Effects of Different Lifting Cadences on Ground Reaction Forces during the Squat Exercise

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Running Title: Cadence Variation and Squatting Forces

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ABSTRACT

INTRODUCTION: The purpose of this investigation was to determine the effect of different cadences on the ground reaction force (GRF_R) during the squat exercise. It is known that squats performed with greater acceleration will produce greater inertial forces; however, it is not well understood how different squat cadences affect GRF_R. It was hypothesized that faster squat cadences will result in greater peak GRF_R. METHODS: Six male subjects (30.8 ± 4.4 y, 179.5 ± 8.9 cm, 88.8 ± 13.3 kg) with previous squat experience performed three sets of three squats using three different cadences (FC = 1 sec descent/1 sec ascent; MC = 3 sec descent/1 sec ascent; SC = 4 sec descent/2 sec ascent) with barbell mass equal to body mass. Ground reaction force was used to calculate inertial force trajectories of the body plus barbell (FI_{system}). Forces were normalized to body mass. RESULTS: Peak GRF_R and peak FI_{system} were significantly higher in FC squats compared to MC (p=0.0002) and SC (p=0.0002). Range of GRF_R and FI_{system} were also significantly higher in FC compared to MC (p<0.05), and MC were significantly higher than SC (p<0.05). DISCUSSION: Faster squat cadences result in significantly greater peak GRF_R due to the inertia of the system. GRF_R was more dependent upon decent cadence than on ascent cadence. PRACTICAL APPLICATION: This study demonstrates that faster squat cadences produce greater ground reaction forces. Therefore, the use of faster squat cadences might enhance strength and power adaptations to long-term resistance exercise training.

Key Words: velocity, weight training, resistive exercise

INTRODUCTION

The squat exercise is a key constituent in training and rehabilitation programs designed to build lower body strength, muscle mass, and bone mineral density (1,10,14). The physiological effects of training are, in part, dependent on the volume and intensity of exercise (1). While volume is determined by the number of sets and repetitions performed, the most common method of manipulating intensity is to modify the load. However, because the total force experienced by the musculoskeletal system is a combination of the resistive mass and inertial force, altering the inertial force during the squat could also be used to manipulate exercise intensity. Therefore, it is necessary to understand how acceleration, which is dictated by the cadence of the exercise, affects inertial force during the squat movement.

The Newtonian definition of force is mass multiplied by acceleration. This can be used to describe the force on the total musculoskeletal system during free weight resistive exercise, which would be the mass of a person's body or body segments plus the resistive mass multiplied by the acceleration of the system. The system is also influenced by the acceleration due to gravity (**g**). Since mass (m) and **g** are known constants, this portion of the total force imparted to the musculoskeletal system is referred to as weight (m·**g**). Another component of total force, referred to as inertial force, is calculated by multiplying mass by the acceleration required to move the mass. Quantifying the inertial forces is critical to understand the total musculoskeletal forces associated with resistive exercise, and might be important for prescribing resistive exercise for conditioning or rehabilitation.

Acceleration during the squat is the rate at which the lifter ascends concentrically with the weight. However, this may not be the only significant factor since the rate of descent, or

eccentric phase of the lift, also affects inertial forces as well as the relative contribution of the stretch-shortening cycle (9). Therefore, in addition to ascent time, it is also important to examine the impact of manipulating descent time.

The purpose of this investigation was to quantify the ground reaction and inertial forces associated with the squat exercise when performed with different cadences, including contributions from both the bar and body. It was hypothesized that faster squat cadences will result in greater inertial forces.

METHODS

Experimental Approach to the Problem

A randomized repeated measures experimental design was used to determine the influence of cadence on inertial forces during the squat exercise. The independent variables in this study were the 3 different cadences used, while the dependent variables included the ground reaction force (GRF_R), inertial force of the bar (**FI_{bar}**), inertial force of the body (**FI_{body}**), and inertial force of the system (**FI_{system}**) associated with each squat cadence.

Subjects

Six healthy males (179.5 ± 8.9 cm, 88.8 ± 13.3 kg, 30.8 ± 4.4 yrs) with at least two years of squatting experience served as subjects. The NASA-Johnson Space Center Committee for the Protection of Human Subjects approved the following test protocol. All subjects read a Layman's summary describing the protocols and procedures before testing began and signed an informed consent document.

Procedures

Data were collected while subjects performed free weight parallel squats, with a barbell placed above the posterior deltoids across the shoulders at the base of the neck, at three different cadences (FC = 1 sec descent/1 sec ascent; MC = 3 sec descent/1 sec ascent; SC = 4 sec descent/2 sec ascent). These cadences were chosen to provide exercise hardware engineers with specific information for new hardware development. All trials were performed with the barbell mass approximately equal to the subject's body mass (difference no greater than ± 1kg). Subjects participated in three separate testing sessions performed on three different days, separated by 2-3 days of rest. During each session, three sets of three repetitions were performed at a single cadence. The order of the cadence was randomized.

Prior to data collection, subjects performed dynamic warm-up exercises and stretches. Subjects then performed a standardized resistance warm-up protocol (see Table 1) to accommodate to the designated lifting cadence. Specifically, the cadence of the warm-up approximated the desired cadence for the designated trial. A minimum two-minute rest period was given between all sets. However, subjects were allowed to increase the rest period relative to their perceived exertion during the testing session.

[Insert Table 1 here.]

Subjects performed squats at the prescribed cadence by synchronizing their motion to an audio metronome set to 1 Hz. A video camera was positioned lateral to the subject and a video monitor was placed in front of the subject to provide immediate visual feedback of squat form.

Test operators provided verbal cues to aid the subject in maintaining appropriate form and cadence.

Three-dimensional ground reaction force (GRF) data were measured using a force platform (Advanced Mechanical Technology, Inc, Watertown, MA). Squats were performed with both feet on the force platform. Linear velocity and displacement of the bar were measured using a position sensor (Patriot Sensors & Control Corporation, Costa Mesa, CA) that was connected to the bar. Electrogoniometers (SG150, Biometrix, Cwmfelinfach, Gwent, UK) were attached to the subject with double-sided tape to measure hip and knee angles. Position sensor, GRF, and electrogoniometer data were recorded simultaneously at 200 Hz. Knee angle was defined as the angle that the lower leg made with the thigh in the sagittal plane. Hip angle was defined as the angle that the thigh made with the trunk in the sagittal plane.

Position and velocity data were smoothed using a 4th-order low-pass digital filter at automated cutoff frequencies (Challis, 1995). GRF data were not filtered during post-processing.

The GRF_R for each trial was calculated as:

$$GRF_R = \sqrt{GRF_x^2 + GRF_y^2 + GRF_z^2} \qquad\qquad (1)$$

where GRF_x, GRF_y, and GRF_z correspond to the ground reaction forces along the fore-aft, mediolateral, and vertical axes of the force plate, respectively. Barbell accelerations were computed by differentiating barbell velocity data. Range of GRF_R was calculated as the difference between the peak and nadir of the GRF_R throughout the full squat movement.

Inertial force is the resultant of all the forces acting on a rigid body applied at the center of mass (17), and is expressed as:

$$\mathbf{FI_i} = \sum \mathbf{F}_i = m_i \mathbf{a}_i \qquad (2)$$

where $\mathbf{FI_i}$ is the inertial force acting upon body i, m_i is the mass of body i, and $\mathbf{a}_i$ is the acceleration applied to body i. Equation 2 can be used to determine the inertial forces due to the motion of the body, the barbell and the system (body + barbell) using Newtonian equations of motion.

For the bar, the inertial force ($\mathbf{FI_{bar}}$) can be calculated as:

$$\mathbf{FI_{bar}} = \mathbf{F_{bar}} + m_{bar}\mathbf{g} = m_{bar}\mathbf{a_{bar}} \qquad (3)$$

where $\mathbf{F_{bar}}$ is the force applied to the bar by the subject, m_{bar} is the mass of the bar, $\mathbf{a_{bar}}$ is the acceleration applied to the bar, and $\mathbf{g}$ is the acceleration due to gravity (9.807 m/s^2).

For the body, the inertial force ($\mathbf{FI_{body}}$) is calculated as:

$$\mathbf{FI_{body}} = \mathbf{GRF} - m_{bar}(\mathbf{a_{bar}} - \mathbf{g}) + m_{body}\mathbf{g} = m_{body}\mathbf{a_{body}} \qquad (4)$$

where $\mathbf{GRF}$ is the ground reaction force, m_{body} is the mass of the body, and $\mathbf{a_{body}}$ is the acceleration of the body.

The inertial forces associated with the system ($\mathbf{FI_{system}}$) are calculated as:

$$\mathbf{FI_{system}} = \mathbf{GRF} + m_{system}\mathbf{g} = m_{system}\mathbf{a_{system}} \qquad (5)$$

where m_{system} is the bar mass (m_{bar}) plus body mass (m_{body}), and $\mathbf{a_{system}}$ is the acceleration of the system ($\mathbf{a_{bar}}$ and $\mathbf{a_{body}}$). The derivations for these equations are outlined in the Appendix.

The start of each repetition was defined as the first of one hundred consecutive decreasing bar position samples (0.5 sec of data) during which the bar velocity was negative and the bar moved at least 3 cm. The midpoint of each repetition, or the point where the bar motion changed from downward to upward, was defined as the minimum position value of the barbell. The end of each repetition was defined as the last of fifty consecutive increasing position samples during which the bar velocity was positive and the bar moved at least 3 cm.

All inertial force values were normalized to body mass to account for subject differences. The maximum, minimum and range of inertial forces for the body, bar and system were found for each phase of each repetition.

Statistical Analysis

All statistical procedures were completed using Statistica software (StatSoft, Inc., Tulsa, OK). A set of squats consisted of three repetitions, except for a few cases when the data acquisition system produced errant data, which was identified as a statistical outlier (>2 SD). In these cases, the corresponding sets consisted of only two repetitions. Each subject performed a total of 9 repetitions of squats, and the mean of the 9 repetitions performed at each cadence (FC, MC, and SC) was calculated for each variable of interest. Measures of squat kinematics, GRF_R, and system inertial force were analyzed using a two-way ANOVA with repeated measures in the cadence. Tukey's post-hoc comparisons were performed to discern significant differences between cadences. The criterion for statistical significance was set at $p < 0.05$.

RESULTS

No differences were found between cadences for bar displacement, peak knee angle, or peak hip angle (Table 2), indicating that subjects achieved the same depth during the squat regardless of the timing condition. As expected, differences were seen in ascent times between the SC and both FC (p=0.0002) and MC (p=0.0004) (Table 2). No statistical differences were noted in ascent time for FC and MC (p=0.07), although the mean ascent time was 0.22 s faster during the FC.

[Insert Table 2 here.]

Figure 1 shows a typical GRF_R during a slow, medium, and fast cadence squat, while Figure 2 illustrates the peak and range of GRF_R and system inertial forces. Peak GRF_R was greater during FC squats than MC (p=0.0002) and SC (p=0.0002). No differences in peak GRF_R were found between MC and SC squats.

The range of GRF_R differed significantly between each cadence. The FC squats had the highest range of GRF_R and the SC squats had the lowest, with the majority of the difference primarily in the nadir rather than the peak. Similar trends were seen in peak system inertial force, where FC was significantly greater than MC (p=0.0002) and SC (p=0.0002). No statistical differences were found between MC and SC (p=0.1112). The range of system inertial force measures was significantly greater for FC squats compared to either MC or SC squats, and for MC squats compared to SC squats.

[Insert Figure 1 here.]

[Insert Figure 2 here.]

Figures 3 and 4 show the peak and range, respectively, of inertial forces generated by the body and barbell for each cadence, given that the mass of the external load provided by a barbell and the mass of the body were approximately equal. Irrespective of cadence, the peak and range of inertial forces generated by the body were significantly greater than those generated by the bar.

[Insert Figure 3 here.]

[Insert Figure 4 here.]

DISCUSSION

This study quantified the impact of lifting cadence on the inertial forces associated with the parallel squat. In addition, the inertial forces of the body and barbell were compared to determine if they were equal given identical static loads. Subjects performed squats using a barbell loaded nearly equal to their body weight at fast, medium and slow cadences. The results of this study indicate that squat cadence significantly affects the GRF_R and the associated inertial forces. The squats performed at faster cadences resulted in greater peak and range of GRF_R than those at slower speeds; furthermore, descent time significantly affects the forces developed, regardless of ascent time. This is reinforced by the fact that differences in the range of GRF_R were primarily in the nadir, thus the differences were primarily from the descent, not the ascent. The differences in GRF_R are due to the inertia of the system.

The peak and range of GRF_R and system inertial forces increased as movement time decreased. This result was expected, since at any given time the GRF_R is the sum of the GRF due to gravity and the GRF due to the acceleration of the system being supported. Because gravity remains constant, any variation in GRF_R will be due to the system's motion, and are

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reflected as the system inertial forces. Since the inertial force is due to acceleration, and decreases in movement time with identical displacement requires an increase in acceleration, faster squats should generate higher inertial forces.

Although the FC and MC ascent times were somewhat dissimilar (FC=1.03 s, MC=1.25 s), the descent times were very different (FC=1.21 s, MC=3.23 s). This suggests that the time of descent primarily affects the forces experienced by the body during ascent, which indicates that the faster descent time accentuated the stretch reflex. However, with similar ascent times, it should be expected that the peak inertial forces developed would be similar between these two cadences. However, this was not the case. The FC squats resulted in greater inertial forces than the MC. This suggests that the peak force developed during the ascent is influenced by the rate of descent, highlighting the importance of the rate of descent on the stretch reflex response. Since the peak force occurs near the initiation of ascent (Figure 1), it is possible that this is due to the greater acceleration occurring when the downward velocity of the system was changed quickly to upward velocity.

While the FC had significantly greater peak GRF_R than the MC and SC, examination of Figure 1 suggests that the range of GRF_R experienced during the FC may be affected by the decreases in GRF_R at the start and end of the repetition. The decrease at the start of the repetition probably occurs because the body becomes temporarily unloaded during the sudden lowering of the barbell. The decrease at the end of the motion may occur because the inertia of the body and barbell cause an unloading effect when all of the joints return to neutral positions. While it is intuitive that lifting greater peak loads will result in greater strength gains, it is unclear if this increase in range of load is of any physiological benefit. Also, for experienced weightlifters,

lifting at faster cadences can be done safely, but faster cadences could pose safety risks if the subject does not possess ability to develop the rate of muscular force necessary to control rapidly changing forces.

We found that the peak forces realized by the body are highly affected by movement time due to inertial effects of the body and barbell motion. It has been shown that squat execution speed affects rate of muscle force development (16). Training with faster concentric squats results in greater improvement in power than slower squats (7,11). It is possible, due to the large ranges and peak force magnitudes associated with high velocity movements, that the benefits of both high load magnitude training and high velocity training are available when lifting at faster cadences. This benefit might be accentuated by increasing the velocity of both the eccentric and concentric phase of the squat.

Since this study required the subjects to reverse their motion immediately from the descent to the ascent, it is not clear if this finding would occur if the subject had paused during the reversal. The increased rate of descent resulted in an enhanced force development of the musculature used during the ascent. It is known that rapid skeletal muscle fiber lengthening results in activation of the stretch-shortening cycle, producing an involuntary contraction known as the stretch reflex (1,6,9). This neuromuscular characteristic is often conditioned with plyometric exercise (3,15). It is also known that force and power can be affected by slower or faster lifting cadences (7,8,13), and that training at slower or faster cadences can affect strength and power gains (11,12). Perhaps future study should focus on the descent cadence and determine if conditioning with a fast descent and fast ascent results in greater human muscle power development than conditioning with a slow descent and fast ascent.

Although the barbell bar may flex slightly during a squat, it is relatively stiff and was considered to be a rigid body. The inertial forces subjected to the barbell are predictable using Newton's second law, and were found by modeling the barbell as a single point in space. However, the human body is a much more complex system consisting of multiple segments of various masses moving at varying rates. Since inertial force is related to the mass of the object, it seems reasonable to assume that the contributions of the body and barbell to the overall system inertia should be similar given that the barbell mass was approximately equal to the body mass. It is interesting that the inertia of the body was not equal to the inertia of the barbell . In fact, the body inertia was larger than the bar inertia regardless of squat cadence. Since the mass of the body and barbell were approximately the same, it is possible that the unequal inertial forces were due to the interactions and various rotations of the segmental masses of the body, which cannot be simplified as the motion of a single point mass.

During the squat, the lower leg, thighs and trunk all undergo significant translations and rotations (5). Each of these segments has a mass, and associated inertial forces. It was not possible, based on the methodology of this experiment, to determine the inertial affects of the various body segments. However, it can be speculated that the squat motion induces inertial forces on each body segment that may affect the respective body segment differently, and that the sum of these forces does not accurately represent the inertial force computed using a single point mass to represent the body.

In conclusion, our findings demonstrate that the peak GRF_R and the inertial forces during a squat are greater when performed at faster cadences. Furthermore, the force during the ascent is affected by the descent cadence. Since these results suggest that inertial force produced

during a squat exercise is affected more by the movement of the body than the barbell, future

studies should attempt to determine how the relative inertial contribution of the barbell and body

to the overall system forces is affected by the magnitude of the external load.

PRACTICAL APPLICATION

Rehabilitation and training prescriptions should account for the descent cadence of the lift performed. While this study cannot determine the long-term physiological effects of performing squat exercises at different cadences, these results suggest that athletes, clients, or patients who perform squats at greater movement velocities will be exposed to greater magnitudes and rates of musculoskeletal loading. This may provide the experienced weightlifter the same benefit of training with increased resistance, namely muscle and bone formation, while operating with a decreased risk because there is less external load to control. While the barbell loads may be lower during faster velocity training, it is possible that the inertial effects of the motion result in peak forces similar in magnitude to training at slower cadences with a higher load.

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APPENDIX: Method used to determine inertial forces

The inertial force ($\textbf{FI}_\textbf{i}$) acting upon the object i is expressed as:

$$\textbf{FI}_\textbf{i} = \sum \textbf{F}_i = m_i \textbf{a}_i \qquad\qquad (6)$$

The external forces acting upon the object include the gravitational force ($m_i\textbf{g}$), forces due to muscular activity, and reaction forces from other objects.

The inertial force of the barbell, $\textbf{FI}_\textbf{bar}$, is found using the equation:

$$\textbf{FI}_\textbf{bar} = \textbf{F}_\textbf{bar} + m_{bar}\textbf{g} = m_{bar}\textbf{a}_\textbf{bar} \qquad\qquad (7)$$

where $\textbf{F}_\textbf{bar}$ is the net force exerted on the bar by the person, m_{bar} is the mass of the bar, $\textbf{g}$ is the acceleration of the bar due to gravity (constant -9.807 m/s^2), and $\textbf{a}_\textbf{bar}$ is the acceleration of the bar in space (See Figure 5).

[Insert Figure 5 here.]

The forces acting upon the body's center of mass (CM, F_{body}) can be summed using equation 6 to determine the inertial force acting upon the body, $\textbf{FI}_\textbf{body}$.

$$\textbf{FI}_\textbf{body} = m_{body}\textbf{a}_\textbf{body} \qquad\qquad (8)$$

Figure 6 shows the FBD of all the forces acting upon the body. If the body is considered a single lumped mass, at any given time the forces acting upon the entire system include the $\textbf{F}_\textbf{bar}$ and the $\textbf{GRF}$. The negative $\textbf{F}_\textbf{bar}$ term reflects the reaction force between the body and barbell, and is equal and opposite to the force of the body acting upon the bar expressed in Figure 5.

[Insert Figure 6 here.]

The forces included in the FBD are related by:

$$\mathbf{FI_{body}} = \mathbf{GRF} - \mathbf{F_{bar}} + m_{body}\mathbf{g} = m_{body}\mathbf{a}_{body} \qquad (9)$$

Equation 7 can be rearranged to solve for $\mathbf{F_{bar}}$

$$\mathbf{F_{bar}} = m_{bar}(\mathbf{a_{bar}} - \mathbf{g}) \qquad (10)$$

resulting in

$$\mathbf{FI_{body}} = \mathbf{GRF} - m_{bar}(\mathbf{a_{bar}} - \mathbf{g}) + m_{body}\mathbf{g} = m_{body}\mathbf{a_{body}} \qquad (11)$$

where m_{body} is the mass of the subject's body and $\mathbf{a_{body}}$ is the acceleration of the body's CM.

In order to determine the inertial forces inherent in the complete barbell and body system, a third FBD is used that models the barbell and body as a single lumped mass with total mass equal to $m_{body} + m_{bar}$ (See Figure 7).

[Insert Figure 7 here.]

The inertial forces associated with the system ($\mathbf{FI_{system}}$) are computed as:

$$\mathbf{FI_{system}} = \mathbf{GRF} + m_{system}\mathbf{g} = m_{system}\mathbf{a_{system}} \qquad (12)$$

Figure Captions:

Figure 1. Barbell position and typical GRF_R during fast, medium and slow cadence squats. All trajectories have been time-normalized so that the lowest bar position occurs at 50% of the repetition.

Figure 2. Peak and range of GRF_R and system inertial force normalized to body weight.

Figure 3. Peak inertial forces of the body and barbell at all cadences normalized to body weight. $*p<0.05$

Figure 4. Range of inertial forces of the body and barbell at each cadence normalized to body weight. $*p<0.05$

Figure 5. Free body diagram (FBD) of forces acting upon barbell.

Figure 6. Free Body Diagram of forces acting upon the body's CM.

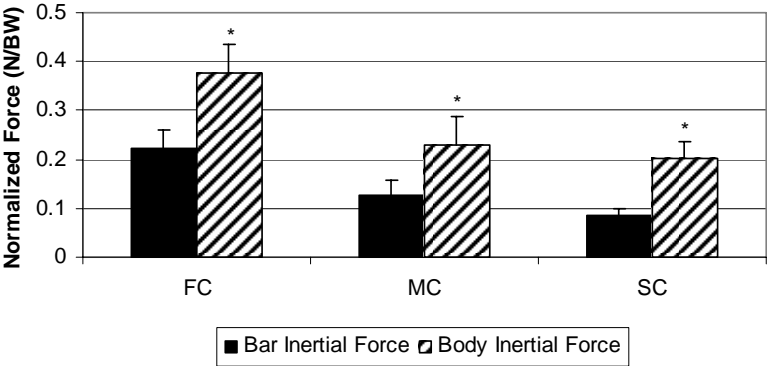Figure 7. FBD of forces acting upon the barbell + body system.

Figure 1:
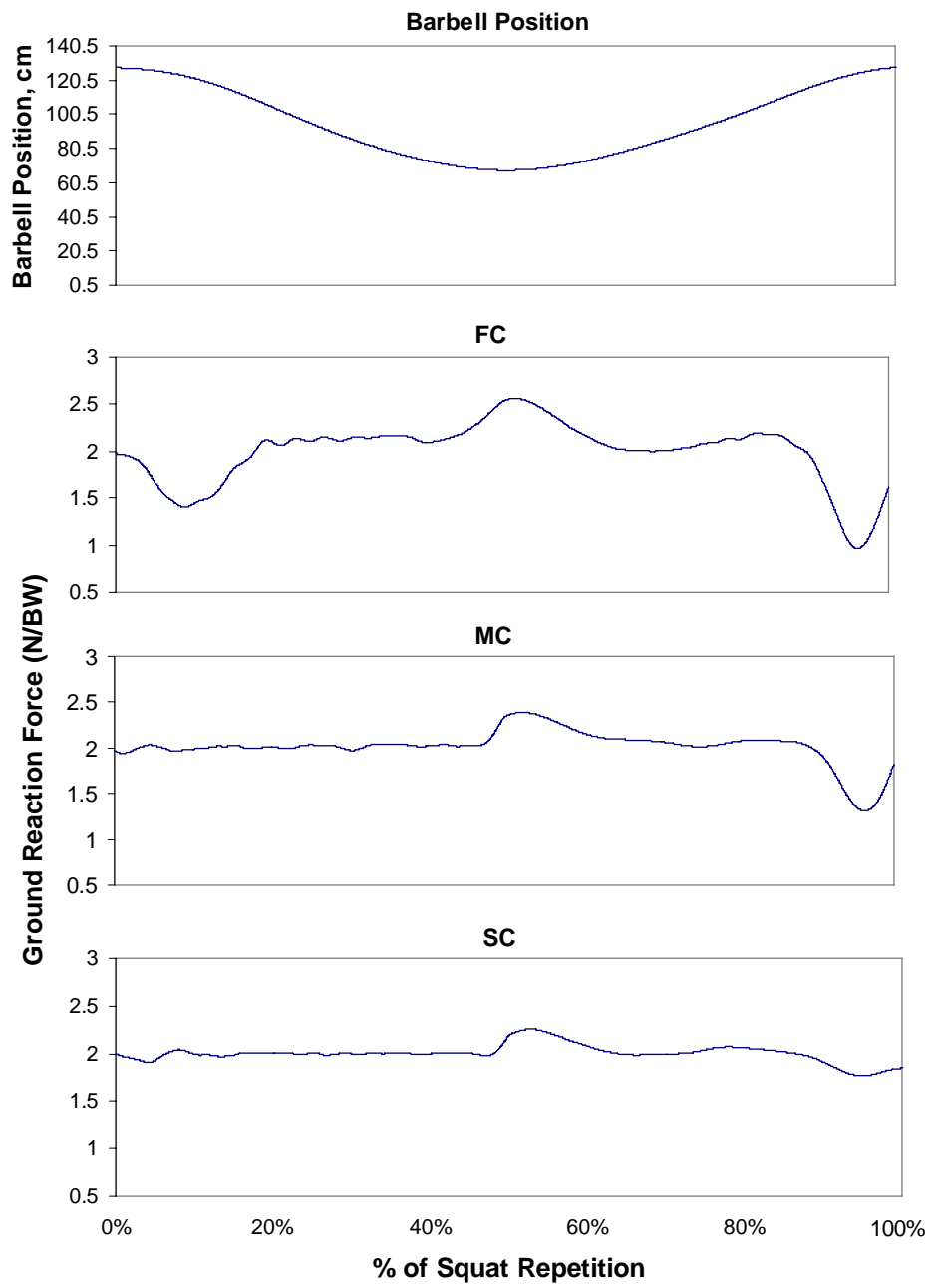
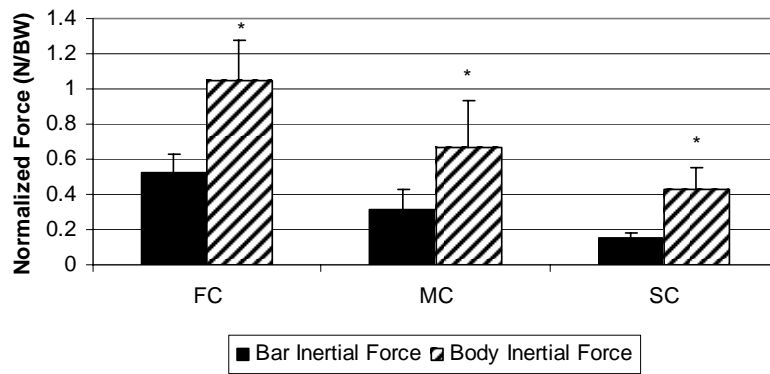Figure 2:
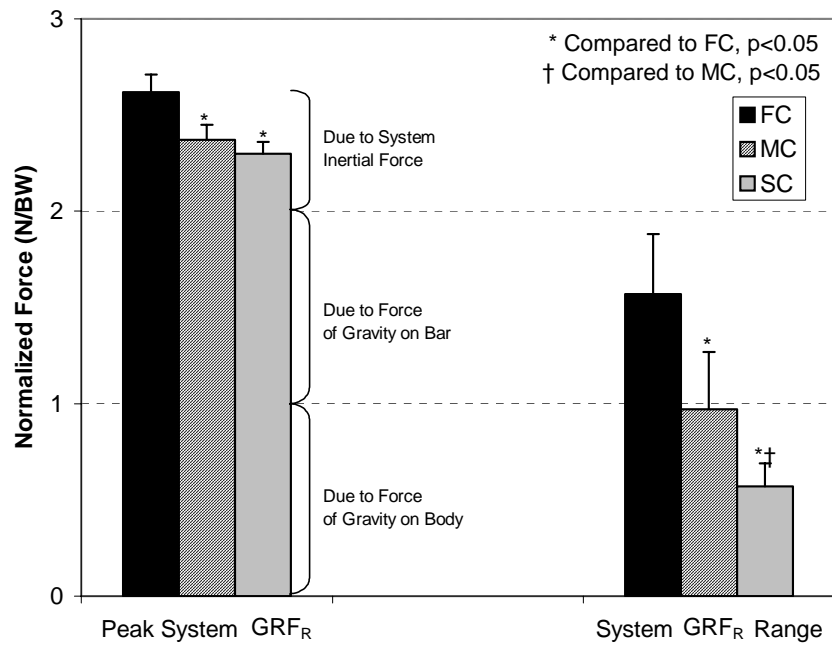
Figure 3:

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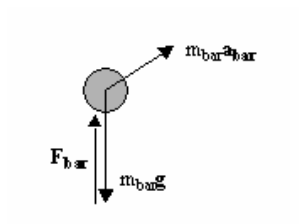
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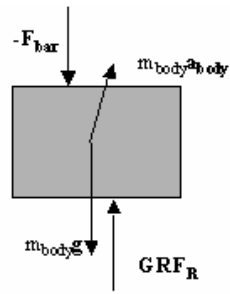
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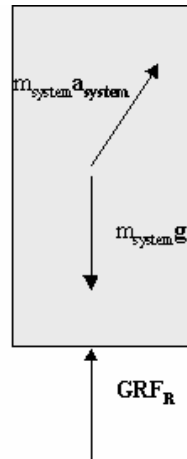
Table 1. Warm-up and testing protocol.

Set	Load	Repetitions
Warm-up	Unloaded	10
Warm-up	50% BW	8
Warm-up	75% BW	5
Warm-up	75-85% BW	3
Warm-up	85-100% BW	1
Set 1	100% BW	3
Set 2	100% BW	3
Set 3	100% BW	3

Table 2. Squat kinematic and temporal measures (mean ± SD) by cadence.

	Bar Displacement (cm)	Peak Knee Angle (deg)	Peak Hip Angle (deg)	Ascent Time (s)
FC	55.1 ± 5.5	104.1 ± 10.1	95.6 ± 10.0	1.03 ± 0.01
MC	55.6 ± 3.8	105.5 ± 6.6	100.3 ± 11.2	1.25 ± 0.14
SC	56.2 ± 3.7	103.6 ± 7.3	92.7 ± 15.1	1.84 ± 0.23 * †

* Compared to FC, $p < 0.05$
† Compared to MC, $p < 0.05$