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Full Title: A biomechanical analysis of straight and hexagonal barbell deadlifts using submaximal loads

Short title: Exercise variation using distinct barbells

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ABSTRACT + KEY WORDS

The purpose of the investigation was to compare the kinematics and kinetics of the deadlift performed with two distinct barbells across a range of submaximal loads. Nineteen male powerlifters performed the deadlift with a conventional straight barbell and a hexagonal barbell that allowed the lifter to stand within its frame. Subjects performed trials at maximum speed with loads of 10, 20, 30, 40, 50, 60, 70 and 80% of their predetermined one-repetition maximum (1RM). Inverse dynamics and spatial tracking of the external resistance were used to quantify kinematic and kinetic variables. Subjects were able to lift a heavier 1RM load in the hexagonal barbell deadlift (HBD) than the straight barbell deadlift (SBD) (265 ± 41 kg vs. 245 ± 39 kg, $p < 0.05$). The design of the hexagonal barbell significantly altered the resistance moment at the joints analyzed ($p < 0.05$), resulting in lower peak moments at the lumbar spine, hip and ankle ($p < 0.05$), and an increased peak moment at the knee ($p < 0.05$). Maximum peak power values of 4388 ± 713 W and 4872 ± 636 W were obtained for the SBD and HBD respectively ($p < 0.05$). Across the submaximal loads significantly greater peak force, peak velocity and peak power values were produced during the HBD compared to the SBD ($p < 0.05$). The results demonstrate that the choice of barbell used to perform the deadlift has a significant effect on a range of kinematic and kinetic variables. The enhanced mechanical stimulus obtained with the hexagonal barbell suggests that in general the HBD is a more effective exercise than the SBD.

Key Words: RESISTANCE TRAINING, POWER, VELOCITY, FORCE, KINETICS, KINEMATICS

INTRODUCTION

The deadlift is a multi-joint resistance exercise that is performed in a variety of training settings. The exercise requires the lifter to grasp a barbell at mid-shank level in a squat position and elevate the load by extending the lower back, hip, knee and ankle joints. Analysis of powerlifting and Olympic weightlifting records show that trained individuals lift heavier loads in the deadlift compared with other free-weight exercises (1, 18). The deadlift is most frequently used to develop maximum strength based on the hypothesis that heavy loads lifted will generate large muscular forces and stimulate adaptation. A number of studies have quantified biomechanical variables during the deadlift (4, 5, 9, 15, 24). Results have confirmed that large muscular moments can be produced with the greatest values recorded at the hip, followed by the lumbar spine, ankle and knee (4, 5). In combination with large muscular moments studies have reported substantial internal forces when the deadlift is performed with heavy loads (4, 5, 15). Brown and Abani (3) reported net joint forces ranging from approximately 1450 N to 1550 N at the hip, knee and ankle joints for adolescent powerlifters during competition. The authors noted that competitors who lifted the heaviest loads experienced the greatest internal forces (4). Studies that have included linked segment models designed to estimate forces at the lumbar spine have reported extremely large disk compression forces during the deadlift. Cholewicki et al. (5) recorded L4/L5 disk compression forces ranging from 14350 N to 17192 N for male and female powerlifters during a national-level competition. For world-class athletes lifting extremely heavy loads lumbar disk compression forces as large as 36400 N have been reported (15). As a consequence of the very large internal forces and moments imposed during the deadlift the potential for injury exists (5, 15).

To minimize the likelihood of sustaining an injury during the deadlift athletes are instructed to position the barbell close to the body throughout the movement (14). Maintaining the barbell in close proximity to the body decreases the overall resistance of the external load by reducing the moment arm at the individual joints. When performing the deadlift with a conventional straight barbell the moment arm of the external resistance can be reduced up to the point where the barbell impinges on the body. To overcome this restriction and further reduce the resistance moment arm a non-conventional barbell was created. The premise of the barbell was to enable the athlete to position the load closer to the joints by creating a frame that the athlete could lift within (Fig.1). Originally the barbell was trapezoidal in shape and commonly referred to as the trap bar (13). In subsequent years the shape of the barbell was altered from trapezoidal to hexagonal to provide greater stability and space (27). The hexagonal barbell is now a standard resistance training implement used widely in the strength and conditioning training of athletes, and is most commonly used to provide a variation of the deadlift exercise (27). It has been theorised that performing the deadlift with the hexagonal barbell reduces lumbar stress (13, 27). The theory is based on the assertion that the hexagonal barbell enables the lifter to adopt a more upright lifting posture and reduce the resistance moment arm at the lumbar spine. To our knowledge there have been no published reports of the kinematics and kinetics of the deadlift performed with the hexagonal barbell or empirical data supporting the theory. Information regarding potential differences in the kinematics and kinetics of deadlift variations would be of practical significance to coaches in their exercise selection.

Recent information suggests that powerlifters use the deadlift as a means of developing muscular power as well as maximum strength (30). It is generally believed that the most effective exercises for developing muscular power enable production of the greatest power outputs (21). A limited number of studies that have quantified biomechanical variables during the deadlift have measured power. Garhammer (12) calculated that elite powerlifters produced approximately 12 W per kilogram of body mass over the concentric phase of the movement. In a study comparing power production during Olympic weightlifting and powerlifting exercises, Garhammer and McLaughlin (11) reported that average power produced in the deadlift was one half to one third that developed during the snatch or clean. The lower power produced during the deadlift was attributed to low vertical velocities generated throughout the movement (12). Previous studies that have measured power during the deadlift have been restricted to maximum loads only. In contrast, research has shown for multi-joint resistance exercises that power is maximized when lifting loads of 30 to 60% 1RM (10, 19, 28, 34). As the deadlift enables large forces to be developed and power is the product of force and velocity, it is possible that submaximal loads similar to those used in previous studies can produce large power outputs. Information regarding power production of the deadlift across submaximal loads will assist coaches and athletes in their exercise and load selection for training programs aimed at developing muscular power.

The purposes of this study were, firstly, to compare the kinematics and kinetics of the deadlift exercise performed with the straight and hexagonal barbell, and secondly, to quantify the power produced during the deadlift variations with submaximal loads. It was hypothesized that the design of the hexagonal barbell would decrease the resistance moment arm and subsequently reduce joint moments. It was further hypothesised that a selection of submaximal loads would enable large power values to be developed during the deadlift variations.

METHODS

Experimental Approach to the Problem. A cross-sectional, repeated measures design was used to quantify and compare kinematics and kinetics of the deadlift exercise using two distinct barbells. Joint moments were calculated to investigate whether the choice of barbell had an effect on the muscular effort and internal stresses developed when lifting a given load. External kinematics and kinetics (e.g. vertical ground reaction force, velocity and power) were calculated across a range of submaximal loads to investigate whether the deadlift could be used to obtain a biomechanical stimulus effective for developing muscular power. Data were collected for each subject over two sessions separated by one week. The first session was performed in the gymnasium and involved one-repetition maximum (1RM) testing in the straight barbell deadlift (SBD) and the hexagonal barbell deadlift (HBD). During the second session subjects reported to the laboratory where they performed the SBD and HBD across loads of 10 to 80% of their predetermined SBD 1RM. Kinematics and kinetics were analysed in the second session only.

Subjects. Nineteen male powerlifters participated in the study (age: 30.2 ± 5.6 yr; stature: 181.5 ± 4.8 cm; mass: 114.5 ± 22.3 kg; SBD 1RM: 244.5 ± 39.5 kg; HBD 1RM: 265.0 ± 41.8 kg; resistance training experience: 13.7 ± 5.2 yr). Subjects were recruited from the Scottish Powerlifting Association and were active competitors at the time of data collection. Based on the powerlifters most recent competition results the average Wilks score of the group was 403.6 ± 39.1 (31). The study was conducted three months after a regional competition where the majority of subjects were nearing the end of a training cycle aimed at matching or exceeding their previous competition performance. All subjects were notified about the potential risks involved and gave their written informed consent, approved by the ethical review panel at Robert Gordon University, Aberdeen, UK.

Procedures.

1RM Testing. Subjects were competitive powerlifters who were experienced in performing 1RM tests and could predict their maximum strength accurately. Based on a predicted 1RM load subjects performed a series of warm-up sets and up to 5 maximal attempts. Two to 4 minute rest periods were provided between maximal attempts with the heaviest load lifted selected for analysis. Deadlifts were performed with a conventional shoulder width stance and deemed to be successful if the barbell was not lowered at any point during the ascent and upon completion of the movement the body posture was erect, the knees were straightened and shoulders retracted. 1RM testing for the SBD and HBD were performed in a randomized order with a 30 minute rest period allocated for recovery between exercises.

Submaximal Testing. Subjects performed their own specific warm-up which generally consisted of 2 to 4 SBD and HBD sets with a light load (e.g., < 40% 1RM) for 6 to 10 repetitions. Once suitably prepared, subjects performed SBD and HBD trials with 10, 20, 30, 40, 50, 60, 70 and 80% of his SBD 1RM in a randomized order. Two repetitions were performed in each trial to assess reliability. Subjects were instructed to perform each repetition with maximal effort attempting to lift the load as fast as possible. A minimum 2 minute rest period was allocated between trials with a longer rest period made available if the subject felt it necessary to produce maximum performance (34). Actual loads lifted were within ± 1 kg of the calculated load. Subjects were instructed to keep their elbows straight throughout the lift and not to jump with the weight. If these requirements were not met the trial was repeated. Subjects were permitted to elevate their heels at the terminal stage of the movement as long as the forefoot remained in contact with the ground. For each trial the repetition that produced the greatest peak power was selected for further analysis.

All testing was completed between the hours of 17:00 and 20:00 to correspond with the powerlifters' regular training times. Subjects followed their individual nutritional practices used prior to training sessions. Consumption of water (500 ml) was permitted during tests. Room temperature was maintained between 22 and 25° C.

Biomechanical Instrumentation. Twelve markers were placed on the following bony landmarks: spinous process of the 7th cervical vertebrae, spinous process of the 10th cervical vertebrae, suprasternal notch, inferior tip of the xiphoid process, left and right anterior superior iliac spine, left and right lateral femoral epicondycle, left and right lateral malleolus, and left and right head of the 2nd metatarsal. Additionally, markers were placed on the sacrum midway between the posterior superior iliac spines and bilaterally at midtibia, midfemur and the calcaneous. The geometric centre of the external load was tracked in three-dimensional space by placing markers at the ends of the barbell and calculating the position of the midpoint. Trials were performed with a separate piezoelectric force platform (Kistler, Type 9281B Kistler Instruments, Winterthur, Switzerland) under each foot, in a capture area defined by a seven-camera motion analysis system (Vicon MX, Vicon Motion Systems, Oxford, UK). Marker position and ground reaction force data were captured at 200 and 1200Hz respectively.

Biomechanical Analyses. Based on a frequency content analysis of the three-dimensional coordinate data, marker trajectories were filtered using a digital fourth-order low-pass Butterworth filter with a cut-off frequency of 8 Hz (23). A three-dimensional lower body model (20) and upper body model (16) were used to calculate joint positions and angles of the torso, hip, knee and ankle, as well as the position of the 5th lumbar vertebrae. Instantaneous velocities and accelerations were calculated by numerical differentiation of the position data (17). Joint moments were calculated using inverse dynamics and anthropometric data with Vicon Nexus 1.4.115 processing software (Oxford Metrics, Oxford, UK) (16). Kinematic and kinetic measures for the hip, knee and ankle were calculated for both left and right sides and averaged to obtain single values. The starting point for each trial was defined as the point where the estimated geometric centre of the barbell was raised 2 mm vertically above its initial resting position. The end of each trial was defined as the point where the estimated geometric centre of the barbell reached maximum vertical elevation. Instantaneous power values were calculated as the product of the vertical ground reaction force and corresponding barbell vertical velocity (6, 34). The moment arm of the resistance was found by calculating the horizontal distance from the geometric centre of the barbell to the joint centres.

Statistical Analyses. intraclass correlation coefficients (ICC's) were calculated to assess intra-trial reliability. ICC's were calculated with a correction factor for number of trials administered (n=2) and number of trials used in the criterion score (n=1) (2). A 2-way repeated measures ANOVA (2 barbell type x 8 load) was used to evaluate differences in kinematic and kinetic variables between deadlift variations and across loads. Bonferroni pairwise comparisons were used as a post hoc analysis if significant differences were found ($p < 0.05$). Effect sizes were determined by partial eta squared (η_P^2) which was calculated as the ratio of the variation accounted for by an individual independent variable to the sum of the variation accounted for by the model as a whole. All statistical procedures were performed using the SPSS software package (SPSS, Version 15.0, SPSS Inc., Chicago, IL).

RESULTS

Intra-trial reliability for peak force, peak velocity, peak power, joint angle, peak net joint moment, relative time of acceleration and resistance moment arm magnitude were all high (ICC = 0.96, 0.87, 0.93, 0.97, 0.93, 0.93, and 0.88), respectively.

No main effects of load were found for the orientation of the torso, hip, knee or ankle at the start of the concentric phase of the deadlift movement. Therefore, joint angles for the SBD and HBD were averaged across loads and are presented in Table 1. The pattern of movement at each joint was assessed by measuring joint angles over 10% intervals of the vertical barbell displacement. Statistical analyses revealed no main effects of load for angles generated at the torso, hip or knee during the deadlift movement. A significant main effect of load was obtained for the ankle joint (p <0.05, $\eta_P^2 = 0.87$). The results showed that as load increased the maximum amount of ankle plantar flexion achieved at the conclusion of the concentric phase decreased.

Analyses of deadlift variation revealed significant main effects for peak moments obtained at the lumbar spine ($p < 0.05$, $\eta_P^2 = 0.53$), hip ($p < 0.05$, $\eta_P^2 = 0.43$) and knee ($p < 0.05$, $\eta_P^2 =$ 0.85) (Table 2). Performing the deadlift with the hexagonal barbell significantly increased the peak moment at the knee and significantly decreased the peak moment at the lumbar spine and hip compared to the deadlifts performed with the straight barbell. The effect of deadlift variation on peak moments was explained by the barbell path associated with each variation (Fig. 2) and the corresponding resistance moment arm at the individual joints (Table 3).

Each of the powerlifters that participated in the study lifted a heavier 1RM load in the HBD than the SBD resulting in an overall significant difference (265.0 ± 41.8 kg vs. 244.5 ± 39.5

kg, p <0.05). Significant main effects of load and deadlift variation were obtained for peak force (p <0.05, $\eta_P^2 = 0.89$, p <0.05, $\eta_P^2 = 0.21$), peak velocity (p <0.05, $\eta_P^2 = 0.97$, p <0.05, $\eta_P^2 = 0.63$), and peak power (p <0.05, $\eta_P^2 = 0.87$, p <0.001, $\eta_P^2 = 0.70$) respectively (Fig. 3). Peak force and peak velocity were significantly ($p < 0.05$) different for each load of the SBD and HBD. No significant differences were found for peak power between loads of 10 to 40% 1RM for the SBD and 20 to 50% 1RM for the HBD. A significant main effect of load was obtained for the relative time spent accelerating the resistance (p <0.05, $\eta_P^2 = 0.93$) (Table 4).

DISCUSSION

The initial lifting posture the athletes adopted at the start of the SBD was similar to that reported in previous studies (9, 24). At the bottom of the movement the hip joint was flexed by the greatest amount, followed by the knee, torso and ankle (Table 1). The magnitude of the load had no effect on initial lifting posture or spatio-temporal extension pattern of the torso, hip and knee. The only joint affected by the magnitude of the load was the ankle. As the resistance increased from 10 to 80% 1RM the amount of plantar flexion during the final phase of the deadlift decreased from 37 to 3°. The consistent initial lifting posture and patterns of joint extension demonstrate that across a range of submaximal loads well-trained athletes employ a similar kinematic lifting strategy when the task objective is to complete the movement as fast as possible. Modifications to the lifting strategy during the final phase of the movement (via different amounts of ankle plantar flexion) are explained by distinct deceleration requirements across loads. Substantial joint velocities are developed when lifting the lightest loads and must be actively decelerated to avoid damaging hyperextension. By rapidly plantar flexing the ankle at the end of the deadlift, power can be transferred from the knee to the ankle through the action of the biarticular gastrocnemius contributing to an overall deceleration at the knee (32). In contrast, smaller joint velocities are developed with heavier loads and the large external resistance can be used to decelerate the body without the need to transfer power through plantar flexion of the ankle.

The choice of barbell selected to perform the deadlift had a significant effect on a range of kinematic and kinetic variables. At liftoff the resistance with the hexagonal barbell was positioned closer to the athletes as measured by the horizontal distance between the load and ankle joint centre. The different positioning of the load at the start of the exercise significantly affected the initial knee angle resulting in greater flexion with the HBD. Using the starting position of the load as a reference point, the hexagonal barbell reduced horizontal displacement away from the body by an average of 75% compared to the straight barbell (Fig. 2). For loads greater than 60% 1RM the hexagonal barbell increased displacement towards the body by an average of 22%. The change in positioning of the load due to the design of the hexagonal barbell significantly reduced the moment arm of the resistance at all joints across the loads (Table 3). As a result, peak moments developed at the lumbar spine, hip and ankle during the HBD were significantly lower than that developed during the SBD (Table 2). In contrast, the peak moment at the knee was significantly increased when performing the HBD. Larger peak moments occurred at the knee when using the hexagonal barbell despite reduction in the magnitude of the resistance moment arm. The effect was explained by the different direction of the resistance moment. During the SBD the load remained in front of the knee and created an extension moment that reduced the muscular effort required to extend the joint. During the HBD the load remained behind knee for the majority of the movement and created a flexor moment that increased the muscular effort and peak moment.

The ability to manipulate joint moments based on selection of the type of barbell provides relevant information for strength and conditioning coaches. The conventional deadlift performed with heavy loads is commonly viewed as the most challenging exercise for the lumbar spine (5). If the goal is to maximise recruitment of the erector spinae muscles and specifically target the lumbar area the results of this study suggest that the deadlift should be performed with the straight barbell. Strength and condition coaches searching for an alternative to the squat may find the deadlift performed with the hexagonal barbell to be an effective alternative. For individuals with a history of lower back pain or currently in the final stages of rehabilitation, performing the deadlift with the hexagonal barbell rather than the straight barbell may be a more prudent strategy to target the lumbar area whilst more evenly distributing the load between the joints of the body

Peak force, peak velocity and peak power values for both variations of the deadlift followed patterns reported previously for other multi-joint resistance training exercises (6, 10, 29, 34). At the lightest loads the resistance was overcome at high velocities and due to the force-velocity relationship of concentric muscle actions relatively low forces were produced (7). As the load increased, velocity progressively declined and enabled greater force to be developed. The peak ground reaction force in the current investigation ranged from 2259 to 3395 N across the submaximal loads. Comparable peak forces have been reported for well trained athletes performing the squat with similar loads (6, 26). Rahamani et al. (26) reported peak forces of 2674 to 3520N for a group of resistance trained international alpine skiing racers. Cormie et al. (6) reported peak forces of approximately 1700 to 2800 N for Division I male athletes. The slightly lower peak forces reported by Cormie et al. (6) may reflect the smaller absolute loads lifted in comparison to those used by the powerlifters in the current investigation.

Previous studies that have quantified velocity and power during the deadlift have reported relatively low values (9, 11). Escamilla et al. (9) reported that it took elite powerlifters over four seconds to complete the concentric phase of the deadlift and that peak velocity was only 0.2 $m \cdot s^{-1}$. The small velocities developed have been acknowledged as the reason why power produced during the deadlift has been reported to be one half to one third that produced during the snatch or clean (12). However, previous studies that have reported velocity and power values for the deadlift have done so with maximum loads only. The current study shows that the deadlift can be used to produce fast velocities and large power outputs when combined with the optimum load. Peak velocity ranged from 2.4 to 0.6 $m \cdot s^{-1}$ in the SBD and 2.4 to 0.9 $m \cdot s^{-1}$ in the HBD. Comparable values to those obtained here have been reported for the squat exercise across similar loads. Cormie et al. (6) and Kellis et al. (22) reported peak velocities ranging from 2.5 to 1.2 $m \cdot s^{-1}$ and 2.5 to 0.8 $m \cdot s^{-1}$ respectively. Larger peak velocities have been reported for Olympic weightlifting movements. Winchester et al. (33) reported peak velocities ranging from 4.1 to 3.2 $m \cdot s^{-1}$ across loads of 50 to 90% 1RM in trained college athletes performing the power clean. Greater velocity developed during Olympic weightlifting movements is explained by longer periods of acceleration that occur during the snatch or clean. However, traditional resistance exercises such as the squat and deadlift enable the lifter to overcome heavier loads and generate larger forces (6). As power is the product of force and velocity it may be possible for traditional resistance exercises to produce similar power values to those developed in weightlifting exercises by emphasising the force component. In the current investigation peak power for the SBD and HBD reached 4388 W and 4872 W respectively, with individual values as high as 6049 W and 6145W recorded. Studies quantifying power during Olympic weightlifting exercises have reported similar maximum peak power values to those obtained here. Winchester et al. (33) and Cormie et al. (6) reported maximum peak power values of 4230 W and 4900 W respectively for college athletes performing the power clean. The finding that the deadlift can be used to produce large power values suggests that it may be advantageous to include the exercise in structured periodized models aimed at improving muscular power. The suggestion coincides with recent research showing that the overall mechanical stimulus of traditional resistance exercises may be similar to movements more commonly used to develop power (10).

An extensive amount of research has been devoted to identifying loads that maximize power due to the belief that these are the most effective resistances to train with (3, 6, 21, 28, 29, 34). However, some researchers have commented that effective resistances are likely to cover a range of loads that may depend on the specific phase of an athlete's development (10). In the present study power was maximized at a load of 30% 1RM for the SBD and 40% 1RM for the HBD. Similar loads have been shown to maximise power in traditional resistance exercises such as the squat (34) and bench press (10, 19, 28). Other studies have reported that power in the squat is maximised with slightly heavier loads of 50 to 60% 1RM (28, 29). Variation in training status of the subjects and methods used to calculate power are expected to account for small discrepancies in loads found to maximise power between studies (3). However, there appears to be a clear distinction between the optimum load for traditional resistance exercises and Olympic weightlifting movements (6). Studies have shown that considerably heavier loads of 70 to 80% 1RM are required to maximize power during the clean (6, 21). Cormie et al. (6) proposed that the difference in optimum load was due to the distinct nature of the movements involved. With Olympic weightlifting exercises the ballistic component of the movement enables large velocities to be produced with near-maximum loads. As a result, power is maximised with relatively heavy resistances. In contrast, traditional resistance exercises produce low velocities with heavy loads and subsequently lighter resistances are required to maximise the product of force and velocity.

Some researchers have asserted that performing traditional resistance exercises with submaximal loads is an ineffective method for developing muscular power (25). This position is based on previous studies reporting extended periods of deceleration and reduced force production to slow the barbell velocity to zero at the end of the movement (8, 25). In one study it was demonstrated that over half the duration of the concentric movement was spent decelerating a load of 81% 1RM (8). However, previous research that has quantified acceleration throughout the duration of traditional resistance exercises has been restricted to the bench press. The results from the present study show that even with very light loads the majority of the exercise duration can be used to accelerate the load (Table 4). The results also demonstrate that the relative time spent accelerating the load increases as the external resistance increases. The contrasting results between the present and previous studies suggest that the exercise chosen may have an effect on the relative duration that the load can be accelerated.

PRACTICAL APPLICATIONS

Exercise selection is a key variable in resistance training design. Selected exercises should recruit the desired muscles and provide an appropriate biomechanical stimulus when combined with suitable acute program variables. The results of this study show that the biomechanical stimulus of the deadlift can be altered by performing the movement with different barbells. Selection of which deadlift variation should be used in a resistance training program will depend on the stimulus required. If the training objective is to target the lumbar area and maximally recruit the erector spinae muscles then it is recommended that the SBD is performed. As the HBD more evenly distributes the load between the joints of the body, practitioners may find deadlifts performed with the hexagonal barbell to be an effective alternative to the squat, and an appropriate exercise to use in the final stages of low back rehabilitation.

This is the first study to demonstrate that the deadlift can be combined with submaximal loads to generate large power outputs. The finding suggests it may be advantageous to include the deadlift in structured periodized models aimed at developing muscular power. The results of the study also demonstrate that the HBD can produce significantly greater peak force, peak velocity and peak power values than the SBD. Strength and conditioning coaches should be aware of the enhanced mechanical stimulus created with the hexagonal barbell when selecting a deadlift exercise.

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Figure Legends.

Figure 1-Deadlifting with a conventional straight barbell (top) and hexagonal barbell (bottom).

Figure 2-Barbell path during the SBD (top) and HBD (bottom) across the loading spectrum.

Figure 3-Load-force, load-velocity and load-power relationships. * Significant ($p < 0.05$) difference between SBD and HBD for corresponding load. Error bars represent ± SD.

Table 1. Joint angles at the starting position of the SBD and HBD averaged across loads.

	Torso (°) (±SD)	Hip (°) (±SD)	Knee (°) (±SD)	Ankle (°) (±SD)
SBD	55.2 (9.8)	89.8 (14.1)	72.5 (13.7)*	28.2 (10.5)
HBD	57.9 (9.8)	91.8 (11.6)	78.8 (11.2)*	29.1 (10.1)

*** Significant difference between SBD and HBD ($P < 0.05$)**

Table 2. Peak joint moments for the SBD and HBD across the loading spectrum.

	10% 1RM	20% 1RM	30% 1RM	40% 1RM	50% 1RM	60% 1RM	70% 1RM	80% 1RM
SBD Spine Peak Moment (N·m ±SD)	245.0 (46.3)*	273.9 (52.6)*	305.2 (54.1)*	326.6 (61.2)*	363.8 (67.4)*	391.6 (70.4)*	418.6 (70.7)	446.9 (73.9)
HBD Spine Peak Moment (N·m ±SD)	209.3 (48.6)*	227.1 (54.1)*	252.0 (60.8)*	272.1 (70.7)*	310.6 (84.7)*	342.5 (89.4)*	377.8 (92.3)	409.2 (98.3)
SBD Hip Peak Moment (N·m ±SD)	205.5 (48.9)*	225.2 (44.7)*	251.2 (41.0)*	267.6 (36.4)*	298.9 (58.4)*	321.0 (56.6)*	338.7 (62.0)*	353.0 (63.6)
HBD Hip Peak Moment (N·m ±SD)	185.9 (30.2)*	197.4 (30.7)*	224.2 (33.6)*	242.0 (38.0)*	257.2 (37.5)*	278.8 (50.0)*	300.1 (53.9)*	325.6 (59.4)
SBD Knee Peak Moment (N·m ±SD)	74.5 (31.3)*	78.1 (33.2)*	80.4 (34.9)*	84.9 (36.0)*	87.5 (31.7)*	90.0 (29.7)*	92.1 (23.4)*	96.0 (17.8)*
HBD Knee Peak Moment (N·m ±SD)	109.5 (34.8)*	119.8 (41.8)*	130.0 (48.6)*	137.2 (49.1)*	147.0 (47.8)*	157.4 (41.2)*	168.4 (53.9)*	182.5 (56.6)*
SBD Ankle Peak Moment (N·m ±SD)	138.3 (33.1)	155.1 (30.7)	177.9 (34.6)	194.7 (38.5)	204.8 (43.9)	215.4 (44.6)	229.4 (44.6)	232.8 (44.0)
HBD Ankle Peak Moment (N·m ±SD)	145.0 (25.4)	160.9 (24.9)	178.3 (31.9)	207.5 (34.8)	213.3 (37.3)	227.3 (43.4)	236.7 (51.8)	246.8 (59.4)

*** Significant difference between SBD and HBD for corresponding load ($P < 0.05$).**

Table 3. Resistance moment arms for the SBD and HBD averaged across loads. + Direction of resistance moment arm creates extensor moment. - Direction of resistance moment arm creates flexor moment.

	L5/S1 (cm) (±SD)	Hip (cm) (±SD)	Knee (cm) (±SD)	Ankle (cm) (±SD)
SBD	- 21.0 (3.0)	- 21.4 (3.8)	+ 8.4 (2.4)*	- 16.5 (2.1)
HBD	- 14.4 (3.0)	- 14.5 (2.6)	- 1.9 (0.8) *	- 11.9 (1.8)

*** Significant difference between SBD and HBD ($P < 0.05$).**

Table 4. Relative time accelerating resistance during the SBD and HBD across the loading spectrum.

	10% 1RM	20% 1RM	30% 1RM	40% 1RM	50% 1RM	60% 1RM	70% 1RM	80% 1RM
SBD Relative Time (±SD)	59.7% (3.6)	62.2% (7.5)	67.3% (5.2)	70.5% (7.3)	75.1% (6.7)	79.8% (8.8)	82.4% (6.0)	80.6%* (4.3)
HBD Relative Time (±SD)	59.1% (6.5)	61.6% (6.4)	65.0% (4.4)	70.3% (3.5)	74.6% (4.1)*	80.6% (5.8)	83.5% (5.1)	87.2%* (4.1)

*** Significant difference between SBD and HBD for corresponding load (P < 0.05).**