Concentric and eccentric inertia-velocity and inertia-power relationships in the flywheel squat

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Keywords: isoinertial, velocity-based training, eccentric overload, resistance exercise, speed

Word count: 4394 after revisions Abstract: 200

Submitted to: Journal of Sports Sciences R1 November 2020

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Acknowledgement

The authors wish to thank Luke Catchpole and Maria Esteves for their contributions to data collection.

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Abstract

The aim of this study was to evaluate the effects of varying flywheel inertia on velocity and power during flywheel squats. Fifteen healthy physically active males performed 6 maximal effort flywheel half-squats at each of 0.029, 0.061, 0.089, and 0.121 $kg \cdot m^2$, with velocity recorded via 3D motion capture and power recorded via inbuilt transducer. Peak concentric velocity ($\chi^2 = 37.9$; $p < 0.001$), peak eccentric velocity ($\chi^2 = 24.9$; $p < 0.001$), mean concentric velocity ($F(3) = 52.7$; $p < 0.001$), and mean eccentric velocity ($\chi^2 = 16.8$; $p < 0.001$) all tended to decrease with increases in flywheel inertia, whereas the ratio of peak eccentric to peak concentric power ($F(3) = 4.26$; $p = 0.010$) tended to increase. Flywheel inertia had no significant effect on peak concentric or eccentric power, or the ratio of eccentric to concentric peak or mean velocities. The best fit subject-specific inertia-velocity relationships were reported for peak concentric velocity (median linear $R^2 = 0.95$, median logarithmic $R^2 = 0.97$). The results suggest that velocity, rather than power, should be used to prescribe and monitor flywheel squat exercise intensities, and that individualized linear relationships between inertia and peak concentric velocity can be used for this purpose.

Introduction

Targeted adaptations to resistance training differ in the prioritisation of muscular strength, endurance, power, and velocity (Jiménez-Reyes, Samozino, Brughelli, & Morin, 2017; Suchomel, Nimphius, Bellon, & Stone, 2018). To target specific adaptations, practitioners typically prescribe intensities relative to an individual's maximal capacity (*e.g.* a percentage of one repetition maximum) (Shimano et al., 2006). Use of previous maximal ability fails to account for adaptations subsequent to the maximal testing (Weakley, Mann, et al., 2020) or variations in daily readiness due to muscular or peripheral fatigue (Sanchez-Medina & Gonzalez-Badillo, 2011). Individual differences in the number of repetitions that can be performed at a given percentage of one repetition maximum also exist (Richens & Cleather, 2014). Velocity-based training has gained popularity as an alternative method of prescribing resistance training intensities and volumes via target mean set velocities and / or velocity loss thresholds (Banyard, Tufano, Delgado, Thompson, & Nosaka, 2019) based on load-velocity profiles (Banyard, Nosaka, Vernon, & Haff, 2018). The theory and application of velocity-based gravitational resistance training have been discussed in detail (Weakley, Mann, et al., 2020), whereas the principle is yet to be applied to isoinertial flywheel resistance exercise (Beato & Dello Iacono, 2020; Beato, McErlain-Naylor, Halperin, & Dello Iacono, 2020).

In recent years, flywheel resistance exercise has become a popular method for stimulating both acute performance enhancements (Beato, McErlain-Naylor, et al., 2020) and chronic adaptations (Beato & Dello Iacono, 2020). The user rotationally accelerates the flywheel (resistance due to the flywheel moment of inertia) with maximal effort during the concentric phase of the movement, resulting in flywheel kinetic energy and inertial torque that imparts high linear resistance during the subsequent eccentric phase of the movement (Gonzalo-Skok et al., 2017). The most frequently cited advantage of flywheel resistance exercise is the potential for much greater intensity during the eccentric phase of the movement compared with traditional resistance exercise methodologies (Raya-González, Castillo, & Beato, 2020). Load-velocity relationships established for barbell back squats, for example, have focused on the concentric phase due to the demands of that particular exercise (Pérez-Castilla, García-Ramos, Padial, Morales-Artacho, & Feriche, 2020; Zink, Perry, Robertson, Roach, & Signorile, 2006). It is therefore necessary to investigate the effects of different inertias on velocity and power measures during not only the concentric phase of flywheel squats but also the eccentric phase. Acute and chronic responses to flywheel resistance training are of similar or greater magnitudes to concentric-dominant exercises (Beato, Bigby, et al., 2019; Madruga-Parera et al., 2020; Nuñez Sanchez & Sáez de Villarreal, 2017). However, training guidelines on the use of this technology remain limited (Beato & Dello Iacono, 2020), especially for velocity-based training. Whilst velocity has been proposed as an avenue of intensity prescription for flywheel squats (Carroll et al., 2019), knowledge of the inertia-velocity relationship in this exercise is needed to inform evidence-based recommendations.

Although some studies have investigated the effects of flywheel inertia on kinetic and kinematic parameters during the flywheel squat (Carroll et al., 2019; Sabido, Hernández-Davó, & Pereyra-Gerber, 2018; Spudić, Smajla, & Šarabon, 2020; Worcester, Baker, & Bollinger, 2020), they have typically neglected the eccentric phase of the movement. Whilst eccentric power and velocity may have lower importance in traditional resistance exercise compared with concentric parameters, the high intensity and load during the eccentric phase are major advantages of flywheel resistance exercise (Beato & Dello Iacono, 2020). Similar to the observed decreases in peak concentric back squat vertical velocity with increases in barbell mass (Pérez-Castilla et al., 2020; Weakley, Mann, et al., 2020; Zink et al., 2006), peak (Carroll et al., 2019) and mean (Carroll et al., 2019; Worcester et al., 2020) concentric vertical velocities tend to decrease with each progressive increase in flywheel inertia up to 0.100 kg·m^2. Although velocity-based prescription in traditional resistance training typically uses linear load-velocity relationships (Banyard, Nosaka, & Haff, 2017; Weakley, Mann, et al., 2020), linear relationships between flywheel inertia and peak ($R^2 = 0.60$) or mean ($R^2 = 0.66$) concentric vertical velocity have not achieved good fits at the group level (Carroll et al., 2019) and are yet to be explored at the level of individual subjects. We do not know the pattern of this relationship at inertias greater than 0.100 kg·m^2 (Carroll et al., 2019; Worcester et al., 2020), nor have the fit of non-linear relationships been investigated. It is possible that the relationship between flywheel inertia and concentric vertical velocity (Worcester et al., 2020) may resemble the non-linear force-velocity relationship typically observed in *in vivo* skeletal muscle fibres (Hill, 1938). Given the potential for eccentric overload, the eccentric inertia-velocity relationship during flywheel squats could facilitate training prescription but is yet to be investigated.

Peak power is often used to quantify flywheel squat intensity or compare to traditional resistance exercises, and is generally the most common load parameter used in the literature (Beato, Bigby, et al., 2019; Beato & Dello Iacono, 2020). Previous research reported an overall effect of decreasing mean concentric power with increases in flywheel inertias (Worcester et al., 2020), but with no significant differences between pairs of inertias. The effects of flywheel inertia on eccentric power were not reported, despite the importance of eccentric muscular contractions during flywheel resistance exercise. Only one study has investigated the effects of inertia on peak concentric or eccentric power during the flywheel squat (Sabido et al., 2018), reporting that peak concentric power decreased with each increase in inertia between 0.025, 0.050, 0.075, and 0.100 kg·m^2. Peak eccentric power decreased with each increase in flywheel inertia above 0.050 kg·m^2. Increases in the ratio of peak eccentric power to peak concentric power were also reported with increases in inertia up to 0.075 kg·m^2. However, the findings of this study are potentially undermined by methodological limitations including relatively low reliability of all power metrics (inter-session intraclass correlation coefficients [ICC] between the final two sessions: 0.72 ± 0.11; range: 0.54 – 0.89) and the use of a statistical method subsequently shown to greatly inflate the type I error rate (Harrison et al., 2020; Sainani, 2018). Further, concentric power in barbell back squats and ballistic alternatives are known to be maximised at intermediate intensities (Baker, Nance, & Moore, 2001; Cormie, Mccaulley, Triplett, & Mcbride, 2007; Izquierdo, Häkkinen, Gonzalez-Badillo, Ibáñez, & Gorostiaga, 2002; McBride, Haines, & Kirby, 2011). Replication of previously reported inertia-power relationships, as well as investigating the effects of flywheel inertia on peak concentric and eccentric velocities during the flywheel squat, are necessary for evidence-based recommendations regarding the best parameter for prescribing and monitoring flywheel squat intensity.

The aim of the current study was to evaluate the effects of varying flywheel inertias within the range of 0.029 to 0.121 kg·m^2 on concentric and eccentric vertical velocity and power during flywheel squats. The inclusion of eccentric parameters is particularly important given the implications for velocity-based training prescription and the unique nature of the eccentric phase of flywheel squats. It was hypothesised that increases in flywheel inertia would result in decreases in all measured peak and mean parameters (concentric and eccentric velocity and power) and increases in the eccentric to concentric ratio for each parameter. No *a priori* hypothesis was made regarding the linearity or fit of these relationships.

Methods

Experimental Approach to the Problem

A randomized crossover design evaluated the effects of flywheel inertia on concentric and eccentric peak vertical velocity and power during flywheel squats. Each subject attended the laboratory on two occasions. The first visit served to familiarize subjects with the flywheel exercise protocol. This protocol used a single familiarisation session because all subjects had previous knowledge of testing procedures and flywheel resistance exercise. All testing was conducted on the second visit, with conditions (flywheel inertias) performed in a random order. Sessions were separated from each other and regular training by at least 48 h. Subjects were required to maintain their normal nutritional intake during the experimental period. Alcohol and caffeine were not permitted prior to the experimental sessions but hydration was allowed during the sessions.

Subjects

An *a priori* power analysis (G*Power version 3.1.9.7, Düsseldorf, Germany) revealed that 14 subjects would provide an 80% chance of achieving $\alpha = 0.05$ in a repeated measures one-way analysis of variance with four repeated measures, assuming an effect size of 0.21 (from a previous relationship between flywheel inertia and average concentric vertical squat velocity (Worcester et al., 2020)) and a *high* correlation ($r = 0.8$) between repeated measures. Fifteen physically active males (actual power = 84.2%; age: 24 ± 5 years; height: 1.77 ± 0.08 m; mass: 76.6 ± 12.6 kg) participated in this study. Inclusion criteria were the absence of injury or illness (Physical Activity Readiness Questionnaire (Thomas, Reading, & Shephard, 1992)) and participation in resistance exercise training at least twice per week. The Ethics Committee of the University of Suffolk approved the study. Testing procedures were explained in accordance with ethical guidelines, and each subject completed an informed consent form. All procedures were conducted according to the Declaration of Helsinki for studies involving human participants.

Procedures

Data Collection

Body mass and stature were recorded by stadiometer (Seca 286dp; Seca, Hamburg, Germany). Each subject performed a standardized warm-up in line with previous studies (Beato, Bigby, et al., 2019; Beato, De Keijzer, et al., 2019; de Keijzer, McErlain-Naylor, Dello Iacono, & Beato, 2020). The warm-up consisted of: 10 min cycling at a constant power (1 $W \cdot kg^{-1}$ body mass) on an ergometer (Sport Excalibur Iode, Groningen, Netherlands); 3 min dynamic mobilization (dynamic half-squat movements mimicking the flywheel exercise and dynamic hip, knee, and ankle movements); and two to three (self-selected) sets of six repetitions of sub-maximal flywheel (D11 Sport; Desmotec, Biella, Italy) half-squats using the lowest inertia rom the experimental protocol (0.029 $kg \cdot m^2$). Two 14 mm retro-reflective markers were attached to each subject over left and right greater trochanters, and the flywheel exercise was recorded using an 8 camera 3D motion capture system (300 Hz; 7+ series; Qualisys; Sweden).

Subjects performed one set of eight repetitions of flywheel half-squats at each of 0.029, 0.061, 0.089, and 0.121 $kg \cdot m^2$ in a random order. Using four inertias provides a valid assessment of kinetic and kinematic relationships in flywheel squats, without the fatiguing effects of greater set quantities (Spudić et al., 2020). Sets were interspersed by 3 min passive recovery. The first two repetitions of each set were submaximal and served to increase the flywheel momentum (Worcester et al., 2020). Assessment of six consecutive repetitions is required for reliable velocity measures (Spudić et al., 2020). Subjects were instructed to perform the concentric phase with maximal velocity. Squat depth was standardized via instructions to achieve approximately 90° of knee flexion during the eccentric phase (practiced during familiarization), as in previous intervention studies (Beato, Bigby, et al., 2019; Beato, De Keijzer, et al., 2019; de Keijzer et al., 2020). Each repetition was qualitatively evaluated by an investigator, offering feedback to the subjects and strong standardized encouragements to maximally perform each repetition.

Data Reduction

Marker position data were manually labelled within Qualisys Track Manager software (v2019.3, Qualisys, Sweden). All further processing was performed in Visual3D software (v6 Professional, C-Motion Inc., Germantown, MD, USA). Marker trajectories were filtered using a recursive fourth-order low-pass Butterworth filter with a cut-off frequency of 10 Hz determined via residual analysis (Winter, 2009) and qualitative evaluation of the data. Vertical velocity was the first differential of marker vertical position (average of left and right markers) with respect to time. Power (normalized to body mass) was calculated for each repetition using a rotary position transducer integrated within the flywheel ergometer and normalized to body mass. For the six maximal effort repetitions at each inertia, concentric (positive), eccentric (negative), and eccentric to concentric ratio values were calculated for each of: peak velocity, mean velocity (while absolute vertical velocity ≥ 0.05 $m \cdot s^{-1}$), and peak power. The six repetitions were then averaged for each parameter. Squat depth (difference between highest and lowest vertical position) was similarly calculated as a secondary parameter to assess consistency of technique. High inter-session reliability (ICC > 0.9, *excellent*) has previously been reported for peak concentric and eccentric power measured by position transducers during flywheel squats (Worcester et al., 2020). Reliability of 3D motion capture marker peak velocity measures during squat movements have also been reported previously (ICC = 0.981, *excellent* (Martínez-Cava et al., 2020)).

Statistical Analyses

All statistical analyses were performed within JASP (Version 0.12.2, Amsterdam, Netherlands). The Shapiro-Wilk test for normality and Mauchly's test of sphericity tested parametric assumptions. Data were presented as mean ± standard deviation, or median [interquartile range (IQR)] where the assumption of normality was violated at one or more inertias (concentric and eccentric peak power, and all velocity parameters except for mean concentric velocity). For normally distributed parameters, one-way repeated measures ANOVA were used to assess the effect of inertia on each parameter, reporting F values. For non-normally distributed parameters, Friedman tests (Sheldon, Fillyaw, & Thompson, 1996) were utilized for the same purpose, reporting χ^2 values. Where a significant effect of inertia was reported, post-hoc comparisons identified differences between individual inertias. For normally distributed parameters, estimates of median standardized effect size (Cohen's d) were calculated, and interpreted as: *trivial* < 0.2; $0.2 \leq$ *small* < 0.6; $0.6 \leq$ *moderate* < 1.2; $1.2 \leq$ *large* < 2.0; *very large* ≥ 2.0 (Hopkins, Marshall, Batterham, & Hanin, 2009). For non-normally distributed parameters, Conover's post-hoc comparisons with T values were utilized (Conover, 1999; Conover & Iman, 1979). A Holm correction controlled for multiple comparisons (Holm, 1979), with a p-value < 0.05 indicating statistical significance. For any peak or mean parameter on which flywheel inertia had a significant effect, subject-specific linear and non-linear (logarithmic) relationships were fit against inertia for each subject in MATLAB (vR2020a, The MathWorks Inc., Natick, MA). R^2 values assessed goodness of fit and were interpreted as: *very high* ≥ 0.81; $0.81 >$ *high* ≥ 0.49; $0.49 >$ *moderate* ≥ 0.25; $0.25 \geq$ *low* > 0.09; *negligible* < 0.09 (Hinkle, Wiersma, & Jurs, 2003).

Results

Increases in flywheel inertia resulted in decreases in peak concentric velocity (Figure 1; $\chi^2 = 37.9$; $p < 0.001$), mean concentric velocity (Figure 2; $F(3) = 52.7$; $p < 0.001$), peak eccentric velocity (Figure 1; $\chi^2 = 24.9$; $p < 0.001$), and mean eccentric velocity (Figure 2; $\chi^2 = 16.8$; $p < 0.001$). Peak concentric velocities at the two lowest inertias were significantly greater than at the two greatest inertias ($2.61 \leq T \leq 5.51$; $p \leq 0.038$), whilst differences between the two lowest inertias ($T = 1.45$; $p = 0.310$) or the two greatest inertias ($T = 1.45$; $p = 0.310$) were not significant. All pairwise differences in mean concentric velocity between different inertias were significant (Figure 1; $0.659 \leq d \leq 2.443$; $p \leq 0.028$). Peak eccentric velocities at 0.029 kg·m^2 were greater than at 0.089 kg·m^2 ($T = 3.63$; $p = 0.004$) and 0.121 kg·m^2 ($T = 4.35$; $p < 0.001$), and those at 0.061 kg·m^2 were greater than at 0.121 kg·m^2 ($T = 3.05$; $p = 0.017$). No other post-hoc comparisons for peak eccentric velocity were significant ($0.73 \leq T \leq 2.32$; $0.077 \leq p \leq 0.473$). Mean eccentric velocity at 0.029 kg·m^2 was significantly greater than that at 0.089 kg·m^2 ($T = 2.90$; $p = 0.031$) and 0.121 kg·m^2 ($T = 3.77$; $p = 0.003$), with no other significant post-hoc differences in mean eccentric velocity ($0.87 \leq T \leq 2.32$; $0.103 \leq p \leq 0.465$).

***** Figures 1 and 2 near here please *****

Flywheel inertia had no significant effect on the eccentric to concentric ratio of peak (Figure 1; $\chi^2 = 3.69$; $p = 0.297$) or mean (Figure 2; $\chi^2 = 7.29$; $p = 0.063$) velocities. The best fit subject-specific inertia-velocity relationships (Table 1) were reported for peak concentric velocity (median linear $R^2 = 0.95$ [quartiles: 0.81, 0.97], median non-linear $R^2 = 0.97$ [0.88, 1.00]).

***** Table 1 near here please *****

Flywheel inertia did not have a significant effect on peak concentric power ($\chi^2 = 3.08$; p = 0.379) or peak eccentric power ($\chi^2 = 2.76$; p = 0.430). The ratio of peak eccentric to peak concentric powers tended to increase with increases in flywheel inertia (Figure 3; $F(3) = 4.26$; $p = 0.010$), although no post-hoc comparisons between pairs of inertias reported significant differences after correction for multiple comparisons ($0.14 \leq d \leq 0.76$; $0.064 \leq p \leq 0.585$). Although inertia had a significant overall effect on squat depth ($F(3) = 3.15$; $p = 0.036$), no post-hoc comparisons between pairs of inertias reported significant differences ($0.083 \leq p \leq 1.00$).

***** Figure 3 near here please *****

Discussion

The aim of this study was to evaluate the effects of varying flywheel inertias within the range of 0.029 to 0.121 kg·m^2 on vertical velocity and power during flywheel squats. As hypothesized, increases in flywheel inertia resulted in decreases in concentric and eccentric peak and mean vertical velocity. In contrast with the *a priori* hypothesis, flywheel inertia had no significant effect on peak concentric or eccentric power. The best fit linear and non-linear inertia-velocity relationships were reported for peak concentric velocity. These findings offer innovative insights for prescription and monitoring of flywheel resistance exercise.

This is the first study to report the effects of flywheel inertia on eccentric squat vertical velocity. In accordance with the force-velocity relationship of *in vivo* skeletal muscle (Hill, 1938) and previously observed decreases in peak vertical velocity with increases in traditional barbell back squat resistance (Pérez-Castilla et al., 2020; Weakley, Mann, et al., 2020; Zink et al., 2006), concentric and eccentric vertical velocity during flywheel squats were also shown to decrease with increases in isoinertial resistance. Interestingly, peak and mean concentric velocities (Figures 1 – 2) were lower than those reported for barbell back squats (Balsalobre-Fernández, Kuzdub, Poveda-Ortiz, & Campo-Vecino, 2016; Lorenzetti, Lamparter, & Lüthy, 2017), possibly due to the application of isoinertial resistance throughout the entire concentric range of motion during flywheel squats. Low inertias may be well suited to stimulating a training-induced rightward shift of the force-velocity curve, whereas higher inertias may be better suited to stimulating an upward shift. Training at higher inertias will likely therefore be more beneficial for individuals with a 'force-deficit', whilst lower inertias are more suitable for addressing 'velocity-deficits' (Jiménez-Reyes et al., 2017). The replication of previous inertia-concentric velocity relationships (Carroll et al., 2019; Spudić et al., 2020; Worcester et al., 2020) within the eccentric phase of the squat is important for practitioners using flywheel squats to overload the eccentric action. It is particularly noteworthy, in contrast to the hypothesis, that the ratios of eccentric to concentric velocities were unaffected by changes in flywheel inertia. This observation reinforces that increases or decreases in flywheel inertia appear to have similar effects on both concentric and eccentric velocities. The standardized squat depth between inertia conditions implies that the observed relationships are not caused by changes in joint range of motion (Worcester et al., 2020).

The subject-specific linear (median $R^2 = 0.95$) and non-linear (median $R^2 = 0.97$) relationships between inertia and peak concentric velocity were similar to previous linear force-velocity relationships during the flywheel squat ($R^2 = 0.96$ (Spudić et al., 2020)) but greater than previous inertia-velocity relationships (peak concentric velocity $R^2 = 0.60$, mean concentric velocity $R^2 = 0.66$ (Carroll et al., 2019)). The difference in comparison to previous inertia-velocity relationships may be a result of a greater range of inertias (≤ 0.121 kg·m^2 rather than ≤ 0.100 kg·m^2 in previous studies (Carroll et al., 2019; Worcester et al., 2020)) or more accurate velocity measurement techniques (*i.e.* 3D motion capture) in the present study. A similar pattern has been reported using inertias as high as 0.250 kg·m^2 (Spudić et al., 2020), although those extreme inertias seem questionable given the participant characteristics, the custom-made flywheel device, and the inertias typically utilized in acute and chronic interventions within athletic populations (Beato & Dello Iacono, 2020). Despite the greater fit of relationships between inertia and peak velocity parameters, it should be noted that the overall shape of these relationships were qualitatively similar to those of mean velocity parameters (Figures 1 – 2). Likewise, the overall effect of flywheel inertia on concentric and eccentric velocity did not differ between mean and peak values.

The observed subject-specific relationships suggest that velocity, rather than power, should be used to prescribe and monitor flywheel squat exercise intensities. The monitoring of velocity may represent a key step forward for practitioners and should be implemented into the current acute and chronic training recommendations (Beato, Bigby, et al., 2019; Beato & Dello Iacono, 2020). The superior fit of inertia-velocity relationships using peak concentric velocity (*very high*, Table 1), and the similar levels of linear and non-linear fit, encourage the transfer of existing linear peak concentric velocity-based gravitational resistance training recommendations to flywheel resistance exercise. However, mean concentric velocity (*high* to *very high*) or peak eccentric velocity (*high* to *very high*) but not mean eccentric velocity (*low* to *very high*), can also be used for this purpose. Peak concentric velocity has previously been recommended, rather than mean velocity, for monitoring traditional resistance exercise intensities below 70% one repetition maximum, with either velocity measure advisable at greater intensities (Weakley, Mann, et al., 2020) and the same may be true for flywheel exercise. The velocity associated with a given relative intensity is consistent across training sessions (Banyard et al., 2018) but may shift due to fatigue (Vernon, Joyce, & Banyard, 2020) or power-oriented resistance training (Weakley, Mann, et al., 2020). It is therefore advisable to periodically assess the inertia-velocity relationship (Weakley, Mann, et al., 2020). This can also inform prescription to target individually identified deficits (*e.g.* ‘force-deficit’ or ‘velocity-deficit’) in the inertia-velocity profile. Two common methods of velocity-based training prescription are to either prescribe a target velocity (Weakley, Ramirez-Lopez, et al., 2020) or a specified load (*i.e.* inertia) that relates to a target velocity in a previously identified load-velocity profile (Dorrell, Smith, & Gee, 2020). These velocity parameters may be monitored to meet prescribed relative intensities regardless of prior adaptations or variations in daily readiness due to muscular or peripheral fatigue (Sanchez-Medina & Gonzalez-Badillo, 2011; Weakley, Mann, et al., 2020). The reliability of test performance is influenced by measurement error and so the device used to measure velocity should be carefully considered (Weakley, Mann, et al., 2020).

The fact that flywheel inertia had no significant effect on peak concentric or eccentric power during the squat contradicts the hypothesised inverse inertia-power relationship. Whilst a previous study on high-level handball players reported greater concentric and eccentric power at 0.025 kg·m^2 compared to at 0.100 kg·m^2 (Sabido et al., 2018), the authors did not report the overall effects of inertia and utilised a method of inference subsequently shown to inflate the type I error rate of false positives to two to six times that of standard hypothesis testing (Harrison et al., 2020; Sainani, 2018). Sabido et al. (2018) used sets of 8 repetitions, compared to the 6 in this study, and noted that decrements in power were observed from the 7th and 8th repetition at certain inertias. Because power is the product of force (greatest at high external loads) and velocity (greatest at low external loads as observed in the present study), power is typically maximised at intermediate intensities. This has previously been reported in both barbell back squats (Cormie et al., 2007; McBride et al., 2011) and in jump squats (Baker et al., 2001). Given individual differences in the inertia at which peak power is likely to occur (median [quartiles] in the current study: concentric 0.061 [0.061, 0.089] kg·m^2; eccentric 0.061 [0.061, 0.121] kg·m^2), it is understandable that there would be no significant overall relationship between inertia and peak power (Baker et al., 2001; Rahmani, Viale, Dalleau, & Lacour, 2001). In back squats, peak concentric power has been reported to occur at an average of 60% of one repetition maximum for untrained men, middle-distance runners, and handball players, and at 45% for weightlifters and road cyclists (Izquierdo et al., 2002). On average, peak power of the bar, body, and combined system have been reported to occur at 90%, 10%, and 50% of one repetition maximum respectively (McBride et al., 2011).

It is therefore advisable for practitioners to utilise measures of velocity for flywheel squat training prescription rather than the more readily available peak power metrics, due to the more consistent relationship with flywheel inertia. Nonetheless, training prescription may still be informed by the ratio of peak eccentric power to peak concentric power. As hypothesized, and in agreement with Sabido et al. (2018), this ratio was reported to increase with increases in inertia. On average, peak concentric power was greater than peak eccentric power at the lowest two inertias, whereas the opposite was true at the two highest inertias (Figure 2), although differences between inertias were not significant. Whilst individual ratios varied, practitioners seeking an eccentric overload may be advised to favour the prescription of higher flywheel inertias and monitor power outputs to quantity any overload.

This study is not without limitations. Firstly, the study recruited physically active, resistance trained males, and it is unclear to what extent the findings can be generalized to different populations (*e.g.* females or elite athletes). It is likely that the fundamental relationships between flywheel inertia and velocity or power remain similar, albeit at greater or lesser absolute values. Additionally, the present subjects were already familiar with flywheel resistance exercise and so a single familiarisation session was utilised. Researchers and practitioners should note previous recommendations of at least two familiarisation sessions in unfamiliar subjects (Sabido et al., 2018). Further research is necessary to determine the validity with which inertia-velocity profiling can be used to estimate subject-specific parameters including maximal inertia and maximal unloaded velocity. These parameters are typically used in the prescription of velocity-based gravitational resistance training intensities (Weakley, Mann, et al., 2020) and the efficacy of similar approaches to flywheel resistance exercise can now be determined. Finally, this study has assessed a flywheel squat exercise and so it is necessary to extend this line of investigation to different flywheel-based exercises (*e.g.* deadlift) (Beato, de Keijzer, et al., 2020).

Conclusions

This study is the first to report that increases in flywheel inertia are associated with decreases in peak and mean velocities during the concentric and eccentric phases of the flywheel squat. This study also reported that flywheel inertia had no significant effect on peak concentric or eccentric power. The best fit linear and non-linear inertia-velocity relationships were reported for peak concentric velocity. These findings offer innovative insights for prescription and monitoring of velocity-based flywheel resistance training. Further research is necessary to confirm the efficacy of velocity-based flywheel squat training and to extend the findings to different flywheel-based exercises.

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Table 1. Median [lower quartile, upper quartile] goodness of fit for linear and non-linear (logarithmic) relationships between flywheel inertia and vertical parameters during the flywheel squat.

parameter	linear		non-linear	
	R^2	interpretation	R^2	interpretation
peak concentric velocity	0.948 [0.812, 0.969]	*very high*	0.966 [0.879, 0.996]	*very high*
mean concentric velocity	0.890 [0.740, 0.964]	*high* to *very high*	0.959 [0.716, 0.986]	*high* to *very high*
peak eccentric velocity	0.850 [0.536, 0.934]	*high* to *very high*	0.804 [0.556, 0.967	*high* to *very high*
mean eccentric velocity	0.726 [0.172, 0.920]	*low* to *very high*	0.621 [0.130, 0.903]	*low* to *very high*

List of Figures

Figure 1. Flywheel squat peak concentric velocity (top left), peak eccentric velocity (top right), and ratio of peak eccentric to peak concentric velocities (bottom) at four different flywheel inertias. Circles and error bars represent median and interquartile range. Dashed horizontal line represents a ratio of 1 (eccentric = concentric). * $p < 0.05$; # $p < 0.01$; \$ $p < 0.001$

Figure 2. Flywheel squat mean concentric velocity (top left), mean eccentric velocity (top right), and ratio of mean eccentric to mean concentric velocity (bottom) at four different flywheel inertias. Circles and error bars represent: mean and 95% confidence intervals for mean concentric velocity; and median and interquartile range for mean eccentric velocity and eccentric to concentric ratios. Dashed horizontal line represents a ratio of 1 (eccentric = concentric). * $p < 0.05$; # $p < 0.01$; \$ $p < 0.001$

Figure 3. Flywheel squat peak concentric power (top left), peak eccentric power (top right), and ratio of peak eccentric to peak concentric powers (bottom) at four different flywheel inertias. Circles and error bars represent: median and interquartile range for peak powers; and mean and 95% confidence intervals for eccentric to concentric ratios. Dashed horizontal line represents a ratio of 1 (eccentric = concentric). * $p < 0.05$; # $p < 0.01$; \$ $p < 0.001$

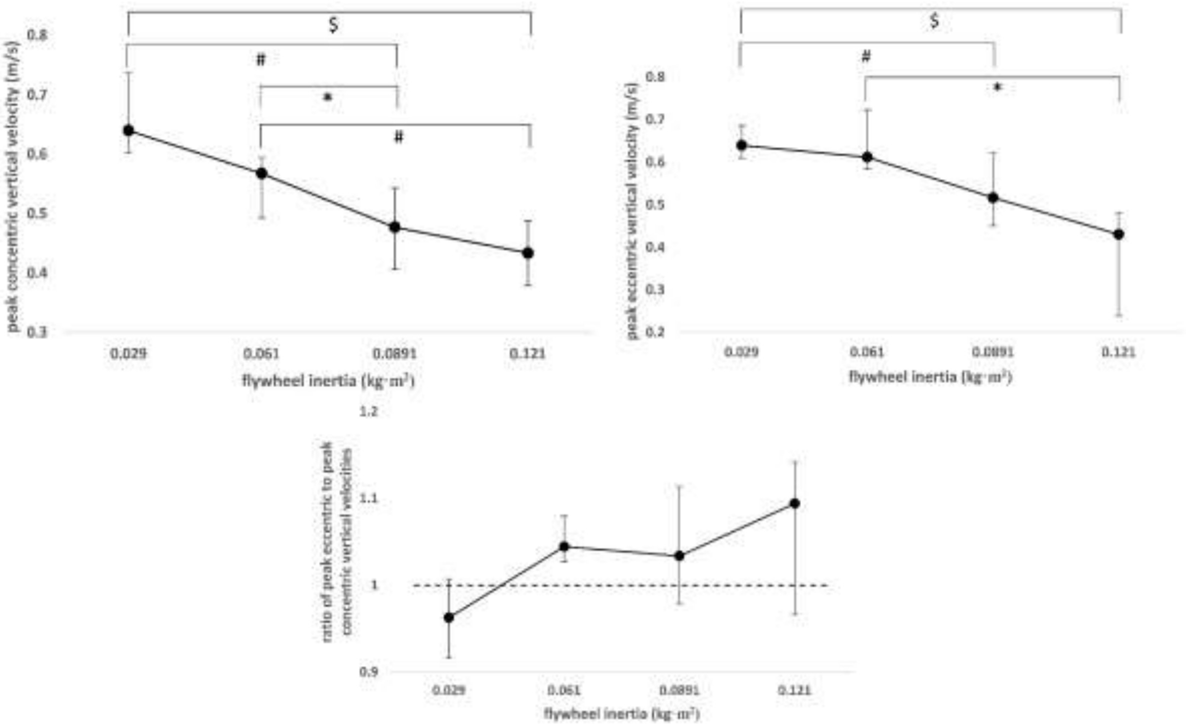
peak concentric vertical velocity (m/s)
0.8
0.7
0.6
0.5
0.4
0.3
$
#
*
#
0.029
0.061
0.0891
0.121
flywheel inertia (kg·m²)
peak eccentric vertical velocity (m/s)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
$
#
*
0.029
0.061
0.0891
0.121
flywheel inertia (kg·m²)
ratio of peak eccentric to peak concentric vertical velocities
1.2
1.1
1
0.9
0.029
0.061
0.0891
0.121
flywheel inertia (kg·m²)

Figure 1

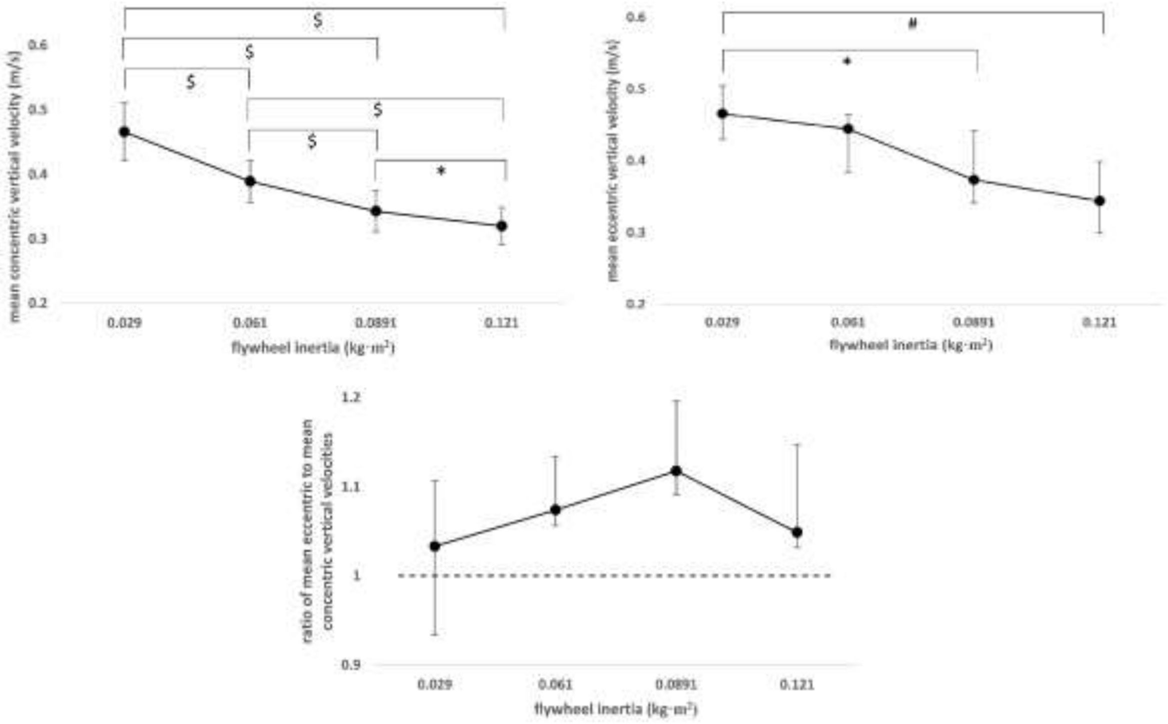

Figure 2

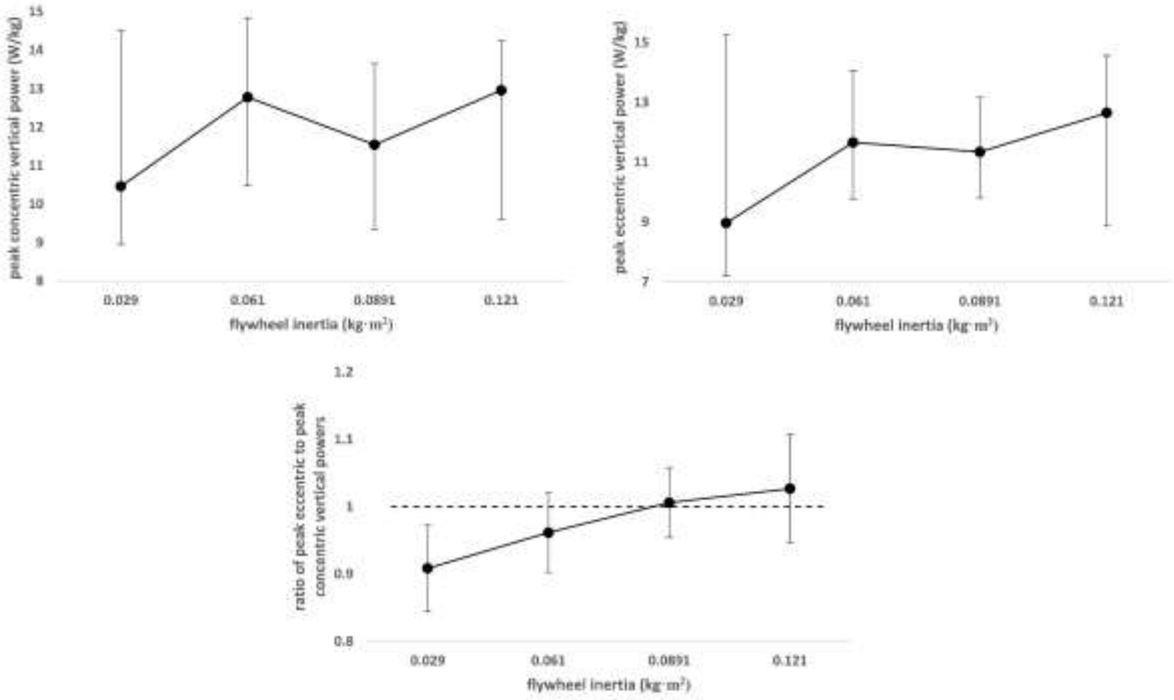

Figure 3