in Flywheel Squats: Validity and Reliability of Force Plates, A Linear Encoder Sensor, and A Rotary Encoder Sensor. *Appl. Sci.*, *11*(22), 10541.

Spudić, D., Smajla, D., Burnard, M. D., & Šarabon, N. (2021). Muscle Activation Sequence in Flywheel Squats. *Int. J. Environ. Res. Public Health, 18*(6), 3168. https://doi.org/doi.org/10.3390/ijerph18063168

Spudić, D., Smajla, D., & Šarabon, N. (2020). Validity and reliability of force–velocity outcome parameters in flywheel squats. *Journal of Biomechanics*, *107*, 109824. https://doi.org/https://doi.org/10.1016/j.jbiomech.2020.109824

Strojnik, V., & Komi, P. V. (1998). Neuromuscular fatigue after maximal stretch-shortening cycle exercise. *Journal of Applied Physiology, 84*(1), 344–350. https://doi.org/10.1152/jappl.1998.84.1.344

Suzovic, D., Markovic, G., Pasic, M., & Jaric, S. (2013). Optimum load in various vertical jumps support the maximum dynamic output hypothesis. *International Journal of Sports Medicine*, *34*(11), 1007–1014. https://doi.org/10.1055/s-0033-1337942

Timon, R., Allemano, S., Camacho-Cardenosa, M., Camacho-Cardenosa, A., Martinez-Guardado, I., & Olcina, G. (2019). Post-Activation Potentiation on Squat Jump Following Two Different Protocols: Traditional vs. Inertial Flywheel. *Journal of Human Kinetics*, *69*(September), 239–247. https://doi.org/10.2478/hukin

van den Tillaar, R., Andersen, V., & Saeterbakken, A. H. (2019). Comparison of muscle activation and kinematics during free-weight back squats with different loads. *PLoS ONE*, *14*(5), 1–13. https://doi.org/10.1371/journal.pone.0217044

Vargas-Molina, S., Salgado-Razirez, U., Chulvi-Medrano, I., Carbone, L., Maroto-Izquierdo, S., & Benittez-Porres, J. (2021). Comparison of post-activation performance enhancement (PAPE) after isometric and isotonic exercise on vertical jump performance. *PLoS ONE*, *16*(12), e0260866. https://doi.org/10.1371/journal.pone.0260866

Xenofondos, A., Patikas, D., Koceja, D. M., Behdad, T., Bassa, E., Kellis, E., & Kotzamanidis, C. (2015). Post-activation potentiation: The neural effects of post-activation depression. *Muscle and Nerve*, *52*(2), 252–259. https://doi.org/10.1002/mus.24533

Zacca, R., de Jesus, K., Cuenca-Fernández, F., de Jesus, K., Mourão, L., Vilas-Boas, J. P., Arellano, R., Fernandes, R. J., & López-Contreras, G. (2018). Eccentric flywheel post-activation potentiation influences swimming start performance kinetics. *Journal of Sports Sciences*, *37*(4), 443–451. https://doi.org/10.1080/02640414.2018.1505183