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EFFECTS OF RELATIVE INERTIAL LOAD ON PERFORMANCE MEASURES AND QUADRICEPS ELECTROMYOGRAPHY DURING FLYWHEEL RESISTANCE TRAINING SQUATS

Jason Todd Brantley Jr.
University of Kentucky, jbrantjr95@gmail.com

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Jason Todd Brantley Jr., Student

Dr. Lance Bollinger, Major Professor

Dr. Melinda Ickes, Director of Graduate Studies

EFFECTS OF RELATIVE INERTIAL LOAD ON PERFORMANCE MEASURES AND QUADRICEPS ELECTROMYOGRAPHY DURING FLYWHEEL RESISTANCE TRAINING SQUATS

THESIS

A thesis submitted in fulfillment of the requirements for the degree of Master of Science in the College of Education at the University of Kentucky

By

Jason Todd Brantley Jr.

Lexington, Kentucky

Director: Dr. Lance Bollinger, Assistant Professor of Kinesiology and Health Promotion

Lexington, Kentucky 2020

ABSTRACT OF THESIS

EFFECTS OF RELATIVE INERTIAL LOAD ON PERFORMANCE MEASURES AND QUADRICEPS ELECTROMYOGRAPHY DURING FLYWHEEL RESISTANCE TRAINING SQUATS

Flywheel resistance training (FRT) has become an increasingly popular modality for exercising due to its unique application of providing external resistance. Little is known about how changes in relative inertial loads affects performance and electromyography (EMG) activity. The purpose of this study was to examine how performance metrics and quadriceps EMG activity are affected by relative inertial load during FRT-based squats. Fifteen resistance trained individuals completed five sets of five repetitions of squats with varying relative inertial loads in random order. Peak Eccentric Power (PEP), Peak Concentric Power (PCP), average force, total work, and repetition time were measured. Surface level EMG activity of the vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF) and knee joint angle and velocity (electrogoniometers) were measured continuously. As relative inertial load is increased during FRT-based squats, we see that PEP and PCP decreased and iEMG activity increased due to a decrease in movement velocity and an increase in stimulus duration, demonstrating that peak recruitment is achieved even at very low relative inertial loads.

Keywords: neuromuscular, flywheel-based exercises, eccentric, electromyography

Jason Todd Brantley Jr.

July 30, 2020

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By

Jason Todd Brantley Jr.

Dr. Lance Bollinger

Director of Thesis

Dr. Melinda Ickes

Director of Graduate Studies

July 30, 2020

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INTRODUCTION

The squat is a complex, multi-joint exercise that is comprised of coordinated flexion and extension of the hips, knees, and ankles. Previous research has shown that athletic performance is directly related to squat power and strength across a multitude of disciplines (53). Quadriceps electromyography (EMG) is routinely used to measure muscle recruitment and has been shown to be directly related to concentric and eccentric forces during the squat (29). This suggest that quadriceps muscle activity is a prime determinant of squat performance.

Flywheel Resistance Training (FRT) has recently emerged as a popular training modality to improve athletic performance due to its unique iso-inertial means of providing external resistance. Unlike traditional, gravity-dependent systems such as weight stack machines or barbell weights, FRT provides its external resistance by the moment of inertia of a flywheel with a known mass and radius. During exercise, the force exerted during the concentric phase to accelerate the flywheel rotation is returned to the user during the eccentric phase. Due to this unique method of creating external resistance, FRT has the ability to provide greater eccentric overload of muscles (40), greater increases in power output and hypertrophy (31,76), and greater enhancement in athletic performance (31). To date, little research has been performed examining EMG activity during FRT, particularly in multi-joint exercises such as the squat.

A study by Norrbrand et al. (39) showed that during a five-week training period, individuals assigned to knee extension FRT showed greater EMG activity of the all individual quadriceps muscles during knee extensions compared to the weight stack group. However, this exercise was a unilateral movement and the methodology for matching loads was unclear. Luera et al. (29) showed that quadriceps EMG activity is related to force output during both concentric and eccentric portions of the squat, suggesting that quadriceps EMG activity would increase with higher force outputs. Indeed, force increases as inertial load is increased during FRT squats (43). To date, it is unknown how relative inertial load affects quadriceps EMG during FRT squats.

Most FRT studies, to date, have used an absolute loading system for prescribing loads for FRT (9, 38, 43, 52). This system does not take into account differences in individual strength among subjects and may be a large limitation in the research to date. Another, and maybe better, way of prescribing inertial loads during studies would be using a relative loading system. Spudic et al. (45) created a method for prescribing relative inertial loads by using the force-velocity relationship and linear regression to pick relative inertial loads. Another group, Carroll et al., (10) used velocity measurements and linear regression to select relative loads for their subjects. However, both of these methods rely on measuring movement velocity during FRT which may be a major limitation for many practitioners prescribing FRT interventions.

The primary purpose of this study was to determine how surface level EMG activity and performance measures of the quadriceps muscles would be affected by increasing relative inertial load during FRT-based squats in resistance trained subjects.

Based on the nature of FRT and previous literature, we hypothesized that as relative inertial load increases, force output would increase, power output would decrease, and that EMG amplitude would increase.

LITERATURE REVIEW

Introduction:

Flywheel-based resistance training (FRT) is a novel resistance training modality. Originally proposed by Francis Lowndes in 1796, this type of training utilizes the moment of inertia of a rotating disk to provide external resistance. Thus, FRT provides a gravity-independent external resistance during exercise and is often referred to as "iso-inertial training." Due to the gravity-independent nature of inertial load, Berg and Tesch proposed FRT as a means of resistance training (and muscle atrophy prevention) during spaceflight (8). It has since been reported that as little as four sets of maximal effort FRT prevents muscle atrophy, prevents fiber type changes, and preserves single-fiber contractile performance during prolonged bedrest mimicking spaceflight (5, 18). Indeed, FRT is currently utilized as an exercise modality aboard the International Space Station (ISS) and is now used in a variety of clinical settings (48). Alkner et al. (6) examined the differences in muscle volume, force, and power output in subjects who were bedridden versus subjects who completed supine squats and calf presses on a flywheel ergometer and reported that all outputs for the subjects who completed the exercises either stayed the same or increased over the 29 day period compared to the subjects who were bedridden who saw a decrease in those measures. A similar study, by the same research group, looked at muscle size and function following 90 days of bed rest with or without resistance exercise using a flywheel ergometer. They and reported that there was a muscle volume decrease (18% and 29%) in the knee extensor and plantar flexor muscles respectively for subjects who did not perform the exercises and muscle volume was completely (knee extensors) or partially maintained (plantar flexion) in the subjects that did complete the FRT intervention (4).

Flywheel-Based Exercises:

As flywheel speed increases, external resistance also increases. Thus, during FRT, contractile force and velocity of movement are directly related. Therefore, force output and movement velocity are expected to be maximal with the first repetition and decrease with each subsequent repetition. Conversely, due to the gravity-dependent nature of dynamic constant external resistance training, external load is fixed for all repetitions in both the concentric and eccentric phases. Thus, concentric muscle actions are often only maximally stimulated during the final repetitions of a given exercise (46). Additionally, since it is well-established that eccentric contractions are more forceful (19) than concentric, the eccentric phase of traditional resistance training is thought to be underloaded for all repetitions as the concentric phase must be completed for each repetition (30). It should be noted that eccentric contractions are defined when the muscle is in the lengthening phase and that concentric contractions are defined when the muscle in in the shortening phase (20). By quickly decelerating the rotating flywheel, it is possible for eccentric force and power to exceed those of the concentric phase during FRT, thus providing and eccentric-overload stimulus. However, since the greater muscle force seen during eccentric contractions is largely driven by increased passive force of muscle, EMG activity during eccentric contractions tend to be lower than during concentric or isometric contractions (51).

Flywheel-Based Exercise versus Traditional Gravity Dependent Exercises:

Compared to gravity dependent training, FRT has been argued to elicit greater muscle hypertrophy, strength, power, and athletic performance (31). Norrbrand et al. (39) conducted a 12-week resistance training study examining differences in muscle volume, maximal isometric force, and average energy. During this study, 8 subjects were assigned to a traditional weight stack machine and 7 subjects were assigned to FRT knee extensions. Subjects completed four sets of seven unilateral knee extensions 2-3 times a week. These authors reported a significant increase in maximal isometric force for all knee joint angles in the subjects performing FRT but not in those assigned to the weight stack machine. Furthermore, these authors reported that the FRT group had a twofold increase in muscle volume growth over the weight stack group (6.2% to 3.0%) but reported that was not statistically significant. Another study, by Norrbrand et. al. (40) looked at EMG differences in subjects who completed 12 sessions of four sets of seven knee extensor exercises either on a FRT device or weight stack machine. They reported that the EMG activity during the eccentric phase for the subjects in the FRT group was significantly higher than that of the subjects in the weight stack group for the vastii muscles. Lastly, Norrbrand et. al. (28) completed another study using 10 strength trained men who performed 5 sets of 10 repetition squats by either a barbell or flywheel device. They were looking at the difference in performance measures between these two groups and saw that the flywheel group display higher force outputs for concentric peak, eccentric peak, and overall peak force in the flywheel group compared to the barbell group.

Eccentric Factor in Flywheel-Based Exercises:

Eccentric overload is thought to be a major driver of FRT-induced increases in muscle size and strength. Eccentric muscle contractions appear to be essential for muscle hypertrophy and strength gains during resistance exercise. Farthing et al. (14) examined muscle hypertrophy in 14 untrained subjects who trained one arm eccentrically and one arm concentrically for 8 weeks and found that, overall, the arm that was trained eccentrically had a higher magnitude of hypertrophy compared to the arm that was trained concentrically. Similarly, Aagaard et al. (1) compared quadriceps strength in those performing concentric only and those performing and similar volume of eccentric only knee extensions. These authors reported that eccentric only training elicited a 15% increase in quadriceps strength compared to an 8% increase when using concentric only training. Lastly, another study examining the differences in hypertrophy between concentric lifts only and concentric/eccentric lifts saw a significant higher hypertrophy rate in the concentric/eccentric lift and stated that optimal muscle hypertrophy is not attained if eccentric muscle actions are not performed (17). Dudley et al. (13) demonstrated that concentric plus eccentric training elicited greater gains in leg press strength than a similar volume of concentric only training suggesting that eliminating eccentric muscle contractions compromises muscle strength gains.

Limitations of Research Regarding Loading in Flywheel-Based Exercises:

Despite the apparent benefits of FRT (48) and widespread commercial availability of this training modality, little is known about the effects of increasing inertial load on exercise performance. Martinez-Aranda et. al. (32) looked at the effects of different inertial settings on power, force, work, and eccentric overload during flywheel resistance exercises for 22 men and women (11 and 11), utilizing 6 different moments of inertia (0.025, 0.0375, 0.075, and 0.100 kg·m^2). They reported that power decreased with increasing inertial load. Specifically, these researchers reported a 36% difference in men and a 29% difference in women from lowest to highest inertial loads. They also reported that there was an increase in concentric and eccentric mean forces from lowest to highest (46-55%, 34-50%) for women and men, respectively (32). Another study by Sabido et. al. (43) looked at the difference in concentric and eccentric power outputs in 24 high-level handball players during flywheel based half-squats at four different inertias (0.025, 0.05, 0.075, 0.100 kg·m^2) and reported that both concentric and eccentric power decreased as inertial load increased. Lastly, a study conducted by Carroll et. al. (10) examined 17 physically active subjects (16 men and 1 women) while completing two sets of thirteen repetitions of the squat using a flywheel device at three different inertial loads (0.010, 0.025, 0.050 kg·m^2) for a total of six sets. They reported that they saw an increase in peak force and a decrease in peak and average velocity as inertial load increased from lowest to highest. Other studies that have looked at performance outcomes during FRT have seen similar results and trends as Carroll et al. (9, 52). While these studies show some implication of load on performance factors during flywheel-based exercises, there is still a lot that needs to be answered.

EMG Activity during Traditional Based Exercises:

Electromyography (EMG) is a widely used technique to measure or record motor unit activation during resistance training (47). Henneman's size principle states that, as there is an increase in force production needed there is an increase in the either the activation or recruitment of more motor units or the same motor units being recruited at a higher frequency. (35). That being said, the differences in EMG activity as there is an increase or decrease in inertial load has not be widely researched. A study by McCaw et. al. (33) looked at nine men who were regularly engaged in a strength exercises and looked at the difference in iEMG levels between a high load (75%) and a low load (60%) of their 1RM squat and reported that there was a 20% increase in iEMG values between the high load and low load. Another study conducted by Paoli et al. (41) looked at the difference in EMG activity in eight different thigh muscles during back squats with three sets of 10 repetitions with varying bar loads (no load, 30%, and 70% 1RM). These researchers reported that the overall mean values of rmsEMG activity of the 8 muscles increased as they increased bar load. Yavuz et al. (53) looked at EMG activity during back squats at three different percentages (80%, 90%, and 100%) of 1RM for 14 healthy male recreational bodybuilders. Subjects completed squats to a metronome (40 beats per minute) at each percentage until failure. Similarly, as reported before, they saw that iEMG activity increased as percent of 1RM increased from lowest to highest. Lastly, van den Tillaar et. al. (49) looked at differences in EMG activity of the vasuts lateralis, vastus medialis, rectus femoris, semitendinosus, bicep femoris, and gluteus maximus during the upward phase of back squats. Thirteen resistance trained males completed two repetitions for each load (30%-60% of 1RM) and one repetition for each load (70%-

100%). They reported that, while not linear, EMG activity increased as the load on the bar was increased and that iEMG activity was similar during certain groups of 1RM ie: 30-60% and 70-90% but reported that 100% was significantly higher than all others.

EMG Activity during Flywheel Based Exercises:

Norrbrand et al., reported that there was no difference in quadriceps EMG activity between flywheel-based leg press and a barbell squat (38). However, these were measured with a single load and it is unclear how external load was matched between these modalities. Alkner et al. (4) conducted a study comparing the EMG activity of 10 resistance trained individuals who completed 8 repetitions of concentric-eccentric actions during a flywheel leg press (FW), knee extension isokinetic dynamometry (ID), barbell front squat (FS), weight stack leg press (LP), and weight stack knee extension (KE). They reported that EMG activity during FW and ID was significantly higher during the concentric phase when compared to LP and FS and that EMG activity during the eccentric phase for FW and ID was significantly higher than all other modes of exercise. Another study, by Luera et. al. (29) looked at EMG activity of 14 resistance-trained men during back squats using a novel pneumatic resistance testing device. Subjects were asked to complete 9 repetitions at 10% increments at their maximum average force (ie: 10%, 20%, 30%, etc.) and it was during these repetitions that EMG activity was collected. They reported that as the load increased from 10% to 90% EMG activity for the vastus lateralis, rectus femoris, and biceps femoris all increased.

During FRT, Carroll et. al. (10) looked at EMG activation of the vastus lateralis, vastus medialis, lateral gastrocnemius, and medial gastrocnemius of 17 physically active participants who were actively engaged in resistance training. They had subjects complete two sets of 13 repetitions of the squat using an inertial flywheel device at three different inertias (0.010, 0.025, and 0.050kg·m^2). The first three repetitions for each set were excluded from data collection and allowed for the subject to develop momentum. Furthermore, they reported that EMG activity was increased during the concentric phase as inertial load was increased from lowest to highest but that as you increased inertial load from lowest to highest that EMG activity was decreased in the eccentric phase.

Relative Inertial Load as a New Method for Prescribing Inertial Loads:

Importantly, previous research examining effects of inertial load on exercise performance have focused on using absolute inertial loads (kg·m^2). The moment of inertia of a disk is calculated by the formula ($I=1/2MR^2$) where I is the inertia, M is the mass of the disk, and r is the radius. Due to inter-individual differences, nearly all traditional resistance training protocols relying on relative loads, typically determined as percentage of one-repetition maximum (1RM). However, it has previously been suggested that differences in muscle size or strength may contribute to sex-dependent differences in exercise performance at a given inertial load (32). Therefore, development of a relative inertial load may be important when assessing exercise performance or prescribing exercise with FRT. However, due to the inertial nature of FRT, it is difficult, if not impossible to establish a 1RM. In practice, a 1RM is measured as the heaviest weight that can be successfully lifted for one repetition and a heavier weight would result in failure (25). Therefore, one would continue to add weight to the barbell until they are no longer able to do a lift successfully. During FRT, one could continue to increase the inertial load by adding plates or increasing the size of the plates but since an ideal disk with no friction or air resistance can be accelerated even by very low forces, it is conceptually possible to rotate disks with very high moments of inertia with very low forces, albeit at a very slow angular velocity. Even though the disk would move at a very slow speed, a force would still be generated and would allow the person to continue moving through their lift. It is because of this factor, a 1RM for this device would be very difficult or impossible to achieve. Importantly, the relative effort needed to accelerate or decelerate a flywheel with a given moment of inertia may vary substantially between participants with differing levels of strength. Therefore, it is essential to establish a means of prescribing relative loads during FRT both for data normalization purposes and for exercise interventions.

Spudic et al. (45) looked at the force-velocity relationship of the flywheel to try and determine a better way of optimizing inertial loads for training. They had 26 resistance trained individuals complete 2 sets of 5 repetition squats at 10 different inertial loads (0.025, 0.050, 0.075, 0.100, 0.125, 0.150, 0.175, 0.200, 0.225, 0.250 $kg \cdot m^2$), and plotted the force-velocity values for those sets. It should be noted, that the first two repetitions for each set were excluded from data analysis and were used to allow subjects to gain momentum. They reported that the force-velocity relationship was linear and by using the inverse relationship, they were able to create two formulas (4-

load method and 10-load method) to help prescribe a relative inertial load. Based off their findings, using the 4-load method (two high and two low) produced lowed bias (5%) and fatigue rating scores in their subjects. Therefore, they suggest using two high loads (0.225 and 0.250 $kg \cdot m^2$) and two low loads (0.025 and 0.075 $kg \cdot m^2$) to create the regression line that should be used to determine the relative inertial loads. The limitation to this study is that data were only analyzed during the concentric phase and are not representative of the entire lift. Furthermore, developing a simpler method of establishing relative inertial load may aid practitioners in developing FRT interventions when the ability to measure movement velocity is limited.

Closing Remarks:

In summary, while there is plenty of research that supports that FRT could be a useful tool in both clinical and performance settings most flywheel-based research has only been done in unilateral, open-chain, single-joint movements. As technology has developed and these devices have become more popular, more research needs to be done on how complex movements are affected utilizing this mode of exercising. Also, more research needs to be conducted on how we prescribe relative loads to patients or subjects as it could play an important role in the performance outcomes that are recorded. By looking at how EMG activity changes as relative inertial load increases, we hope to have a better understanding of how relative loads play a role in flywheel-based exercises and how complex movements are affected.

METHODS

Subjects:

Fifteen (8M, 7F) recreationally resistance trained (> 6 months of resistance training, specifically squats), subjects presenting with no more than minimal risk according to ACSM guidelines (1) and no recent injuries were recruited for the study. Electronic scale and stadiometer were used to record body weight and height, respectively. Percent body fat and predicted muscle mass were measured by using a (Body Stat 1500) (at 50 kHz) (24). Subject characteristics are presented in Table 1. Participants were screened for participation by use of a health history questionnaire, a Physical Activity Readiness Questionnaire (PARQ), and resting electrocardiogram. All subjects provided written informed consent prior to participation. All research procedures were approved by the university non-medical institutional review board.

Participants visited the exercise physiology laboratory on three separate occasions, separated by at least three days for the first two sessions and seven days between the second at third visit (Figure 1). Anthropometric measures (Height and Weight), body composition (BIA), and one repetition maximum (1RM) testing for squat were completed on the first visit. Visit two served as a familiarization session for FRT. The third visit consisted of exercise performance data and quadriceps surface electromyography during FRT-based squats with varying relative inertial loads.

1RM Testing:

Muscular strength was assessed by performing a 1RM for the barbell back squat. Subjects were asked to warm up by cycling for 3 minutes on a cycle ergometer, performing lower body stretches (front and side lunges and standing quad and hamstring stretches), and ended by performing sets of 5, 3, and 3 repetitions using familiar weights to themselves to warm up prior to the first 1RM attempt. Subjects then performed a near maximal 1 repetition effort for each lift. Weight lifted was increased by 5-10% for subsequent sets until the weight could no longer be successfully lifted. The highest load successfully lifted was recorded as the 1RM. For safety purposes, spotters were provided during all 1RM testing.

Flywheel-based resistance exercise testing:

During the second visit and third visits, subjects performed a 3-minute warm-up on a cycle ergometer followed by a dynamic stretching routine as stated previously in the 1RM testing section. Subjects then completed five sets of five maximal effort repetition squats, at five different inertial loads. To account for differences in muscle strength among subjects, squats were performed using relative inertial loads based on multiplying subjects' 1RM. Thus, rather than the absolute moment of inertia ($kg \cdot m^2$), inertial load was expressed as a percentage of subjects' squat ($\%1RM \cdot m^2$). Subjects performed squats with relative inertial loads of: 0.025, 0.075, 0.100, 0.125, and 0.150 $\%1RM \cdot m^2$ in random order. Each set consisted of 6 repetitions, 1 pre-rep and 5 maximal concentric and eccentric contractions as this has been found to be the range at which peak PCP, PEP, and force are achieved.

Subjects were asked to descend, flexing at the knees until thighs were approximately parallel to the floor, then stand until fully erect. Throughout testing, flywheel rotation was measured through the kmeter®, a laser rotary encoder, averaged over a 40 msec window and transmitted via Bluetooth to an iOS mobile device. Peak concentric power (PCP), peak eccentric power (PEP), average force (AF), and total energy (TE) were recorded as we have done previously. The highest observed measures for PCP and PEP was reported. We have previously demonstrated this system provides valid measures of force and power (9). Using absolute inertial loads of 0.050, 0.075, and 0.100 kg·m^2, we previously found excellent agreement (Cronbach's Alpha 0.84-0.96), low bias (-17 to 3.9%), and low coefficient of variation (4.2 to 17.9%) of these performance metrics within a single session of squats using absolute inertial loads of 0.050, 0.075, and 0.100 kg·m^2 (unpublished data).

Electromyography:

For the third session, muscle activity was measured using a Delsys Trigno Avanti wireless electromyography (EMG) system (Delsys, Natick, MA). Following shaving, minor skin abrasion, and alcohol swabbing, electrodes were placed over the muscle belly of the superficial quadriceps (vastus lateralis: VL, vastus medialis: VM, and rectus femoris: RF) of the subject's right leg according to SENIAM guidelines. EMG data were recorded at 1000Hz and band-pass filtered at 10 and 400Hz. The linear envelope was developed with a RMS of 0.125s and normalized to the maximal voluntary isometric contraction (MVIC). Unilateral MVICs (3 trials per muscle, 5 s per trial; 30 s rest between trials) were performed at 120^o knee flexion using a knee extension machine with a fixed arm (Cybex, Rosemont, IL). A wireless electrogoniometer (Biometrics Ltd, Ladysmith, VA) was used to track knee joint angle throughout testing and time synchronized with EMG data. Calibration for the goniometer was completed at 0, 30, 60, and 90 degrees in the frontal and sagittal planes immediately prior to each data collection session. The proximal end of the goniometer was placed in line with the greater trochanter and lateral epicondyle of the femur and the distal end was placed in line with the head and lateral malleolus of the fibula. All sensors were secured to the body with double sided adhesive as well as elastic wrap for the duration of data collection.

Data processing was performed using EMGworks (Delsys, Natick, MA). Peak knee flexion angle was used to determine transitions between concentric and eccentric phases of the squat. Data analysis was performed on five consecutive squats. Total muscle activity (integrated EMG, iEMG) was determined for the total duration of the squat. It should be noted that iEMG relates to “total muscle activity” as the area under the amplitude-normalized curve which includes both an amplitude and duration component. Additionally, mean EMG amplitude of the concentric and eccentric phases were determined independently. Lastly, EMG power spectral analysis was performed to assess effects of inertial load on motor unit recruitment. Specifically, we analyzed median frequency of the EMG signal to assess potential effects of fatigue on the EMG signal and effects of inertial load on motor unit recruitment pools.

Statistical Analyses:

Due to non-normal distribution of data and violations of equal variance, statistical comparisons were made by the non-parametric repeated measures ANOVA on ranks (Freidman Test) with $\alpha = 0.05$ and Tukey’s post-test using SigmaPlot 14.0 (Systat, San Jose, CA). Data are presented as median with lower and upper quartiles unless otherwise noted.

Table 1. Subject Characteristics. Muscle mass was measured by bioelectrical impedance analysis as previously described. Data are presented as mean ± SD.

	Males (n = 8)			Females (n = 7)		
Age (y)	25.5	±	4.8	22.6	±	2.9
Ht (cm)	177.9	±	10.7	166.1	±	5.5
Wt (kg)	80.7	±	10.8	65.6	±	8.0
Muscle Mass (%)	47.0	±	4.1	39.3	±	4.0
1RM (kg)	130.8	±	21.2	89.7	±	20.8

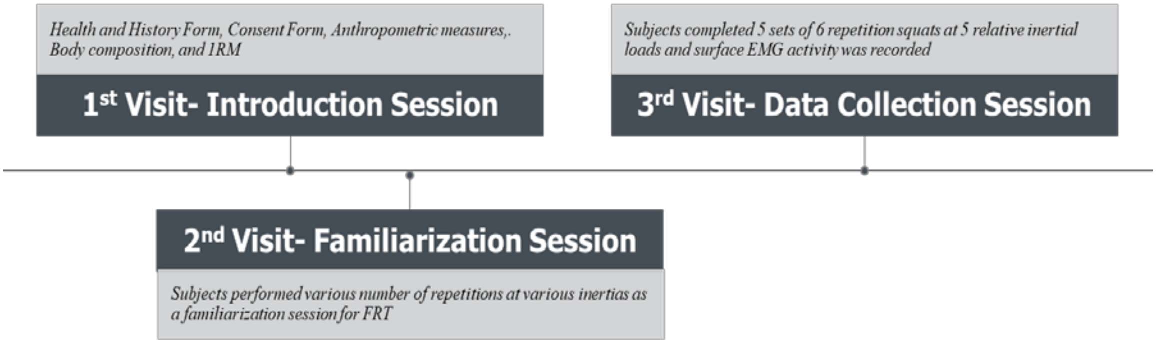

Figure 1. Timeline of present study.

RESULTS

Knee Angle:

In table 2, it is shown that there was no significant difference between minimal (p=0.24) or maximal knee joint angle (p=0.31) among the different inertial loads. There was also no significant difference between the inertial loads for knee excursion (p=0.410). As inertial load increased from lowest to highest (0.025-0.150), there was a decrease in both concentric and eccentric knee angular velocity. There was no significant difference between the inertial loads of 0.025 compared to the inertial load of 0.075 for either concentric or eccentric knee extension velocity. When comparing the knee extension velocity during the concentric phase of inertial loads 0.100, 0.125, and 0.150 to the inertial load of 0.025 there was a significant difference of p=0.003, p<0.001, and p=<0.001, respectively. When compared to the knee extension velocity of the concentric phase for the inertial load of 0.075, there was also a significant difference when compared to the velocity for the inertial loads of 0.125 (p=0.007) and 0.150 (p<0.001). For the eccentric phase, similar results were seen. When comparing the eccentric knee extension velocity there was a significant decrease between inertial loads of 0.100 (p=0.005), 0.125 (p<0.001), and 0.150 (p<0.001) compared to the inertial load of 0.025. Furthermore, when comparing the inertial loads of 0.125 and 0.150 to the inertial load of 0.075 there was a significant decrease in knee extension velocity of (p=0.016) and (p=0.001) respectively.

Performance Outcomes:

In table 3 and figure 2, as inertial load increased from lowest to highest (0.025 vs. 0.150) the median peak concentric power was 35% lower. When comparing the PCP of inertial loads 0.125 and 0.150 to inertial load 0.025 there was a significant difference of ($p=0.003$) and ($p<0.001$), respectively. There was also a significant difference in the PCP when comparing the inertial load 0.150 ($p=0.013$) to the inertial load of 0.075. Likewise, there is a similar trend seen when comparing the peak eccentric power (PEP) from the lowest load (0.025) and highest load (0.150). When comparing the PEP of the highest load and lowest load, the median PEP was 25% lower. Additionally, there was a significant difference in PEP when comparing the inertial loads of 0.125 ($p=0.061$) and 0.150 ($p=0.002$) to the inertial load of 0.025. There was no significant difference between the inertial load of 0.150 and 0.075 in PEP, as there was in PCP. When looking at average force the opposite effect is found, except for inertial load of 0.125 (590N), as you increase in inertial load from lowest to highest. The median average force had a 28% increase as you increased the inertial load from lowest to highest. Furthermore, there is a significant difference in average force between the inertial loads of 0.100 ($p<0.005$) and 0.150 ($p<0.005$) compared to the inertial load of 0.025. Lastly, average repetition time increased as inertial load increased from lowest to highest. There was a significant increase between the average repetition time of inertial loads 0.100 ($p<0.05$), 0.125 ($p<0.05$), and 0.150 ($p<0.05$) when compared to the inertial load 0.025. Additionally, inertial loads 0.125 ($p<0.05$) and 0.150 ($p<0.05$) were significantly higher than the inertial load 0.075.

Total EMG Activity:

In table 4, iEMG activity increases as inertial load increased from lowest to highest (0.025 vs. 0.150) for all individual muscles (VL, VM, RF) and for all muscles combined. For VL, the median value was 70% greater when comparing the lowest inertia (0.025) to the highest inertia (0.150). Furthermore, iEMG activity for inertial loads 0.125 and 0.150 was significantly higher (p=0.003 and p<0.001, respectively) than the iEMG activity of inertial load 0.025. Additionally, there was a significant increase in iEMG activity for the inertial load for 0.150 when compared to the inertial load 0.075 (p=0.003) and 0.100 (p=0.011). For VM, the median value was 95% greater when comparing as inertial the lowest inertial load (0.025) to the highest highest (0.150). Furthermore, iEMG activity for inertial loads 0.125 and 0.150 was also significantly higher (p=0.003 and p<0.001, respectively) when compared to the iEMG activity for inertial load 0.025. Likewise, inertial load 0.150 was significantly higher when compared to the inertial loads of 0.075 (p=0.016) and 0.100 (p=0.032). For RF, the median value was 87% greater when comparing the lowest inertial load to the highest inertial load (0.025 vs. 0.150) and saw a significant increase in iEMG activity in inertial loads 0.125 (p<0.001) and 0.150 (p<0.001) compared to the inertial load of 0.025. Lastly, combined quadriceps iEMG saw the median value increase 72% when comparing the lowest inertial load to the highest inertial load with a significant increase in iEMG activity for inertial loads 0.125 (p<0.001) and 0.150 (p<0.001) when compared to inertial load 0.025. In table 5 and figure 3, we see that there is no significant difference in the mean EMG amplitude during the concentric phase for either VL (p=0.3345), VM (p=0.087), or

RF (p=0.315). Likewise, the same trend is seen for the mean EMG amplitude during the eccentric phase for VL (p=0.642), VM (p=0.592), or RF (p=0.422).

Median Power Frequency:

In table 6, median EMG frequency was measured during five consecutive repetitions. The only significant difference that was measured among the three different muscles was the VL when comparing 0.150 %1RM·m^2 to 0.025 and 0.100%1RM·m^2**.** While no other values were significantly different, a trend can be seen that as relative inertial load was increased median power frequency was decreased.

Table 2. With Increasing inertial load knee angular velocity decrease, but knee joint angles and knee excursion does not change during flywheel-based squats at different relative inertial loads. Electrogoniometers measured minimal knee angle, maximal knee angle, and total knee excursion within the sagittal plane during five consecutive repetitions at each inertial load. Average concentric and eccentric angular velocity were calculated over each repetition. * p < 0.05 v. column 1, # p < 0.05 v. column 2.

	Relative Inertial Load (%1RM·m^2)				
	0.025	**0.075**	**0.100**	**0.125**	**0.150**
Min knee (deg)	18.4 (7.6, 28.3)	13.0 (4.3, 25.4)	13.1 (3.4, 24.1)	12.9 (5.9, 20.9)	13.9 (4.6, 23.5)
Max knee (deg)	114.7 (111.0, 119.8)	116.0 (110.3, 120.5)	111.9 (107.8, 118.7)	114.5 (107.9, 123.0)	114.0 (109.0, 122.6)
Knee exc. (deg)	94.7 (86.5, 111.1)	102.1 (91.2, 110.1)	104.9 (81.3, 109.4)	102.4 (100.5, 110.5)	104.4 (96.0, 111.4)
Con Vel. (deg/s)	121.5 (89.7, 132.3)	80.0 (70.7, 97.0)	69.3* (57.9, 79.9)	66.7*# (51.9, 71.8)	65.5*# (47.7, 71.0)
Ecc Vel. (deg/s)	121.5 (93.6, 138.8)	87.4 (68.5, 92.0)	72.8* (68.2, 79.7)	67.4*# (57.7, 70.2)	62.0*# (51.9, 69.6)

Table 3. Effects of increasing inertial load on squat performance outcomes. Peak concentric power (PCP), peak eccentric power (PEP), average force, and repetition duration during five consecutive flywheel-based squats was recorded using a laser rotary encoder. Data are median (25th, 75th percentiles). * $p < 0.05$ v. column 1; # $p < 0.05$ v. column 2; † $p < 0.05$ v. column 3

Relative Inertial Load (%1RM·m^2)

	0.025	**0.075**	**0.100**	**0.125**	**0.150**
PCP	573	470	460	451*	370*#
(W)	(404, 741)	(339, 678)	(366, 608)	(341, 598)	(307, 544)
PEP	649	553	531	457*	488*
(W)	(422, 784)	(409, 743)	(442, 669)	(383, 661)	(371, 635)
Ave.	487	605	639*	590	623*
Force (N)	(383, 544)	(412, 767)	(435, 739)	(410, 761)	(386, 753)
Rep. Time	1.75	2.60	2.97*	3.30*#	3.48*#
(s)	(1.46, 2.13)	(2.37, 2.85)	(2.73, 3.17)	(3.13, 3.58)	(3.30, 3.81)

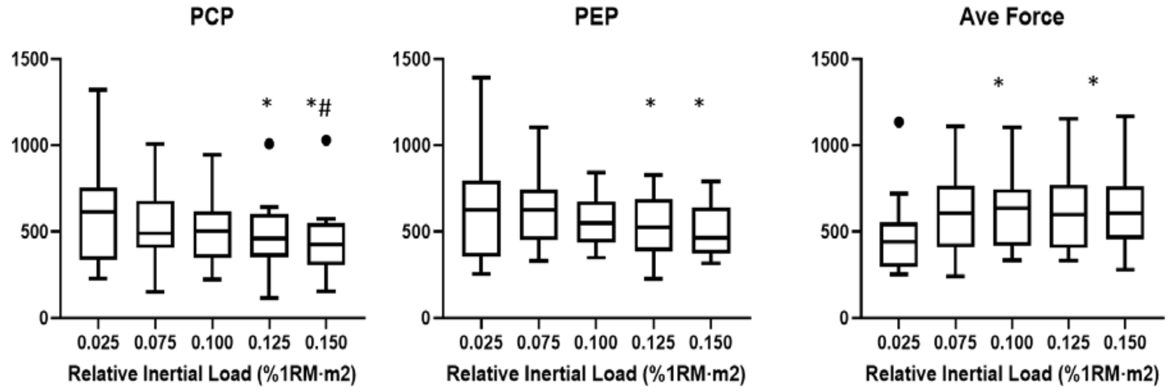

Figure 2. Effects of increasing inertial load on squat performance outcomes. Peak concentric power (PCP), peak eccentric power (PEP), and average force during five consecutive flywheel-based squats was recorded using a laser rotary encoder. Data are median (25th, 75th percentiles). * $p < 0.05$ v. column 1; # $p < 0.05$ v. column 2

Table 4. Increasing inertial load leads to an increase in superficial iEMG activity of the quadriceps muscles during FRT-based squats. Integrated electromyography (iEMG) was calculated over the course of five consecutive repetitions after normalizing to maximal voluntary isometric contraction. Data are median (25th, 75th percentiles). * $p < 0.05$ v. column 1; # $p < 0.05$ v. column 2; † $p < 0.05$ v. column 3

	Relative Inertial Load (%1RM·m^2)				
	0.025	**0.075**	**0.100**	**0.125**	**0.150**
VL	765.6	972.3	1052.4	1206.9 *	1301.5 *#†
	(550.2, 1025.2)	(838.7, 1118.6)	(799.3, 1320.7)	(914.2, 1515.2)	(1117.6, 1709.4)
VM	738.6	1005.4	1156.8	1359.9 *	1442.3 *#†
	(595.5, 1040.4)	(857.5, 1271.3)	(809.5, 1402.8)	(776.0, 1679.5)	(820.6, 1642.8)
RF	688.3	1051.3	1168.4	1183.8 *	1284.7 *
	(430.4, 1055.2)	(833.8, 1569.5)	(824.6, 1363.0)	(987.9, 1597.4)	(1002.6, 1953.6)
Combo	2362.6	3174.6	3314.5	3633.6 *	4056.5 *#†
	(1687.0, 2814.8)	(2572.4, 3687.9)	(2445.0, 3930.9)	(2707.8,4718.6)	(3211.4, 5013.7)

Table 5. Increasing inertial load had no difference on mean EMG amplitudes for either concentric or eccentric phases during FRT-based squats. Mean electromyography (iEMG) was calculated during the concentric and eccentric phases of five consecutive repetitions and normalized to maximal voluntary isometric contraction. Data are median (25th, 75th percentiles).

		Relative Inertial Load (%1RM·m^2)				
		0.025	**0.075**	**0.100**	**0.125**	**0.150**
Concentric	**VL**	74.6	81.0	79.8	79.2	69.6
		(59.8, 95.2)	(71.0, 102.3)	(53.4, 95.2)	(51.1, 103.0)	(45.7, 96.6)
	VM	86.6	92.0	85.9	87.1	80.5
		(55.2, 107.6)	(69.2, 133.7)	(66.9, 97.4)	(68.5, 99.9)	(120.2)
	RF	69.7	82.4	70.5	77.7	76.7
		(48.9, 101.8)	(64.2, 127.9)	(56.9, 89.2)	(48.7, 119.1)	(53.5, 93.4)
Eccentric	**VL**	66.1	88.2	76.9	80.3	63.5
		(53.3, 93.2)	(57.4, 103.1)	(46.5, 93.7)	(52.9, 99.0)	(47.0, 93.6)
	VM	72.0	91.9	78.1	87.4	78.6
		(53.3, 96.5)	(64.3, 111.1)	(65.8, 114.8)	(73.8, 105.1)	(66.3, 95.6)
	RF	74.4	108.6	78.5	93.9	95.2
		(42.9, 116.3)	(67.9, 144.7)	(56.6, 148.1)	(76.2, 138.9)	(56.1, 147.1)

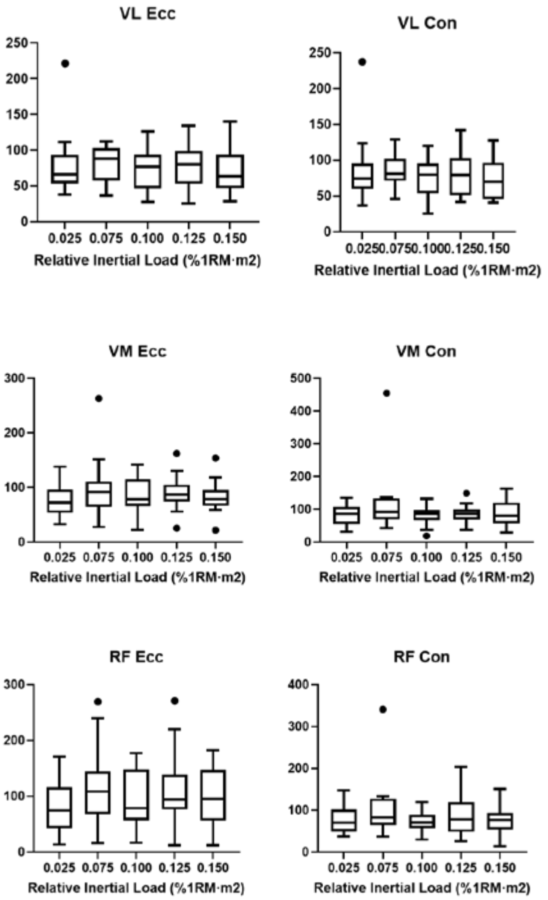

Figure 3. Increasing inertial load had no difference on mean EMG amplitudes for either concentric or eccentric phases during FRT-based squats. Mean electromyography (iEMG) was calculated during the concentric and eccentric phases of five consecutive repetitions and normalized to maximal voluntary isometric contraction. Data are median (25th, 75th percentiles).

Table 6. Effect of relatvie inertial load on median electromyography during flywheel-based squats. Median electromyography frequecny was measured during five consecutive repetitions at various inertial loads. Data are median (25th , 75th percentiles). * $p < 0.05$ v. column 1; # $p < 0.05$ v. column 2; † $p < 0.05$ v. column 3

	Relative Inertial Load (%1RM·m^2)				
	0.025	**0.075**	**0.100**	**0.125**	**0.150**
VL	74	74	77	69	69*†
	(67, 90)	(63, 87)	(66, 87)	(62, 82)	(62, 84)
VM	68	63	66	64	64
	(62, 79)	(59, 80)	(62, 85)	(59, 79)	(59, 73)
RF	76	70	76	73	73
	(58, 83)	(54, 80)	(58, 78)	(61, 91)	(61, 103)

DISCUSION AND CONCLUSION

From these results, we see the effects of increasing relative inertial load on surface level EMG activity and performance measures during FRT squats. Based on our data, we suggest that differences in performance variables measured during FRT squats may be driven by changes in knee angular velocity or movement velocity and not changes in motor recruitment or frequency. It should be noted, that there were several limitations to this study that may alter or change some of the results that were recorded. Not being able to measure recruitment of individual motor units with bipolar surface EMG is a large limitation due to us not being able to see if motor unit action potentials are affected by inertial load. This may help explain why EMG amplitude did not change. Other limitations in our study include: limited sample size, size of inertial disk, and potential differences in training status among subjects.

Our data are consistent with previous data from our lab and that of others (32, 53), in that we show that as relative inertial load increases we see a decrease in concentric and eccentric power outputs but an increase in force output. Studies mentioned previously (4-6, 8, 13, 18, 32, 38-40) used absolute loads as means to prescribe exercise intensity, while we used a novel way of calculating a relative load to determine inertial load. We believe that implementing and using a relative inertial load is a better and important method that should be used when prescribing inertial loads to someone. Validation of our relative inertial loading method is needed before prescribing this to subjects moving forward. Validation could be accounted by having subjects perform these movements at both the relative and absolute loads and comparing the regression of both outcomes. When comparing the outcomes, if the relative inertial load showed a greater decrease in performance outcomes may suggest that this method is more sensitive than using an absolute method. This is because subjects with different levels of strength are going to have to work at different relative intensities to overcome the same absolute load. For example, someone a 1RM of 150kg would have to exert a lower percentage of their 1RM to accelerate a moment of inertia of 0.200 $kg \cdot m^2$ to a similar velocity as someone with a 1RM of 100kg working at maximal effort. We believe that to get accurate and reliable performance outcomes, that a relative inertial load should be selected because of this. It should be noted that other methods of prescribing relative inertial loads have been discussed in recent research. Spudic et al. (45) used the force-velocity outcomes from their study to create a regression line that could be used to select relative inertial loads and Carroll et al. (10) suggested that velocity measures could be used to prescribe relative inertial loads. Both designs differ in nature in how we calculated and determined relative inertial load. Specifically, both of these previous methods relied on examining the force-velocity relationship during FRT whereas our method relies on normalizing the inertial load to subjects maximal strength.

It is also important to note that Carroll et al. (10) saw similar results in their performance outcomes but noted some different results in their EMG activity data. They reported that as inertial load increased, they saw an increase in force production as well as an increase in EMG activity in the concentric phase. Interestingly, they reported that during the eccentric phase they saw a decrease in EMG activity as inertial loads increased from lowest to highest. In contrast, we found that EMG activity between different phases did not significantly change as relative inertial load was increased. This may be partially explained by the fact that the current study employed higher inertial loads. Carrol et al. (10) used inertial loads of 0.010, 0.025, and 0.050 $kg \cdot m^2$. Conversely, absolute loads of the present study ranged from 0.025 to 0.200 $kg \cdot m^2$. It is possible that Carrol et al. failed to see a plateau in force output and EMG activity that are achieved with higher inertial loads such as those used in the present study.

As stated earlier, FRT exercises are initiated by a pushing through the concentric phase and resisting through the eccentric phase while a flywheel, with a known mass and radius, spins. This means that that external resistance is dependent on how fast the wheel is spinning during the concentric phase. We reported that knee angular velocity decreased as relative inertial load increased during both the concentric and eccentric phases. Because of this, we believe that the decrease in muscle power can in large part be explained by decrease in movement velocity. It is important to note, that during this study and another conducted in our lab (52) that as inertial load was increased minimal and maximal knee joint angles were not changed, reinforcing that the mechanics of the lift are not (in large part) responsible for the differences in performance outcomes as well as EMG activity.

It is also shown in our data that iEMG activity of the quadriceps muscles increased with increasing relative inertial load but that there were no differences in EMG amplitude during the concentric or eccentric phases. Our data demonstrates that increasing relative inertial load results in a decrease in movement velocity. Due to the fact that there were no changes in EMG amplitude as inertial load increased, we believe that the changes in iEMG activity levels are attributed to increased duration (time under tension) and not to increase motor unit activation or recruitment. A limitation to this study is that we were not able to measure the effects of relative inertial load on firing rate or recruitment of individual motor units which could give insight on to why would did not see any changes in the mean EMG amplitude. Research has shown that as force production increases during exercise motor unit firing rate increases and that motor units that are recruited at higher force outputs usually have a higher firing frequency (28).

It is also possible, that the lack of change in EMG amplitude is due to how the flywheel device generates its external resistance. In traditional based exercises (free weight or weight stack) the external force that one experiences is provided by gravity. This is not the case for FRT-based exercises. As stated previously, FRT's external force is generate by the moment of inertia of a flywheel with a known mass and radius. Exercises on the flywheel are completed at maximal effort, to maximize the external force that is provided by the flywheel. With this in mind, the discrepancy that we see in EMG amplitude compared to traditional gravity dependent exercises (34, 54) may be due to the fact maximal force output is achieved at very low loads (0.075) and therefore EMG amplitude is maximal, even at lower relative inertial levels.

Cramer et al. (12) looked at the mechanomyography (muscular contractile activity) of the VL, VM, and RF during isokinetic knee extensions and reported that there was a velocity-dependency of quadriceps EMG activity at velocities >240°/s for the VL and VM and at a velocity of >180°/s for the RF and suggests that the mechanomyography activity but not the EMG activity is affected during that range. During our study, we saw that the average angular velocity of the knee was approximately 60-120°/s. As stated previously, due the fact that EMG amplitude remains the same as relative inertial load increases, we can assume that motor unit recruitment stays the same as relative inertial load increases. Therefore, if motor unit recruitment remains unchanged as relative inertial load increases a change in the percentage (increase) of cross-bridges that remain in the force production stage could explain how we see an increase in force production but maintaining levels of motor unit recruitment as relative inertial load increases. Therefore, it is possible that performing maximal loaded squats (as seen during FRT) will elicit maximal EMG activity even at low inertial loads.

For median power frequency, a significant difference was only seen for the VL when comparing the relative inertial load 0.150%1RM·m^2 to 0.025 and 0.100%1RM·m^2. It is shown through our data that at lower relative inertial loads movement velocity is increased. It has previously been reported that as movement velocity increases, faster fiber types have to be recruited to be able to perform those faster movements (21, 50). This suggest that at our relative lower inertial loads that we are seeing a higher percentage of type II fibers being recruited. This may explain why we are seeing a downward shift in median power frequency as we increase the relative inertial load. Again, while we only saw a significant difference for the VL the trend mentioned above can be seen for all three of our muscles.

Contrary to our hypothesis, our data shows that there is an increase in force production when comparing the highest relative inertial load to the lowest relative inertial load, but that force production plateaued among our four highest relative inertial loads. This contradicts research that has been published previously (29) and may explain why we did not see any differences in EMG amplitude among the four higher relative inertial loads. That being said, our data supports our hypothesis on power output and that we see a significant decrease in PCP and PEP as relative inertial load is increased.

In conclusion, we see that there was a decrease in eccentric and concentric power as relative inertial load increases and the iEMG activity was increased. We hypothesize that this is because there are more active cross-bridges in the force production stage, due to a decrease in movement velocity, and not a change in motor unit recruitment since there was no change in EMG amplitude recorded across different relative inertial loading. This may play an important role for how FRT is prescribed and used in a performance setting. Based on our data, someone that is wanting to increase movement velocity while still maximizing muscular effort should train at lower relative inertial loads. This kind of training is more likely to lead to an increase in movement velocity and an increase in conduction velocity. For someone that is looking to increase muscular volume or for an increase in hypertrophy, they should train at higher relative inertial loads. Training at higher relative inertial loads is going to ensure that they are receiving a muscular overload stimulus which is going to result in a greater rate of hypertrophy compared to training at lower relative inertial loads. Future research should be conducted to examine the differences of low vs. high relative inertial loads on neuromuscular adaptations during FRT exercises.

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Vita

Place of Birth:

- Aiken, South Caroline

Educational Institution:

- University of South Carolina Aiken: 2017
  - B.S. Exercise and Sports Science

Professional Positions:

- Graduate Assistant: University of North Carolina Greensboro
  - May 2019- Current
- Graduate Advisor for the Student Government Association: University of Kentucky
  - June 2017- May 2019
- Student Coordinator for Student Life: University of South Carolina Aiken
  - January 2014- May 2017
- Student Coordinator for Enrollment Services: University of South Carolina Aiken
  - May 2015- May 2017

Scholastic and Professional Honors:

- Robert E Alexander Leadership Hall of Fame: University of South Carolina Aiken
  - May 2017

Professional Publications:

- Bollinger, L. **Brantley, J.** Tarlton, K., Baker, P,. & Abel, M,. (2017). Construct Validity, Test-retest Reliability, and Repeatability of Performance Variables using a Flywheel Resistance Training Device. Journal of Strength and Conditioning Research.

Jason Todd Brantley Jr.