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Post flywheel squat vs. flywheel deadlift potentiation of lower limb isokinetic peak torques in male athletes

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ABSTRACT

The present study investigated the post-activation performance enhancement (PAPE) of isokinetic quadriceps and hamstrings torque after flywheel (FW)-squat vs. FW-deadlift in comparison to a control condition. Fifteen male athletes were enrolled in this randomised, crossover study. Each protocol consisted of 3 sets of 6 repetitions, with an inertial load of 0.029 kg·m^2. Isokinetic quadriceps (knee extension) and hamstrings (knee flexion) concentric peak torque (60º/s) and hamstring eccentric peak torque (-60º/s) were measured 5 min after experimental or control conditions. A significant condition (PAPE) effect was reported (f = 4.067, p = 0.008) for isokinetic hamstrings eccentric peak torque following FW-squat and FW-deadlift, but no significant differences were found for quadriceps and hamstrings concentric peak torques. The significant difference averaged 14 Nm between FW-squat vs. control (95% CI: 2, 28; d = 0.75, *moderate*; p = 0.033), and 13 Nm between FW-deadlift vs. control (95% CI: 1, 25; d = 0.68, *moderate*; p = 0.038). This study reported that both FW-squat and FW-deadlift exercises are equivalently capable of generating PAPE of isokinetic hamstrings eccentric torque. Practitioners may use these findings to inform strength and power development during complex training sessions consisting of flywheel-based exercises prior to a sport-specific task.

Keywords: iso-inertial; eccentric overload; post-activation potentiation; hamstrings; PAPE

INTRODUCTION

Post activation performance enhancement (PAPE) is a physiological phenomenon associated with an acute improvement in neuromuscular and sport-specific capabilities (Blazevich & Babault, 2019; Boullosa, Del Rosso, Behm, & Foster, 2018). The exact physiological mechanisms of this phenomenon are not yet clear and differing theories exist (Blazevich & Babault, 2019; Boullosa et al., 2018). Very recently, Boullosa et al. have reported further insights into the taxonomy of post-activation and its application in sport (Boullosa et al., 2020). The most frequently accredited mechanism relates to myosin regulatory light chain phosphorylation and an increased sensitivity to calcium (Ca^{2+}) (Tillin & Bishop, 2009). Such changes increase the number of cross-bridges formed in myofilaments, increasing the rate and magnitude of force generated (Beato, McErlain-Naylor, Halperin, & Dello Iacono, 2020; Bishop, 2003). However, it is not clear to what extent the time frame of these responses relate to the time frame of observed PAPE (Blazevich & Babault, 2019). PAPE-based warm up protocols have been shown to acutely enhance sporting performance in a variety of populations (Beato et al., 2020). The performance enhancement is generally reported 3 min after the pre-load activity and persists for up to 9-12 minutes after the initial conditioning activity (Beato, Stiff, & Coratella, 2019; Robbins, 2005; Tillin & Bishop, 2009).

High-intensity traditional resistance exercises have achieved PAPE - proving attractive for a variety of physical preparation objectives (Dello Iacono & Seitz, 2018;

Doma, Leicht, Boullosa, & Woods, 2020; Seitz & Haff, 2016). However, PAPE activities using traditional barbell methodologies may not always be practical for field-based sports. Application of these traditional methods may be limited by equipment access, training locations, or the use of high-intensity load (*e.g.*, 90% repetition maximum) prior to training (Bauer et al., 2019; Doma et al., 2020). Recent research has supported the use of flywheel-based exercises as alternative PAPE protocols (Beato et al., 2020; de Keijzer, McErlain-Naylor, Dello Iacono, & Beato, 2020). Currently, it appears that both methodologies – flywheel and traditional resistance exercises – can similarly enhance acute strength and jump performance (Beato, Bigby, et al., 2019; Seitz & Haff, 2016). However, flywheel-based protocols present some technological advantages. For instance, an overload is generally obtained during the eccentric phase due to the active deceleration of the disc angular momentum generated during the previous concentric phase (Beato, Bigby, et al., 2019; Carroll et al., 2019). The ability to achieve high intensities in the eccentric phase is a clear advantage of flywheel technology in comparison to traditional resistance exercise (Beato, Bigby, et al., 2019; Maroto-Izquierdo et al., 2019; Norrbrand, Pozzo, & Tesch, 2010). However, the current body of research investigating flywheel-based PAPE protocols is very limited and further studies are needed (Beato et al., 2020; de Keijzer et al., 2020). Current recommendations have focused on protocols involving flywheel squats (FW-squat), suggesting to utilise inertial loads ranging from 0.029 - 0.110 $kg{\cdot}m^2$ for 2 - 3 sets to acutely enhance jumping performance (Beato et al., 2020; de Keijzer et al., 2020). Isokinetic testing may shed further light on changes in lower-limb joint torques and offer additional information regarding the acute response of specific muscles groups, such as the quadriceps and hamstrings, in both concentric and eccentric modality (Beato, Stiff, et al., 2019; Morin et al., 2015). Considering the importance of quadriceps and hamstring strength in many sporting activities, it may be beneficial for practitioners to understand how specific conditioning activities can help acutely enhance these capabilities (Beato, Stiff, et al., 2019; Coratella, Beato, Cè, Scurati, & Milanese, 2019). Furthermore, the necessary time window (*e.g.*, 3 - 9 minutes) for recovery post-conditioning activity has also been highlighted as important for ensuring a successful PAPE response with FW-squat-based protocols (Beato, Stiff, et al., 2019). A lot remains unknown about other modulating factors, including the effects of different conditioning exercises such as the flywheel deadlift (FW-deadlift).

Barbell deadlifts and squats differ biomechanically, with the deadlift demonstrating a sequential rather than synergistic movement (Hales, Johnson, & Johnson, 2009). Greater hamstrings and lesser quadriceps activity has been reported during traditional deadlift compared to squat exercise (Ebben et al., 2009). This may influence the hamstrings vs. quadriceps-specific PAPE responses to such exercises (Scott, Ditroilo, & Marshall, 2017). Previous research reported that near-maximal concentric-only deadlifts acutely enhanced jumping performance within rugby league players (Scott et al., 2017). Contrary to this, Gahreman et al. (2020) enrolled 15 resistance-trained youth wrestlers, who enhanced repeated jump performance after a back squat protocol but not after a traditional deadlift protocol. Similarly, Till and Cooke (2009) reported that a 5 repetition maximum traditional deadlift protocol did not acutely enhance sprint or jump performance. These studies reported contrasting evidence regarding the PAPE effect of traditional resistance deadlift exercises. However, no research evaluating the PAPE effect of the deadlift exercise has utilised flywheel devices to overload the eccentric phase of the exercise, nor have effects on the hamstrings vs. quadriceps torque ratio (H:Q) been assessed. The conventional ratio of concentric hamstrings to concentric quadriceps peak torques (Hconc:Qconc) and functional ratio of eccentric hamstrings to concentric quadriceps peak torques

(Hecc:Qconc) offer insights about the strength balance, which have relevance for sport performance and injuries (Beato et al., 2019; Coratella et al., 2015). For example, a greater Hecc:Qconc ratio may indicate a greater capacity of the hamstring muscles to provide dynamic knee joint stability (Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998) during activities such as the final swing phase of sprinting where eccentric hamstring strength must be sufficient to decelerate the knee extension generated by the quadriceps muscle (Yeung, Suen, & Yeung, 2009). An overload in the eccentric phase of the conditioning exercise may be an important strategy for those individuals who have a deficit in eccentric strength or possible muscle imbalances. Knowledge about the PAPE effects on these parameters could offer further insights into the utility of flywheel-based PAPE protocols to prepare the lower limbs for the demands of sport such as sprinting (Beato & Dello Iacono, 2020), accelerations (Morin et al., 2015), and changes of direction (Beato, De Keijzer, et al., 2019).

The growth in application of flywheel resistance training due to its unique characteristics (*e.g.* greater eccentric load than traditional resistance exercises) has necessitated an investigation into acute PAPE responses following such novel protocols. The available early studies into flywheel PAPE protocols have focused primarily on squat protocols, showing positive results. However, no research has investigated these effects following flywheel deadlifts and so a comparison is useful and informative. Therefore, the aims of this study were: firstly, to investigate PAPE on lower limb joint torques after FW-squat and FW-deadlift compared to a control condition; and secondly, to compare the effectiveness of these two flywheel-based protocols at stimulating PAPE effects on lower limb joint torques. It was hypothesised that both protocols would generate a PAPE effect on concentric and eccentric isokinetic hamstrings and quadriceps torques, but no *a priori* hypothesis was made about the difference in effectiveness between FW-squat and FW-deadlift protocols.

METHODS

Participants

An *a priori* power analysis using G*power (Düsseldorf, Germany) indicated that a sample of 15 participants was required to detect a *moderate* effect (f = 0.35) with 80% power and an alpha of 0.05. Fifteen male amateur university athletes (mean ± SD: age 22 ± 3 years; body mass 79.4 ± 9.5 kg; height 1.84 ± 0.06 m) participated in this study. The participants regularly engaged in either soccer training or resistance training. Inclusion criteria were: the absence of any injury or illness; regular participation in training activities (a minimum of 2 training sessions per week); and at least 6 months of resistance training experience. All participants were informed about the potential risks and benefits associated with the procedures of this study before giving written consent. The Ethics Committee of the School of Health and Sports Sciences at the University of Suffolk (UK) approved this study (SREC013/RT). All procedures were conducted according to the Declaration of Helsinki for studies involving human participants.

Experimental design

The acute effects induced by FW-squat and FW-deadlift (experimental conditions) on isokinetic hamstrings and quadriceps peak torques compared to a control condition were investigated in the present randomised, crossover study. Each participant attended the laboratory on 4 separate occasions (Figure 1). All sessions were performed two to four days apart and at least 48 hours after the last competition or training session to avoid the effects of accumulated fatigue on performance.

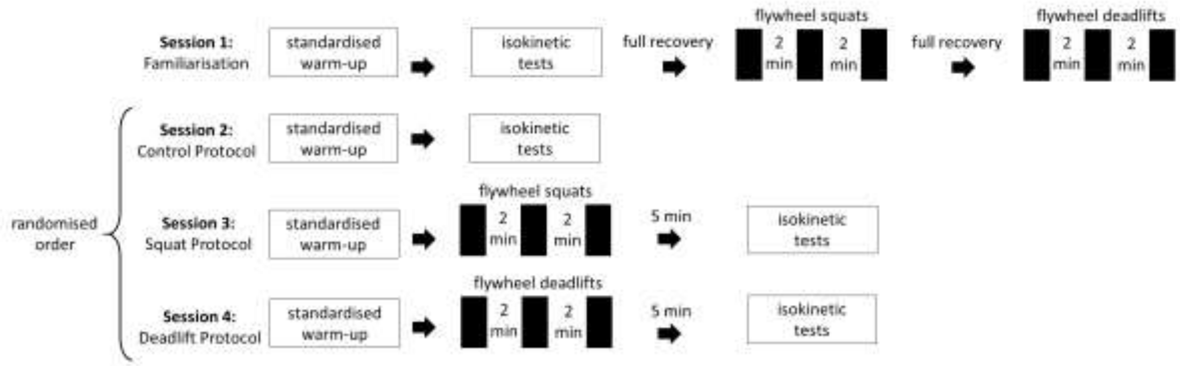

Figure 1 - Experimental procedure.

During the first (familiarisation) visit, participants' body mass and height were recorded through a stadiometer (Seca 286dp; Seca, Hamburg, Germany). The participants were familiarised with the same flywheel exercise and isokinetic testing protocols used during the experimental protocol. Full self-selected recovery was provided between familiarisation of isokinetic testing, flywheel squats and flywheel deadlifts. Isokinetic tests were familiarised first to enable comparison with the control condition for inter-session reliability analysis. Within the remaining visits, the participants performed one of the 3 test protocols in a randomised order after a standardised warm-up: FW-squat; FW-deadlift; or control (no exercise between the standardised warm-up and standardised isokinetic testing) condition. The sessions were randomised to reduce any learning effect on the isokinetic tests. The use of a control (no pre-load exercise) condition enabled investigation of the PAPE effect without the increased likelihood of fatigue that would be associated with performing two sets of isokinetic tests and maximal pre-load exercise within a single session. Between the protocol and subsequent isokinetic test, 5 min of passive standing recovery were required to limit transient effects of fatigue on the following isokinetic task. PAPE can be obtained after 3 - 9 min of recovery (Beato, Stiff, et al., 2019), and so 5 min represents a compromise between any remaining fatigue (*e.g.* at 3 min) and possible reduced PAPE magnitude (*e.g.* at 9 min).

Standardised warm-up

During each session, participants performed a standardised warm-up of 10 min cycling at a constant power (1 W/kg body mass) on an ergometer (Sport Excalibur lode, Groningen, Netherlands) followed by dynamic mobilisation exercises (bodyweight squats, lunges, and deadlifts). Each participant performed all testing sessions at the same time of day to reduce the effect of circadian rhythms on performance. Participants were instructed to avoid stimulants or depressant substances 24 hours prior to each testing session and to rehydrate ad libitum.

Isokinetic tests

An isokinetic dynamometer (Bide Medical Systems, Shirley, NY, USA) was used to measure quadriceps and hamstrings peak torque. The device was calibrated according to the manufacturer's guidelines and the centre of rotation was aligned with the tested knee (dominant leg: the preferred limb used to kick a ball). Participants were seated on the dynamometer chair, with a hip angle of 95 degrees. The quadriceps (knee extension) peak torque was measured in the concentric phase, and the hamstrings (knee flexion) peak torque was measured in concentric and eccentric phases (all 60º/s). Each testing modality consisted of 5 consecutive maximal repetitions. Peak torques (from single greatest repetition) were extracted for further analysis. Strong standardised verbal encouragements were provided to the participants to maximise performance. The conventional ratio (Hconc:Qconc) and functional ratio (Hecc:Qconc) were also calculated.

Flywheel half squat and deadlift

FW-squat and FW-deadlift were performed using a standardised ergometer (D11 Full, Desmotec, Biella, Italy). The protocols each consisted of 3 sets of 6 repetitions (2 initial submaximal repetitions were performed to attain the initial momentum) at maximal concentric velocity, interspersed by 2 min of passive recovery (de Keijzer et al., 2020). The following combined load was used for each participant during both FW-squat and FW-deadlift exercises: 1 large disc (diameter = 0.285 m; mass = 1.9 kg; moment of inertia = 0.02 kg·m^2) and 1 medium disk (diameter = 0.240 m; mass = 1.1 kg; moment of inertia = 0.008 kg·m^2). The moment of inertia of the ergometer was estimated as 0.0011 kg·m^2, therefore the total moment of inertia was 0.029 kg·m^2. This inertial load was selected based on power outputs and inertial loads previously used to enhance performance following flywheel squat exercises (Beato, De Keijzer, et al., 2019). Power outputs for both concentric and eccentric phases were collected for each repetition using an integrated rotatory position transducer. The participants were instructed, in both FW-squat and FW-deadlift exercises, to perform the concentric phase with maximal velocity and to achieve approximately 90° of knee flexion during the eccentric phase. Each movement was evaluated qualitatively by an investigator, offering kinematic feedback to the athletes as well as strong standardised encouragements to maximally perform each repetition.

Statistical Analyses

All statistical analyses were performed using JASP software (version 0.9.2; JASP, Amsterdam, The Netherlands). The Shapiro-Wilk test was used to determine normality of distributions. Data were presented as mean ± standard deviation (SD). Inter-session reliability (two-way mixed model) was assessed via comparison to the control condition using an intraclass correlation coefficient (ICC) and interpreted as follows: *excellent* ≥ 0.9; 0.9 > *good* ≥ 0.8; 0.8 > *acceptable* ≥ 0.7; 0.7 > *questionable* ≥ 0.6; 0.6 > *poor* ≥ 0.5; *unacceptable* < 0.5 (Atkinson & Nevill, 1998). Smallest worthwhile change (SWC) was calculated as 0.2 × the between-participant SD. One-way repeated measures analysis of variance (ANOVA) reporting *f* values was used to detect possible between-condition effects. Post-hoc analysis was performed using Holm's corrections (applied to the alpha value). Delta difference with 95% confidence intervals (CI) were also reported (Harrison et al., 2020). Significance was set at $p < 0.05$ and reported to indicate the strength of the evidence. The effect size based on the Cohen's *d* principle was calculated and interpreted as follows: *trivial* < 0.2; 0.2 ≤ *small* < 0.6; 0.6 ≤ *moderate* < 1.2; 1.2 ≤ *large* < 2.0; *very large* > 2.0 (Hopkins, Marshall, Batterham, & Hanin, 2009).

RESULTS

The following test-retest reliability (ICC) and SWC were reported: isokinetic quadriceps concentric peak torque ICC = 0.88, *good,* SWC = 8 Nm; hamstring concentric peak torque ICC = 0.89, *good,* SWC = 4 Nm; and hamstring eccentric peak torque ICC = 0.93, *excellent,* SWC = 7 Nm; FW-Squat concentric power output ICC = 0.98, *excellent,* SWC = 58W; FW-squat eccentric power output ICC = 0.97, *excellent,* SWC = 59 W; FW-deadlift concentric power output ICC = 0.96, *excellent,* SWC = 62 W; and FW-deadlift eccentric power output ICC = 0.96, *excellent,* SWC = 58 W.

FW-squat concentric and eccentric power outputs were 1132 ± 289 W and 1040 ± 292 W, respectively. FW-deadlift concentric and eccentric power outputs were 1026 ± 311 W and 992 ± 288 W, respectively. A significant difference of Δ 106 W (95% CI 34, 178; p = 0.007, d = 0.81, *moderate*) in concentric power output was reported between FW-squat and FW-deadlift. No significant difference (Δ 48 W; 95% CI -31, 127; p = 0.216, d = 0.33, *small*) in eccentric power output was reported between FW-squat and FW-deadlift.

No significant condition (PAPE) effect was reported (f = 1.538, p = 0.233) for isokinetic quadriceps concentric peak torque following FW-squat and FW-deadlift (Figure 2). Standardised differences (effect size) between FW-squat vs. control (p = 0.528, d = 0.31, *small*) and FW-deadlift vs. control (p = 0.518, d = 0.37, *small*) were reported. Comparison between FW-squat vs. FW-deadlift did not report any significant difference (p = 0.552, d = 0.157, *trivial*).

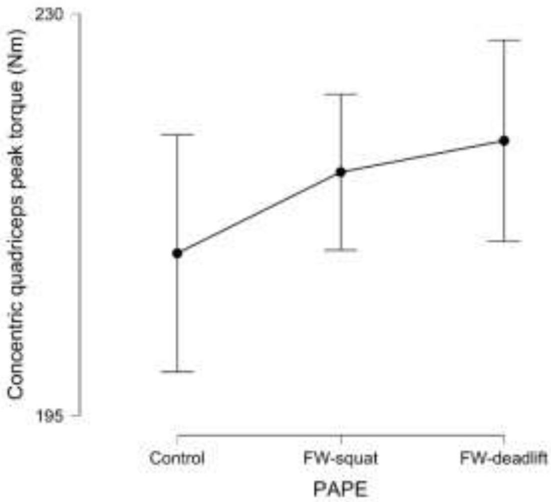

Figure 2 - Quadriceps concentric peak torque following flywheel squat (FW-squat) and flywheel deadlift (FW-deadlift) post-activation performance enhancement (PAPE) conditions compared to control condition. Error bars represent 95% confidence intervals. *: p < 0.05 compared with Control.

No significant condition (PAPE) effect was reported (f = 2.456, p = 0.104) for isokinetic hamstrings concentric peak torque following FW-squat and FW-deadlift (Figure 3). Standardised differences (effect size) between FW-squat vs. control (p = 0.101, d = 0.61, *moderate*) and FW-deadlift vs. control (p = 0.585, d = 0.27, *small*) were reported. Comparison between FW-squat vs. FW-deadlift did not report any significant difference (p = 0.587, d = 0.282, *small*).

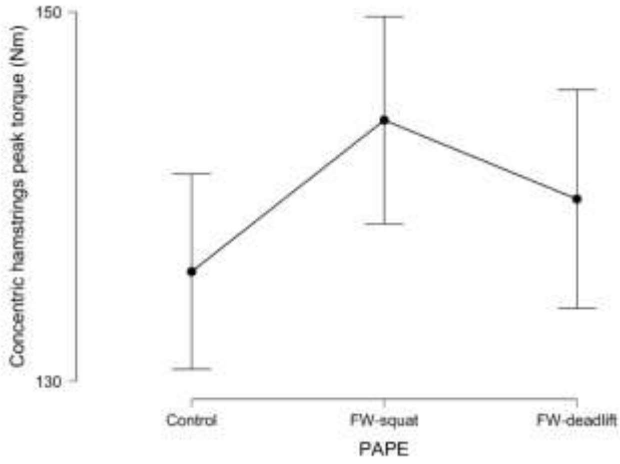

Figure 3 - Hamstrings concentric peak torque following flywheel squat (FW-squat) and flywheel deadlift (FW-deadlift) post-activation performance enhancement (PAPE) conditions compared to control condition. Error bars represent 95% confidence intervals. *: p < 0.05 compared with Control.

A significant condition (PAPE) effect was reported (f = 4.067, p = 0.008) on isokinetic hamstrings eccentric peak torque following FW-squat and FW-deadlift (Figure 4). The significant difference (Δ) was 14 Nm between FW-squat vs. control was (95% CI: 2, 28; d = 0.75, *moderate*; p = 0.033), and 13 Nm between FW-deadlift vs. control (95% CI: 1, 25; d = 0.68, *moderate*; p = 0.038). Comparison between FW-squat vs. FW-deadlift did not reported any significant difference (p = 0.688, d = 0.106, *trivial*).

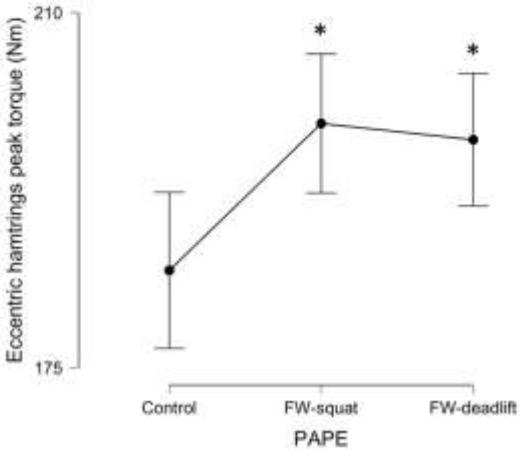

Figure 4 - Hamstrings eccentric peak torque following flywheel squat (FW-squat) and flywheel deadlift (FW-deadlift) post-activation performance enhancement (PAPE) conditions compared to control condition. Error bars represent 95% confidence intervals. *: p < 0.05 compared with Control.

No significant condition (PAPE) effect was reported (f = 0.639, p = 0.535) for isokinetic conventional Hconc:Qconc ratio following FW-squat and FW-deadlift (Figure 5). Standardised differences (effect size) between FW-squat vs. control (p = 0.101, d = 0.18, trivial) and FW-deadlift vs. control (p = 0.587, d = 0.08, trivial) were reported. Comparison between FW-Squat vs. FW-Deadlift did not reported any significant difference (p = 0.536, d = 0.36, small).

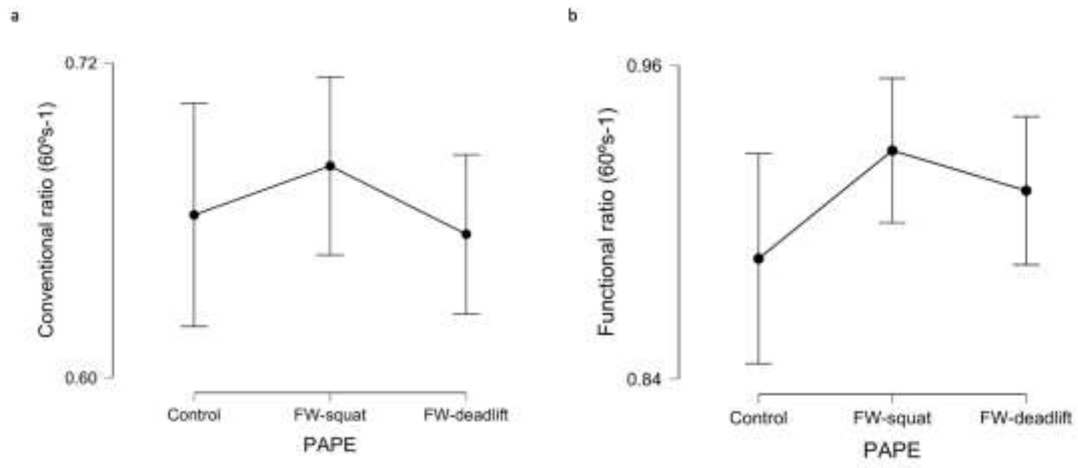

Figure 5 - Conventional (a) and functional (b) hamstrings:quadriceps peak torque ratio following flywheel squat (FW-squat) and flywheel deadlift (FW-deadlift) post-activation performance enhancement (PAPE) conditions compared to control condition. Error bars represent 95% confidence intervals. *: $p < 0.05$ compared with Control.

No significant condition (PAPE) effect was reported ($f = 1.895$, $p = 0.169$) for isokinetic functional Hecc:Qconc ratio following FW-squat and FW-deadlift (Figure 5). Standardised differences (effect size) between FW-squat vs. control ($p = 0.309$, $d = 0.44$, *small*) and FW-deadlift vs. control ($p = 0.602$, $d = 0.27$, *small*) were reported. Comparison between FW-squat vs. FW-deadlift did not report any significant difference ($p = 0.605$, $d = 0.25$, *small*).

DISCUSSION AND IMPLICATIONS

The present study investigated the PAPE of hamstrings and quadriceps isokinetic torque after FW-squat and FW-deadlift compared to a control condition. For both protocols, the capacity to generate PAPE has been confirmed in isokinetic hamstring eccentric peak torque only. Additionally, conventional Hconc:Qconc ratio reported *trivial* changes in both FW-squat and FW-deadlift, whereas functional Hecc:Qconc ratio reported *small* positive (however non-significant) increments. The second aim was to compare PAPE responses between FW-squat and FW-deadlift protocols, and this study found them equivalently capable of enhancing hamstring eccentric performance. Practitioners may use the present findings to optimise strength and power development during complex training sessions using flywheel-based PAPE protocols.

The rationale for using a flywheel device to obtain a PAPE response was associated with the eccentric overload that can be generated, and which is not achievable using traditional resistance exercises (Beato, Bigby, et al., 2019; Norrbrand et al., 2010). During the eccentric phase of the flywheel exercise, the athlete actively decelerate the disc angular momentum generated during the concentric phase (Beato, Bigby, et al., 2019; Beato et al., 2020). This results in greater force and power generation which can contribute to the acute enhancement of the subsequent performance (Beato et al., 2020; Norrbrand et al., 2010). The physiological and mechanical advantages of the eccentric contraction (and overload) have been largely reported in the literature (Maroto-Izquierdo et al., 2017), presenting characteristics such as greater forces, lower energy requirement, selective recruitment of higher-order motor units, preferential recruitment of predominantly fast-twitch synergists, and a greater cortical excitability but a lower motor unit discharge compared to concentric contraction (Beato et al., 2020; Douglas, Pearson, Ross, & McGuigan, 2017).

In the current study, both FW-squat and FW-deadlift PAPE responses reported a *moderate* effect on isokinetic hamstring eccentric, but not quadriceps concentric or hamstring concentric, peak torque. It should also be noted that the mean difference in hamstring eccentric peak torques in both conditions (14 Nm for FW-squat and 13 Nm for FW-deadlift) are greater than the SWC (7 Nm) for these parameters, which represent meaningful changes in performance. The present findings are supported by a previous *small* significant change in hamstring eccentric and *trivial* change in concentric quadriceps peak torques following FW-squat exercise, but are partially in contrast with the previous significant *small* change in hamstring concentric peak torques (Beato, Stiff, et al., 2019). These results in combination imply that the hamstrings (particularly during eccentric contractions) may be more susceptible to flywheel-PAPE protocols than the quadriceps. This could be related to different recruitment strategies during the FW-squat eccentric hamstring activity such as preferential recruitment of fast-twitch and higher-order motor units or the higher percentage of fast-twitch fibres of the hamstring compared to the quadriceps (Coratella, Bellin, Beato, & Schena, 2015; Douglas et al., 2017). These factors may make the hamstrings more responsive to particularly eccentric PAPE protocols. However, an exhaustive explanation of these differences cannot be reported. The limited PAPE effect on isokinetic quadriceps peak torque may relate to differing fibre composition between the muscle groups and to kinematic differences between the pre-load exercise and the following test. Previous research reported that a FW-squat protocol can stimulate PAPE in rapid closed-kinetic chains movements such as long and vertical jumps (Beato, De Keijzer, et al., 2019; Beato et al., 2020), whereas transfer to open-kinetic chain exercises (such as isokinetic tests) may be more limited.

This is the first study comparing PAPE between FW-squat and FW-deadlift protocols, observing that the FW-squat protocol enhanced quadriceps and hamstrings peak torque to a similar extent to FW-deadlift. Significantly and moderately greater concentric power was achieved during the FW-squat than the FW-deadlift, while no difference was observed during the eccentric phase. These findings underline that similar eccentric power production between exercises may explain the similar PAPE responses reported in this study. It is not clear why the difference in concentric power outputs did not favour the generation of a larger PAPE following the FW-squat protocol. Based on the current results, it might be argued that the difference in concentric power output is not a discriminant to obtain acute performance enchantments using flywheel exercises (Beato, Bigby, et al., 2019). Moreover, based on previous research, PAPE response may depend on the biomechanical or muscle activation pattern similarities between pre-load and subsequent tasks. Deadlift and squat exercises differ biomechanically from one another (Hales et al., 2009), and particularly greater hamstrings vs. quadriceps activity was reported during traditional deadlift compared to the squat (Ebben et al., 2009). This may influence the lower limb musculature PAPE responses (Scott et al., 2017). Instead, in this study there were no significant differences in PAPE response between the two flywheel protocols. These findings are supported by another recent study which found no differences in PAPE response on change of direction tasks between flywheel exercises with fundamental biomechanical differences such as flywheel leg extension, squat, and cross-cutting step exercises (Beato, Madruga-Parera, Piqueras-Sanchiz, Moreno-Pérez, & Romero-Rodriguez, 2019). These findings suggest that PAPE response may not be strongly associated with the biomechanical similarity between pre-load and subsequent exercises.

The conventional Hconc:Qconc ratio reported only *trivial* changes following both FW-squat and FW-deadlift, whereas the functional Hecc:Qconc ratio reported *small* positive (however non-significant) increments. Previous research similarly reported a *trivial* variation in conventional Hconc:Qconc ratio following a FW-squat protocol but a significant *small* enhancement in functional Hecc:Qconc ratio (Beato, Stiff, et al., 2019). The cumulative evidence of these two studies suggest that the greater effect on the functional compared with conventional ratio is likely due to the acute enhancement of eccentric hamstring peak torque. An explanation for the apparent greater sensitivity of the hamstring than the quadriceps to flywheel-based PAPE protocols may be related to greater muscle activity in the hamstring in comparison to the quadriceps during the eccentric phase of a squat (Yoo, 2016). This greater hamstring activation during the eccentric phase of the squat or deadlift can be accentuated during flywheel exercise (Beato et al., 2020; Maroto-Izquierdo et al., 2019). This greater sensitivity of the hamstring to flywheel-based PAPE protocols may be beneficial for transfer to sporting performance, making it an attractive method to prepare the hamstrings for the demands of sport – including sprinting accelerations (Morin et al., 2015), changes of direction (Beato, De Keijzer, et al., 2019) and possible injury risk reduction (Coratella et al., 2015). This is particularly true in sports where lack of hamstrings eccentric force to decelerate the knee extension may be a predisposing factor to hamstring strains (*e.g.* on the final swing phase during sprinting). Although thresholds of 0.6 and 0.8 have been previously used for the conventional (Zvijac, Toriscelli, Merrick, & Kiebzak, 2013) and functional (Croisier, Ganteaume, Binet, Genty, & Ferret, 2008) ratios, respectively, any increase in eccentric hamstrings strength will likely be beneficial in this regard. Although eccentric quadriceps peak torque is not utilised in the calculation of either H:Q ratio, future investigation into the acute effect of flywheel squats and deadlifts on this parameter is of interest. This is particularly true given the possibility for eccentric overload during flywheel pre-load exercise and the present study's significant PAPE effect on eccentric hamstring peak torque.

The current study presents some limitations. First, it involved male amateur athletes only. Therefore, generalisation to other sport-specific populations such as professional athletes may be limited. Future studies may replicate the protocols reported in this study within different populations. Second, this study utilised a moment of inertia of 0.029 $kg{\cdot}m^2$, which may have been sub-optimal to generate optimal PAPE responses, even though this load was previously used with success to acutely enhance performance (Beato, De Keijzer, et al., 2019). Future studies using different inertial loads are necessary to provide more specific recommendations regarding PAPE effects of both FW-squat and FW-deadlift on isokinetic lower limb torque parameters.

CONCLUSION

Both FW-squat and FW-deadlift exercises can significantly enhance acute isokinetic hamstring eccentric performance in male athletes. *Small to moderate* but non-significant effects on concentric quadriceps and hamstring peak torques were also reported. This study did not report any significant difference between FW-squat and FW-deadlift exercises in PAPE on isokinetic lower limb parameters and as such these exercises should be considered equivalently capable for the specific purpose of generating PAPE. Practitioners may use these findings to inform strength and power development during complex training sessions consisting of flywheel-based exercises prior to a sport-specific task.

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