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Comparison of Peak Ground Reaction Force, Joint Kinetics and Kinematics, and Muscle Activity Between a Flexible and Steel Barbell During the Back Squat Exercise

by
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The flexible barbell is purported to improve training gains compared with an Olympic steel barbell (SB) during the back squat exercise with Division I collegiate American football programs. The two bars loaded at 30% 1-repetition maximum were compared with ten trained Division I American football players (n = 10; age = 19.5 years; body mass = 89.4 kg; body height = 182.0 cm) completing 10 repetitions of the back squat exercise. Analysis included integrated-peak values of electromyography of the rectus femoris, biceps femoris, rectus abdominis, erector spinae, external oblique, vastus lateralis, ground reaction forces, and joint kinematics and kinetics of the hip, knee, and ankle. The flexible bar elicited significant increases in peak joint kinetics (Hip Moment: 229 ± 54 Nm vs. 209 ± 52 Nm; Hip Power: 494 ± 151 W vs. 382 ± 134 W; Knee Power: 305 ± 108 W vs. 241 ± 63 W), peak vertical ground reaction forces (1195 ± 209 N vs. 1120 ± 203 N), and muscle activity (Vastus Lateralis: 75.7 vs. 66.5%, Rectus Abdominis: 190 vs. 115%, Rectus Femoris: 69.8 vs. 59.9%, External Oblique: 115 vs. 69.0%). Greater vertical ground reaction forces, hip moment, hip power, knee power, and muscle activity of the vastus lateralis, rectus abdominis, rectus femoris, and external oblique suggest the FB provides biomechanical and physiological mechanisms for training gains over the SB for 30% of 1-repetition maximum loads.

Key words: *biomechanics, electromyography, joint power.*

Introduction

To improve performance on the field, Division I Collegiate American football programs include athletic conditioning exercises to develop strength, power, and speed (Kellis et al., 2005; Rahmani et al., 2001; Wallace et al., 2006; Walshe et al., 1998). Based on the American College of Sports Medicine position paper for development of strength and power during the back squat exercise (American College of Sports Medicine, 2009), explosive movements with lighter loads should be incorporated into workout routines to enable increased accelerations and lifting velocities.

Power is the product of both force and velocity, and correlates with increases in athletic performances (Cronin and Sleivert, 2005; Haff et al., 2001; Kawamori and Haff, 2004; Maszczyk et al., 2016; Newton and Kraemer, 1994). Practitioners should appreciate the development of both strength and performance specific velocities, which are dictated by biomechanical principles. One such a principle is from the Newton's second law, which states that the net force is proportional to the product of mass and acceleration. Fundamentally for a given mass, if the acceleration is increased, the resulting force

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will also increase. During constant weight resistance with an Olympic steel bar (SB), the largest accelerations tend to occur at the reversal point between eccentric and concentric portions of the lift due to the large changes in velocity in a very short time period (Frost et al., 2010). Applying this law, traditional constant weight resistance with an SB must always be accelerated from a resting position, which may limit the maximum velocity attained for any given repetition (Elliott et al., 1989; Newton et al., 1996). Vice versa, if the lift specifically focuses on maximum force to elicit increased motor unit recruitment, maximal velocity is compromised.

In an effort to develop power by increasing explosive movements with lighter lifting loads (American College of Sports Medicine, 2009), a flexible barbell (FB) has been designed to increase lifting velocities and accelerations at 30% 1-Repetition Maximum (1RM), while also increasing the effective resistance felt by the subject. To accomplish this, theoretically the upward and downward bend of the FB would provide a larger displacement of the loaded weights during a multi-repetition lift. Larger displacements of the loaded weights for a given time would require increased velocities, which in turn, would increase accelerations. Again, based on the Newton's second law, this would require a larger force to reverse the direction of the bar for these lifts. To resist these larger forces also would hypothetically require an increase in muscle tension across joints responsible for raising and lowering the bar (Elliott et al., 1989; Frost et al., 2010). The manufacturer suggests this maximal displacement occurs close to 30% 1RM, which was the rational for using this load for the comparison between the FB and SB and has been used for other studies focused on maximal power for the squat exercise (Golas et al., 2016, 2017; Jandacka et al., 2014; McBride et al., 2002, 2011).

In this study, we hypothesized that during a back squat exercise, an FB lifted at the same rate as an SB would allow for greater maximal values of velocities and accelerations of the subject as well as elicit greater maximal vertical ground reaction forces (GRFs), motor unit recruitment (I-EMG) for the involved muscles, joint moments (Mhip, Mknee, Mankle), and joint powers (Phip, Pknee, Pankle) for the lower extremity. The purpose of this study was to compare the FB to the SB for a multi-repetition back squat exercise in order to provide biomechanical and physiological differences between the bars to aid and inform strength and conditioning programs.

Methods

Participants

Ten male NCAA Division I freshman football players (age = 19.5 ± 1.4 yrs., body mass = 89.4 ± 17.1 kg, body height = 182.0 ± 7.4 cm), who had been familiarized and trained with both the SB and FB under the supervision of a certified FB trainer, volunteered to participate in the study. All participants read and signed a written informed consent form previously approved by the Furman University Human Subjects Review Board.

Procedures

In addition to previous training with the FB and SB, each participant attended a familiarization trial in order for the players to become proficient at moving both the FB and SB in time with a metronome set to 52 repetitions per minute based on FB manufacturer recommendations. For the familiarization trials, the bars were loaded with 30% of their approximate 1RM with a SB. A 3-D 8-camera motion capture system (ProReflex MCU 240, Qualisys Track Manager, Qualisys, Gothenburg, Sweden) was used to ensure consistent squat depth based on seventh cervical vertebrae spine (C7) marker height, as well as joint angle of the knee to greater than 80° at the bottom of the lift. Familiarization trials were repeated until the maximum and minimum of these measured variables for the FB were consistent with the SB. Once the participant was comfortable lifting the barbells at the required pace and consistent squat depth was ensured between the bars, he was allowed a 5-min rest period. Before electrodes were placed on the skin, excess hair was removed with a razor and the skin was cleaned and abraded using an alcohol swab. EMG silver/silver chloride pre-gelled surface electrodes (BIOPAC product #504, BIOPAC systems, Inc. Goleta, CA) were then placed on six major muscles: the rectus femoris (RF), biceps femoris (BF), rectus abdominis (RA), erector spinae (ES), external oblique (EO), and vastus lateralis (VL). The

SENIAM protocol (Hermens et al., 1999) was followed for the muscle groups BF, ES, RF and VL as well as similar validated methods (Ng et al., 2001, 2002a, 2002b1) for muscle groups of the trunk not listed under the SENIAM methods. Electrodes were placed along the axes of the muscle fibers: VL at 2/3 of the distance between the anterior spine iliac and the superior aspect of the lateral side of the patella; RF at 50% on the line from the anterior spine iliac to the superior part of patella; RA at 1 cm above the umbilicus and 2 cm lateral to the midline; EO at just below the rib cage and along a line connecting the most inferior point of the costal margin and the contralateral pubic tubercle; ES at 1 cm medial from the line from the posterior spine iliac superior to the lowest point of the lower rib at the level of L2; and BF at 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia. For each muscle, ground electrodes were placed on a bony surface such as the patella, iliac crest, manubrium, and clavicle. The participant then performed a 1-repetition maximum (1RM) with the SB to normalize EMG activity and establish loading for the following lifts based on slightly modified established protocols previously described (Hermens et al., 1999; Stone and O'Bryant, 1987) where a 30% load of the estimated 1RM was additionally used for 8-10 repetitions during the warm-up.

After a minimum of 5 min rest (Martorelli et al., 2015), 30% of the participant's 1RM (Kraemer and Ratamess, 2004) was loaded onto either the FB or SB, which was randomly assigned. The bar was placed across the shoulders below the seventh cervical spine vertebral, and the athlete then performed ten repetitions in time with the metronome at the prescribed rate, which has been shown as a valid method for controlling lifting velocity (Moras et al., 2009). On the second beat of the metronome corresponding to the top position, the participant was instructed to oppose the upward momentum of the bar, pulling it down into the original starting position. Once the participant completed that set with a minimum of 5 min rest (Martorelli et al., 2015), he performed another set of ten repetitions on the whichever barbell he had not previously used. The sets were not performed to failure in order to avoid fatigue as a variable for the comparison between the SB and FB. The different experimental conditions were randomly assigned based on the bar type (FB or SB).

Data Acquisition and Processing

In all trials, the EMG surface electrodes were connected to a wireless transmitter and continuously streamed through to an analog to digital converter (BIOPAC systems, Inc. Goleta, CA) connected to a Windows-based PC. Using methods described by Winter (2009), all EMG data were collected at 1000 Hz with a 10-500 Hz band pass 2nd order Butterworth filter. The EMG data were normalized to a peak voltage from a 1000 millisecond window of the 1RM SQ so that values for each contraction were represented as %MVC. For the 30% 1RM load trials (Kraemer and Ratamess, 2004), the EMG signal was full-wave rectified, and the peak was taken from the integration of each muscle contraction. To provide an average value of the peak integrated EMG (I-EMG), the first and last repetition were excluded and then the mean from the remaining peaks of the integrated muscle contractions was calculated.

To collect kinetic and kinematic subject data, vertical GRFs were recorded through the force plate (AMTI LG6-4-200, Advanced Mechanical Technology, Inc., Watertown, MA) embedded in the floor, collected at a sampling rate of 2,000 Hz. The force plate data were zeroed to minimize GRF variability and then collected for the entire duration of the trial. The joint position, velocity, acceleration, moment and power were calculated from a 6-degree of freedom retro reflective marker set placed on the participant's lower extremity and pelvis defining 7 segments including bilateral foot, shank, thigh, and single pelvis. For the lower extremity, markers were placed on the bilateral shoe above the first, second, and fifth metatarsal heads of the foot, on the posterior and lateral aspect of the heel, the medial and lateral malleolus, the medial and lateral femoral epicondyles, and on the greater trochanter of the femur. Lightweight, rigid plates holding four tracking markers (Selbie et al., 2014) were attached to the shank and the thigh. In addition, bilateral markers were placed on the anterior superior iliac spines, posterior superior iliac spines, iliac crest, C7, as well as markers on each bar end. Data from an 8-camera motion camera system (ProReflex MCU 240, Qualisys, Gothenburg, Sweden) were collected at 240 Hz via a Qualisys Track Manager (Qualisys, Gothenburg, Sweden).

Synchronized marker and force plate data were processed by Visual 3d software (C-Motion Inc., Germantown, MD, USA). The lower extremity segments were modeled as a frustrum of right circular cones, while the pelvis was modeled as a cylinder. A fourth order, low-pass filter with a 12 Hz cut-off frequency was used to filter coordinate and force data (Yu et al., 1999). The hip, knee, and ankle moments in the sagittal plane were expressed in the proximal local coordinate system and calculated using a Newton-Euler inverse dynamics technique (Selbie et al., 2014). Joint powers were calculated by the product of the joint moment and joint angular velocity. Positive powers indicated energy generation through concentric contractions and vice versa. The portion of motion generating positive powers was analyzed for the squat exercise.

Statistical Analysis

Comparisons were made between the SB and FB for the maximum joint angle, velocity, acceleration, moment, and power of the ankle, knee, and hip, as well as vertical GRFs and the I-EMG using paired sampled t-tests with alpha set at .05. The data were analyzed using SPSS statistical software (Version 21.0, IBM Corp., Armonk, NY, USA) with significance reported in the tables below (Tables 1 and 2). The Shapiro-Wilk test indicated that data were normally distributed. Within-set reliability for each participant was assessed by the coefficient of variation (CV) for maximum and minimum joint angles as well as maximum vertical ground reaction forces per repetition. CVs for all variable sets for all participants ranged from 1 to 5%.

Results

There were no significant differences between the FB and SB for the maximum height, minimum height, and ROM of C7, as well as maximum flexion angles and ROM, at the ankle, knee and hip. The FB elicited significantly higher maximum height, ROM, velocity, and acceleration for the bar ends, as well as significantly lower bar end height. C7 and the knee also had larger maximum velocities and accelerations for the FB. Additionally, there was higher maximum Mhip and maximum Phip and Pknee. There were no significant kinematic or kinetic differences seen at the ankle (Tables 1 and 2). There were also significantly greater peak vertical GRFs and I-EMG for the VL, RA, RF, and EO for the FB, while the BF and ES showed no significant differences (Tables 2 and 3).

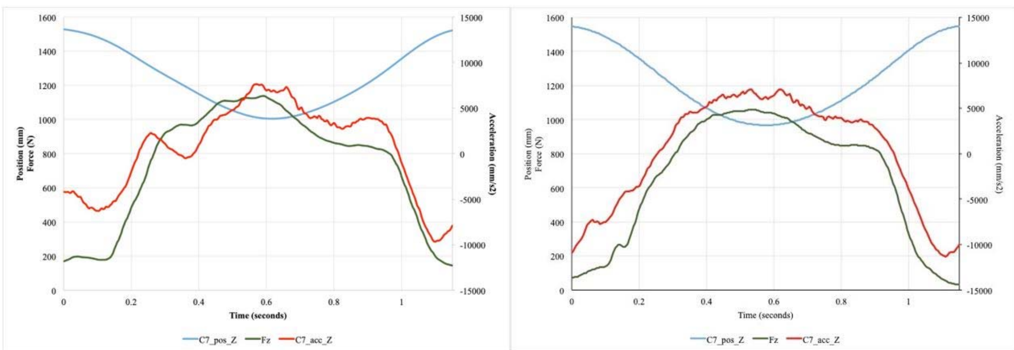

Figure 1

Comparisons of vertical components of ground reaction force (Fz), acceleration of the C7 marker (C7_acc_z), and position of the C7 marker (C7_pos_Z) versus time for one typical repetition of a representative subject for both the flexible bar (Left) and steel bar (Right).

Table 1

Peak Kinematic Values of the Bar Ends (BE) and C7 Marker on the participant during the Back Squat Exercise for the Steel Bar (SB) and Flexible Bar (FB). Mean ± SD. (Cohen's D Effect Size listed for significantly different values).

Kinematic Variable	SB	FB
C7 Maximum Height (mm)	1540 ± 75	1565 ± 77
C7 Minimum Height (mm)	987 ± 53	986 ± 94
C7 ROM (mm)	553 ± 46	578 ± 106
C7 Maximum Velocity (mm/s)	1533 ± 204	1717 ± 158 (1.0)*
C7 Maximum Acceleration (mm/s^2)	7949 ± 1065	10182 ± 1259 (1.9)*
Bar End Maximum Height (mm)	1500 ± 76	1623 ± 100 (1.4)*
Bar End Minimum Height (mm)	924 ± 74	814 ± 97 (1.3)*
Bar End ROM	575 ± 92	808 ± 121 (2.2)*
Bar End Maximum Velocity (mm/s)	1523 ± 197	1991 ± 331 (1.7)*
Bar End Maximum Acceleration (mm/s^2)	7668 ± 1118	11583 ± 1987 (2.4)*

**signifies significantly higher value at $p < 0.05$*

Table 2

Comparison between the Flexible Bar and Steel Bar of Peak Kinetic and Kinematic Values during the Concentric Phase of the Back Squat Exercise defined from the minimum to maximum C7 position each repetition. Mean ± SD. (Cohen's D Effect Size listed for significantly different values).

Peak Kinetic or Kinematic Variable	SB	FB
Vertical Ground Reaction Force (N)	1077 ± 210	1144 ± 213 (.32)*
Hip		
Maximum Flexion Angle (deg)	92 ± 11	91 ± 10
Maximum Angular Velocity (deg/s)	355 ± 75	380 ± 70
Maximum Angular Acceleration (deg/s^2)	37518 ± 12665	38401 ± 11367
Maximum Moment (N·m)	324 ± 52	381 ± 94 (.75)*
Maximum Power (W)	1024 ± 213	1387 ± 429 (1.1)*
Knee		
Maximum Flexion Angle (deg)	89 ± 8	87 ± 8
Maximum Angular Velocity (deg/s)	328 ± 27	353 ± 24 (.96)*
Maximum Angular Acceleration (deg/s^2)	18535 ± 2714	21024 ± 3116 (.85)*
Maximum Moment (N·m)	157 ± 34	170 ± 51
Maximum Power (W)	401 ± 84	499 ± 166 (.74)*
Ankle		
Maximum Flexion Angle (deg)	88 ± 8	86 ± 6
Maximum Angular Velocity (deg/s)	237 ± 83	256 ± 84
Maximum Angular Acceleration (deg/s^2)	22698 ± 8852	24107 ± 6845
Maximum Moment (N·m)	90 ± 24	93 ± 26
Maximum Power (W)	157 ± 94	185 ± 94

**signifies significantly higher value at $p<0.05$*

Table 3

Comparison between the steel bar and flexible bar for mean peak ground reaction forces (GRFs) and mean peak integrated electromyographic (I-EMG) response during the squat exercise.

I-EMG	Steel Bar (%MVC)	Flexible Bar (%MVC)	*p*
VL	67 ± 16	76 ± 19*	0.03
BF	52 ± 34	58 ± 45	0.468
RA	115 ± 54	190 ± 115*	0.03
ES	66 ± 30	71 ± 29	0.07
RF	60 ± 18	70 ± 17*	0.013
EO	69 ± 30	115 ± 53*	0.0004

** signifies statistically significantly higher values at stated p-values.*
I-EMG: %MVC of squat 1RM, mean ± SD for the Vastus Lateralis (VL), Biceps Femoris (BF), Rectus Abdominus (RA), Erector Spinae (ES), Rectus Femoris (RF

Discussion

Despite anecdotal evidence from the manufacturer (Abernethy and Brown, 2016) supporting performance gains for Division I football programs training with an FB, studies have not been conducted to support such claims. With the adoption of FBs in these programs, it is important to assess how the FB may potentially hinder or promote these physiological adaptations based on biomechanical mechanisms. The results of this study provide insight into these phenomena by partially confirming the hypotheses that the increased bar end weight displacements for a given time required increased velocities for the same time, and hence accelerations. The participants were required to resist these accelerations to maintain the prescribed lifting cadence, which resulted in larger vertical GRFs and hence joint kinetics, including joint powers and motor unit activity based on the Henneman's size principle (Henneman, 1957). Specifically, the supporting results include: the FB solicited greater 1) bar end ROM, maximum velocities, and maximum accelerations, 2) C7 maximum velocities and maximum accelerations, 3) peak knee joint velocities and joint accelerations, 4) peak vertical GRFs, 5) peak Mhip, Phip, Pknee, and 6) I-EMG activity for the VL, RA, RF, and EO. Of note, in this paper all of the preceding results were reported with no significant differences in peak joint angles of the ankle, knee, and hip between the SB and FB, as well as C7 Maximum Height, C7 Minimum Height and C7 ROM (Table 1) (Moras et al., 2009). The only potential alteration in the movement pattern would be regarding the velocities and accelerations, not the linear or angular ROM for the joints or C7 marker. The absolute ROM of marker C7 was not significantly different between the SB and FB, while the maximum velocity was significantly higher for the FB. The same pattern is true for the knee. The angular ROM for the knee was not significantly different between the SB and FB, while the maximum angular velocity was significantly higher for the FB. This would mean that these maximum velocities of C7 and maximum angular velocity of the knee would occur midway through the range of motion. As can be seen in Figure 1, the pattern does not indicate a shifting in the timing of the lift, but does show increases in the peak acceleration of C7 (C7_acc_z) as well as the vertical ground reaction force (Fz).

However, contrary to our predictions, increases were not seen in I-EMG for the BF and ES, Mknee, Mankle, and Pankle, as well as joint velocities and joint accelerations at the hip and ankle. This may be explained in part by Jandacka and colleagues (2014) who demonstrated that while maximum system power for a squat exercise occurred at 30% 1RM, it is not physiologically possible to optimize muscle shortening contracting velocity to maximize power for all muscles during a multi-joint exercise (Wakeling et al., 2010). Although it is recommended to be lifted for 30% 1RM and 52 repetitions per minute by the manufacturer, a limitation to the design of the bar is that it might not be used to elicit maximal power at each individual joint because of differing characteristics at other barbell loading percentages and lifting cadences. Also, the FB is designed based on an absolute load, which would have limitations based on relative 30% 1RM loading of populations with substantially higher or lower loads than seen in this group. Since these subjects had only been familiarized at these loading percentages, lack of safely familiarizing the subjects at these other various cadences and loads limited testing these additional hypotheses at this time.

To our knowledge, these results have not been previously reported in the literature and any other findings in the literature on the FB are sparse at best. For example, Bryce and colleagues (Bryce et al., 2015) reported no differences between the FB and SB in terms of peak force production for a single-repetition bench press for loads corresponding to between 40 and 80% of a self-reported 1RM. The single repetition included eccentric and concentric phases, in that order, moving the bar as quickly as possible. Their hypothesis, however, did not focus on multi-repetition motion nor did they measure bar end displacement, which points to a key difference in lifting characteristics between the FB and SB in this study.

A single-repetition lift begins in a fully extended, static position with the FB already downwardly bent due to the weight of the loaded plates. Next, there is only one change in direction, and hence change in velocity, between the eccentric and concentric phase occurring at the bottom of the lift. Alternatively, a multi-repetition lift has an additional concentric to eccentric velocity reversal at the top of the lift. This allows for the FB to bend up and down, increasing the total displacement of the loaded plates on the bar. When the FB flexes upward during multi-repetition lifts, increased stored elastic potential energy of the bar in the upward position could increase the downward velocity during the eccentric phase. An increase in downward eccentric velocity has been shown to accentuate the stretch-shortening cycle by eliciting more muscle tension and result in an increased peak GRF during the following concentric phases (Cronin and Mcnair, 2003; Bosco et al., 1982; Stevenson et al., 2010; Wilson et al., 1991). This would explain the results in this study of increased agonist muscle activity of the VL, peak GRF, Pknee, Phip, and Mhip. Interestingly, these results point to the increase in Pknee and relate it to the increase in joint angular velocity at the knee as opposed to Phip increasing due to the increase in Mhip (Cronin et al., 2001; Cronin and Mcnair, 2003; Frost et al., 2010). The increase in the muscle activity of the RA, EO may be explained by increased trunk muscle activity with unstable squat movements as found by Anderson and Behm (2005). Familiarization to the bar motion may limit the increases in trunk muscle activity as subjects become more accustomed to the motion of the FB. The calculated moments at the knee were similar to other studies in which subjects performed back squats to parallel (Fry et al., 2003; Wretenberg et al., 1996). They reported moments ranging from 150.1 to 191 Nm, which our results fall within that range. Likewise, our SB data were a similar match for hip moments, but as indicated by our data, the FB was higher than the steel bar results in the studies mentioned (Fry et al., 2003; Wretenberg et al., 1996).

Additional variations in FB experimental protocols should include additional lifts, various lifting rates, and percentages of maximum loading to see if the same trends hold true. Thus, FB configurations of differing bar properties, weight placement on the bar, and/or different lifting frequencies may be reasons for accentuating or hindering acute increases in motor unit activity, ground reaction forces, and angular joint kinetics. Likewise, longitudinal studies for gains in strength, power and performance need to be conducted to validate claims of long-term physiological adaptations.

Conclusions

In conclusion, fitness and strength coaching professionals using the back squat to work with Division I American football athletes may incorporate the flexible bar for increases in GRFs and motor unit activation during the back squat due to the significant increases in peak integrated vastus lateralis, rectus femoris, rectus abdominis, and external oblique activity, but only for this configuration of the loading percentage, lift, specific FB, and lifting cadence. Familiarization is suggested to prepare athletes for this inherent additional motion of the loaded plates on the FB and to limit any safety concerns. Findings in this research study apply for this protocol for the back squat exercise. The results of this study provide biomechanical and physiological mechanisms for future longitudinal training studies using the FB as well as comparisons with other model FBs that may be useful at additional loading patterns other than 30% 1RM.

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