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Characterising overload in inertial flywheel devices for use in exercise training

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ABSTRACT
The purposes of this investigation were to: (1) assess kinetic characteristics of overload, (2) examine eccentric and concentric muscle activations and (3) explore velocity measurement as a method of intensity prescription in inertial flywheel squat training. A series of two experiments were performed: one assessing kinetic and muscle activation characteristics of flywheel squat training using three progressive inertial loads. The second experiment assessed inertial load-velocity relationships using six progressive inertial loads. Peak force, net impulse, positive–negative impulse ratio and positive–negative impulse duration ratio were each statistically significant between all three load conditions ($p < 0.05$). Concentric vastus lateralis muscle activation was the only significant increase between inertial loads ($p < 0.05$). Although not statistically significant, concentric quadricep muscle activation was increased from the lowest to highest inertia. Conversely, eccentric quadricep muscle activation was reduced from the lowest to highest inertia. In the second experiment, statistically significant regression equations were observed for average concentric velocity ($R^2 = 0.66$) and peak concentric velocity ($R^2 = 0.60$). In conclusion, our results indicate (1) overload is possible kinetically, (2) phase-specific muscle activation responds differently to increased inertia and (3) velocity has the potential to be used for load prescription in the inertial flywheel squat.

Introduction
The physiological and performance outcomes of a training plan are largely dependent on the proper prescription and manipulation of basic principles. Overload, one of the basic tenets of training, involves applying an appropriate stimulus that disrupts homeostasis and elicits improved levels of physical performance so long as sufficient recovery is provided (DeWeese, Hornsby, Stone, & Stone, 2015; Stone, Collins, Plisk, Haff, & Stone, 2000). One method of overload application is increasing the absolute intensity (e.g., load) or relative intensity (e.g., percentage of maximum) of a given exercise (Stone, Stone, & Sands, 2007). A
wide range of training modalities are available to strength and conditioning coaches to apply overload during training (DeWeese et al., 2015). As new methods of applying overload are created, it is important that strength coaches understand the application and characteristics of each method in order to properly implement them into the training programme (Calvert, Banister, Savage, & Bach, 1976; Sale, 2004).

Typically, for overload, the athlete encounters an absolute load which remains constant for both eccentric and concentric portions of the exercise. Investigations of single fibre and whole muscle contractions have demonstrated that during lengthening, more force can be produced than during shortening (Jorgensen, 1976; Katz, 1939; Westing, Seger, Karlson, & Ekblom, 1988). Consequently, loads based upon concentric prescription may underload the eccentric portion of exercises. Recently, variable loading devices have been developed to provide alternatives to traditional weight training. Flywheel inertial resistance, one alternative to traditional loading, uses inertial torque to impart linear resistance (Chiu & Salem, 2006). Additionally, the resistance encountered by athletes using flywheel devices is dependent upon absolute and relative elements. The absolute elements include the mass and radius of the disc, while the relative elements include the athlete-generated angular acceleration of the disc and perpendicular distance of the tether to the centre of the disc (Chiu & Salem, 2006; Moras & Vázquez-Guerrero, 2015).

To appropriately integrate flywheel resistance training as an overload mechanism, the mechanical demands of progressive loading must first be examined. Several studies have examined the mechanical demands (Berg & Tesch, 1994; Chiu & Salem, 2006) and overload characteristics (Martínez-Aranda & Fernández-Gonzalo, 2017; Sabido, Hernández-Davó, & Pereyra-Gerber, 2017) of flywheel resistance previously. However, most of the studies examining overload have been conducted using single-joint exercises. Chiu and Salem (2006) examined joint kinetics using multi-joint inertial flywheel resistance previously. While this research elucidated joint-specific characteristics of flywheel training, they did not examine progressive overload. Sabido et al. (2017) recently characterised overload in peak power with progressive inertial loads in the squat. Further characterisation of overload in multi-joint flywheel exercise is warranted. Moreover, the absolute and relative nature of flywheel resistance draws attention to the need for external indicators (i.e., kinetic, kinematic characteristics) and internal indicators (i.e., muscle activation patterns) of such demands (Norrbrand, Pozzo, & Tesch, 2010; Vázquez-Guerrero, Moras, Baeza, & Rodríguez-Jimenez, 2016). The presence and magnitude of overload between inertial loading conditions in flywheel training should be examined thoroughly before strength and conditioning coaches can reasonably utilise this training tool (DeWeese et al., 2015).

Therefore, the purposes of our investigation were: (1) to assess the kinetic characteristics of progressive overload using inertial flywheel devices; (2) to examine muscle activations using an inertial flywheel device in the squat; and (3) to explore the use of movement velocity as a potential method of intensity prescription for inertial flywheel training. We hypothesised that overload would be apparent via kinetic and muscle activation pattern and increases with increasing inertial loads, and that velocity would decrease with increasing inertial load.
Methods

General experimental set-up

To assess the research questions, a sequence of two experiments were performed. Before both experiments, a familiarisation session was administered to introduce participants to inertial flywheel training. These experiments were done separately and in succession. Therefore, a different set of participants were used for each experimental phase. The first experiment used repeated measures (i.e., multiple sets) at three progressive inertial loads and measured muscle activation and kinetic characteristics. Due to the nature of inertial flywheel training, prescription and quantification of training load are current potential limitations. Therefore, the second experimental session utilised velocity measurement and six progressive inertial loads to explore the load-velocity relationship and its use as a way to prescribe training or monitor training intensity. During each testing session, participants were verbally encouraged to perform each repetition with maximum effort throughout the concentric phase and resist the eccentric phase.

Participants

Seventeen physically active participants (16 male, 1 female) who were actively engaging in resistance training and familiar with the squat exercise volunteered to participate in the first experimental phase (Table 1). Eleven male participants (Table 1) agreed to participate in the second phase of the experiment and had the same inclusion criteria as the participants of the first phase. Participants signed written informed consent approved by the East Tennessee State University Institutional Review Board and had no current injuries prior completing the protocol.

Procedures

All participants performed one familiarisation session, which was identical to the protocol used during the testing session, seven days before the data collection to avoid the effects of acute fatigue on the performance testing session (Nosaka, Lavender, Newton, & Sacco, 2003). For the first experiment, two sets of thirteen repetitions of the squat were performed using an inertial flywheel training device (Exxentric AB, Sweden) at each of three progressive inertial loading conditions: Load 1a = 0.010 kg·m², Load 2a = 0.025 kg·m² and Load 3a = 0.050 kg·m². A total of six sets of squats were performed in the first experiment. The first three repetitions of each set were used to develop momentum and were not included in analysis. Dual platform force plates (PASCO, Roseville, CA, USA) were used to collect kinetic data. The centre of each force plate was marked with athletic tape to provide a guideline for foot placement (Sato & Heise, 2012). Surface electromyography (EMG) data were collected on the following muscles: vastus lateralis (VL), vastus medialis (VM), lateral

<table>
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<th>Table 1. Participant descriptive characteristics, mean ± SD.</th>
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<td>Age (y)</td>
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gastrocnemius (LG) and medial gastrocnemius (MG) using the Noraxon TeleMyo 2400GT (Noraxon USA, Inc.) sampling at 1,000 Hz and commercially available electrodes (HEX Dual Electrodes, Noraxon USA, Inc.). Following determination of electrode site placement, the area was shaved and wiped with alcohol preparation pads prior to electrode application. Data were processed within the EMG device’s software. Additionally, all participants wore the same type of shoes (Supernova, Adidas, Germany) to minimise potential confounding effects from different footwear (Sato, Fortenbaugh, & Hydock, 2012). The participants were given a rest period of two minutes between sets using the same inertial load, while three minutes of rest were given between loading conditions. Peak force (PF), net impulse (NI), positive–negative impulse ratio (P:N-I) and positive–negative impulse ratio duration (P:N-DU) were assessed. Kinetic characteristics were calculated based on each complete repetition. Positive impulse was the impulse observed above system weight, while negative impulse was the impulse below system weight. Net impulse was calculated as the sum of all positive and negative impulses for each entire repetition. Concerning EMG, average activation within the eccentric or concentric phase of each repetition was considered for the measured muscles. Figure 1 displays the experimental setting for our flywheel intervention. Reliability of EMG measurement, measured by between-participant intraclass correlation coefficient (ICC) and within-participant coefficient of variation (CV) was: VM (ICC = 0.95, CV = 9.9%), VL (ICC = 0.70, CV = 13.7%), LG (ICC = 0.22, CV = 17.4%), MG (ICC = 0.54,
16.7%). For kinetic measurements, reliability was as follows: PF (ICC = 0.95, CV = 2.7%), NI (ICC = 0.99, CV = 8.3%), P:N-I (ICC = 0.69, CV = 16.8%), P:N-DU (ICC = 0.90, CV = 9.9%).

The second experimental phase consisted of one set of thirteen squats at each of six progressive inertial loads: Load 1b = 0.010 kg·m², Load 2b = 0.035 kg·m², Load 3b = 0.050 kg·m², Load 4b = 0.060 kg·m², Load 5b = 0.075 kg·m² and Load 6b = 0.100 kg·m². A total of six sets of squats were performed during the second experiment. Again, the first three repetitions were used to develop momentum and were not included in the analysis. A PVC pipe was placed on each participant’s shoulders, a similar manner to that of a barbell back squat, and velocity data were collected using a wireless inertial-sensing device (PUSH, Inc., Toronto, Canada) placed on the right forearm of each participant. This device has previously been shown to be valid and reliable for measures of concentric velocity (Sato et al., 2015). Three minutes of rest were given between each set of exercise. Peak and mean concentric bar velocity (PV and MV, respectively) were determined for each repetition.

Kinetic data were collected directly into the PASCO Capstone software (PASCO, Roseville, CA, USA) and were sampled at 500 Hz. Subsequent processing of force data was performed in Microsoft Excel™ (Version 2010, Redmond, WA, USA) to obtain PF, NI, P:N-I and P:N-DU. Each of these variables was calculated from force-time data. Net impulse was calculated as the summation of all positive and negative impulses (Hall, 2014). The P:N-I was calculated as impulse above system mass (positive) divided by the impulse below system mass (negative). Lastly, the P:N-DU was calculated as the total time which the impulse was above system mass (positive) divided by the total time which the impulse was below system mass (negative). EMG data were full-wave rectified, smoothed using the Root Mean Squared method at 100 ms windows and were filtered using the band-pass method between 10 and 450 Hz. Eccentric and concentric phases were determined for the EMG data using the electrogoniometer, which was fastened directly adjacent to the lateral epicondyle. Using the electrogoniometer, the initiation of the eccentric phase of each repetition was defined as the maximum internal knee angle and the transition from eccentric to concentric defined as the minimum knee angle for each repetition. The EMG data are represented as average activation within each movement phase. Important to note, the first three repetitions of each set were used to gain momentum and therefore were not included in analysis. The final repetition was also discarded, as an investigator physically stopped the flywheel’s motion to complete the set.

**Statistical analysis**

One-way within-participant analysis of variance (ANOVA) was performed for each dependent variable against the independent variable of inertial load. Before statistical analysis, data were screened for sphericity using Mauchly’s sphericity test. If the assumption of sphericity was violated, a Greenhouse–Geisser correction was performed prior to further analysis. Initial alpha-level was set as \( p < 0.05 \). If a main effect was observed, *post hoc* comparisons were performed using effect size, Cohen’s \( d \) (calculated as the difference between load condition means divided by the pooled standard deviation). Effect size magnitude was assessed using the following scale: 0.0–0.2 (trivial); 0.2–0.6 (small); 0.6–1.2 (moderate); 1.2–2.0 (large); 2.0–4.0 (very large); 4.0–∞ (nearly perfect) (Hopkins, Marshall, Batterham, & Hanin, 2009). A linear regression was performed using peak and average velocity data.
to predict the inertial load. This analysis was performed to establish any potential inertial load-velocity relationship from the investigation.

Results

First experimental phase

ANOVA was significant for PF, NI, P:N-I and P:N-DU ($p < 0.05$). Post hoc analyses revealed significant increases from Load 1a–Load 2a, Load 2a–Load 3a and Load 1a–Load 3a for PF ($d = 0.45–0.99$), NI ($d = 2.12–4.45$), P:N-I ($d = 1.24–1.94$) and P:N-DU ($d = 0.87–1.37$) ($p < 0.05$) (Figure 2). Although statistically significant increases in all kinetic variables were observed, impulse variables increased to a larger degree based on effect size estimates (Figure 2). Concentric average activation was statistically significant for only VM ($p < 0.05$, $d = 0.10–0.26$). Although the VL did not reach statistical significance ($p = 0.058$), concentric average activation seemed to increase between Load 2a–Load 3a ($d = 0.38$) and Load 1a–Load 3a ($d = 0.33$), but not Load 1a–Load 2a ($d = -0.01$) (Figure 3). There were no statistically significant changes in average eccentric activation ($p > 0.05$), although eccentric muscle activations of LG and MG were greater during Load 3a when compared to Load 1a ($d = 0.07–0.26$) (Figure 4).

Second experimental phase

ANOVA was significant for both MV and PV ($p < 0.05$). Additionally, a statistically significant regression equation was observed for MV ($F(1, 63) = 117.89, p < 0.001$) with $R^2 = 0.66$ (Figure 5). A significant regression was also observed for PV ($F(1, 63) = 88.94, p < 0.001$) with $R^2 = 0.60$ (Figure 5).

Figure 2. Kinetic variables from phase 1 of experimentation for (A) peak Force, (B) net impulse, (C) positive:negative (P:N) impulse ratio and (D) P:N-impulse duration ratio.
Discussion and implications

Our investigation aimed to assess the potential utility of inertial flywheel resistance in...
strength and conditioning programs. Specifically, this study aimed to identify (1) the potential for overload (kinetics), (2) eccentric/concentric muscle activation characteristics and (3) a potential means for load prescription (velocity) in inertial flywheel training using the squat exercise. Our results indicate that there are considerable increases in kinetic variables as inertial loads are increased, supporting previous research (Martinez-Aranda & Fernandez-Gonzalo, 2017; Sabido et al., 2017). Additionally, concentric muscle activation exhibited different characteristics to eccentric muscle activation across loading conditions. Specifically, concentric muscle activation in the VM and VL were increased between Load 1a and Load 3a loading conditions, and reached statistical significance for VL between Load 2a and Load 3a only ($p < 0.05$). Eccentrically, the activation of the VM and VL decreased between Load 1a and Load 3a loading conditions. In the second experimental phase, there were statistically significant reductions in velocity between all six load conditions. Significant linear regression equations were observed for both MV and PV. Our investigation suggests that there is indeed the potential for progressive overload within inertial flywheel training, and velocity measurement may be a useful tool for intensity prescription.

Kinetic variables (PF, NI, P:N-I, P:N-DU) each increased significantly between all load conditions. This finding convincingly indicates appreciable overload may be applied using inertial flywheel resistance in the squat exercise. While PF increased significantly between load conditions, impulse characteristics may provide a clearer description of differences in overload and experienced mechanical tension between load conditions. This is likely due to the instantaneous nature of PF measures within each repetition, while the impulse characteristics in this study are representative of the full repetition. Peak force yielded effect size differences between load conditions of $d = 0.45–0.99$, while impulse variables such as net impulse ($d = 2.12–4.45$), P:N-I ($d = 1.24–1.71$) and P:N-DU ($d = 0.87–1.37$) yielded much larger effect magnitudes, indicating a large role of impulse variables for characterising overload in inertial flywheel devices. Specifically, the large increases in NI and P:N-I suggest that as inertial load increased, the positive impulse increased to a greater extent than did negative impulse. Such a finding indicates the overload experienced by the participants during the squat on an inertial flywheel device was primarily a product of impulse characteristics. Summarising, the preferential increases in positive impulses represents that as inertial load increases, there is likely less unweighting phase and a greater time under mechanical tension. Previous studies have observed favourable strength and hypertrophy adaptations following inertial flywheel training (Fernandez-Gonzalo, Lundberg, Alvarez-Alvarez, & de Paz, 2014; Greenwood, Morrissey, Rutherford, & Narici, 2007; Gual, Fort-Vanmeerhaeghe,
While increased muscle activations of the VM and VL were observed for the concentric phases of our flywheel squat protocol between Load 1a and Load 3a ($d = 0.26–0.33$) load conditions, the opposite was true for the eccentric phase, where the VM and VL muscle activations were reduced from Load 1a to Load 3a ($d = -0.11–0.15$). Previous research provides a potential explanation for this finding as larger increases in concentric phase muscle activation patterns relative to the eccentric phase during the barbell squat exercise have been observed (Boyden, Kingman, & Dyson, 2000; Gullett, Tillman, Gutierrez, & Chow, 2009; Norrbrand, Tous-Fajardo, Vargas, & Tesch, 2011; Paoli, Marcolin, & Petrone, 2009; Schaub & Worrell, 1995). Therefore, it seems that inertial flywheel squat training does not require additional neuromuscular input during the eccentric phase from a muscle activation standpoint. This finding is in disagreement with prior studies where eccentric muscle activations were observed to be greater than concentric activations during leg extension exercise (Norrbrand et al., 2010). Interestingly, an increase in eccentric muscle activation was observed in the LG and MG during the Load 3a load condition ($d = 0.07–0.26$). This may have been due to increased need for stabilisation at the ankle during the greater inertial loads. Due to the nature of squatting using flywheel devices, higher inertias may necessitate technical compensations in order to maintain upright posture, therefore requiring input from muscular involvement during ankle stabilisation. The relatively low reliability observed in the activation of LG and MG muscles should be noted (ICC = 0.22 and 0.54, respectively) and may have impacted these results. Our results might suggest the overall pattern of muscle activation in the quadriceps and gastrocnemius muscles is somewhat similar to traditional back squat training, and does not result in additional activation during the eccentric phase of the movement.

MV and PV resulted in similar trends, each yielding statistically significant regression equations to predict inertial loads. However, a stronger relationship was observed between load and MV ($R^2 = 0.66$) compared to PV ($R^2 = 0.60$). This is in agreement with previous research supporting MV as a useful tool for assessing concentric performance of an exercise (Jovanović & Flanagan, 2014). However, the limitation of MV measurement should be noted as this may not account for variance during the exercise. Due to the reasonable inertial load—velocity relationships observed in our data, these data suggest that velocity—particularly MV—could be used as an appropriate tool to approximate the prescription of inertial loads in flywheel squat training. Velocity has been shown to be an important factor for training adaptation following inertial training (Naczk, Naczk, Brzenczek-Owczarzak, Arlet, & Adach, 2016). Due to the inherent reliance of flywheel training on concentric output, prescribing intensities based on inertias alone could become problematic in a training programme that necessitates the prescription of specific training loads. This could especially be the case for competitive athletes, either in seeking improvement in a desired motor characteristic or in rehabilitating from an injury. Therefore, using a measure such as MV can provide objective feedback on the concentric outputs during the flywheel exercise for more precise intensity prescription and monitoring. This could also enable relative intensities to be quantified (between athletes or within-athlete at a given inertial load).

One of the shortcomings of the use of flywheel devices is the potential issues with prescribing specific intensities and ensuring overload. This study has described the kinetic and
EMG overload experienced when progressive flywheel inertias are utilised. Additionally, we have shown velocity to be a potentially useful metric for coaches to use in intensity prescription or monitoring. Coaches should consider using some form of objective feedback when implementing flywheel training to ensure training is carried out as prescribed.

Conclusions

We have demonstrated (1) progressive overload may be applied using inertial flywheel resistance; (2) Muscle activation does not seem to result in markedly different phase patterns (i.e., eccentric vs. concentric); (3) Our results provide evidence for velocity as a measure of exercise intensity in inertial flywheel squat training. Velocity could be used as an avenue of intensity prescription for practitioners. Overall, our results provide further understanding the overload principle using inertial flywheel resistance and additionally provide practitioners with options for accurate load prescription.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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