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Journal of Strength and Conditioning Research (ISSN 1064-8011, eISSN 1533-4287)

Citation Details

Citation for the version of the work held in 'OpenAIR@RGU':

SWINTON, P. A., LLOYD, R., KEOGH, J. W. L., AGOURIS, I., and STEWART, A., 2012. A biomechanical comparison of the traditional squat, powerlifting squat and box squat. Available from *OpenAIR@RGU*. [online]. Available from: http://openair.rgu.ac.uk

Citation for the publisher's version:

SWINTON, P. A., LLOYD, R., KEOGH, J. W. L., AGOURIS, I., and STEWART, A., 2012. A biomechanical comparison of the traditional squat, powerlifting squat and box squat. Journal of Strength and Conditioning Research, 26 (7), pp. 1805-1816.

This is a non-final version of an article published in final form in Journal of Strength and Conditioning Research, Volume 26, Number 7, pp. 1805-1816.

Full Title: A biomechanical comparison of the traditional squat, powerlifting squat and box squat.

Short Title: Comparison of squatting exercises

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ABSTRACT

The purpose of this study was to compare the biomechanics of the traditional squat with two popular exercise variations commonly referred to as the powerlifting squat and box squat. Twelve male powerlifters performed the exercises with 30, 50 and 70% of their measured 1RM, with instruction to lift the loads as fast as possible. Inverse dynamics and spatial tracking of the external resistance were used to quantify biomechanical variables. A range of significant kinematic and kinetic differences ($p<0.05$) emerged between the exercises. The traditional squat was performed with a narrow stance, whereas the powerlifting squat and box squat were performed with similar wide stances (48.3 ± 3.8cm, 89.6 ± 4.9cm, 92.1 ± 5.1cm, respectively). During the eccentric phase of the traditional squat the knee travelled past the toes resulting in anterior displacement of the system center of mass (COM). In contrast, during the powerlifting squat and box squat a more vertical shin position was maintained, resulting in posterior displacements of the system COM. These differences in linear displacements had a significant effect ($p<0.05$) on a number of peak joint moments, with the greatest effects measured at the spine and ankle. For both joints the largest peak moment was produced during the traditional squat, followed by the powerlifting squat, then box squat. Significant differences ($p<0.05$) were also noted at the hip joint where the largest moment in all 3 planes were produced during the powerlifting squat. Coaches and athletes should be aware of the biomechanical differences between the squatting variations and select according to the kinematic and kinetic profile that best match the training goals.

Key words: Kinematics, Kinetics, RFD, submaximum loads, technique

INTRODUCTION

The squat is one of the most frequently utilized resistance exercises for strength development in both athletic and rehabilitation settings. As a result of its widespread use, the exercise has been the focus of a large number of biomechanical studies (10-12, 19, 21, 23, 24, 28). The results present the squat as a complex movement which requires coordinated actions of the torso and all major joints of the lower extremities (10, 20). Furthermore, this complexity enables individuals to select different movement strategies to perform the exercise. From a performance enhancement and injury risk perspective, it is commonly recommended that movement strategies used to perform the squat should minimize anterior displacement of the knee (5). This recommendation is based on the reasoning that maintenance of a near vertical shin position during the squat reduces internal forces at the knee and emphasizes recruitment of the hip extensor muscles (5, 6). The first study to investigate the effects of controlling anterior knee displacement during the squat was conducted Fry et al. (12). The investigators measured joint torques produced at the hip and knee when squats were performed under two conditions with differing amounts of anterior knee displacement. During the first condition subjects were permitted to displace the knee beyond the toes, whereas, during the second condition displacement was restricted by placing a vertical board at the subjects' feet. The results showed that creating a more vertical shin position by restricting anterior displacement decreased torque at the knee whilst concomitantly increasing torque at the hip. Fry et al. (12) also reported that restricting anterior displacement of the knee created a more horizontal torso position which suggested greater shear forces were developed at the lumbar spine. The authors proposed that a more horizontal posture was adopted to compensate for changes in positioning of the lower leg and maintain the system center of mass (COM) over the base of support (12). The results obtained by Fry et al. (12) have caused some to propose that restricting anterior displacement of the knee during squatting may create potentially injurious forces at the lower back (6, 12)

The intention to restrict anterior displacement of the knee and maintain a near vertical shin position is a key feature of the movement strategies used by powerlifters to perform the squat. To achieve this posture, many powerlifters adopt a wide stance and focus on moving the hips posteriorly during the descent phase of the movement. In practical settings, this movement strategy is often referred to as “sitting back” and is the characterisation of what is considered to represent the powerlifting squat (6, 14) (Figure 1, middle). In contrast to result presented by Fry et al. (12), observation of skilled powerlifters suggests that some individuals can squat with relatively upright torso positions whilst restricting anterior displacement of the knee. At present, is not fully understood how these individuals successfully perform this task. However, to develop proficiency in the movement many powerlifters perform the squat onto a box placed behind the lower leg (26) (Figure 1, bottom). The box enables the performer to maximize posterior displacement of the hip and maintain a vertical shin position by acting as a safety device to catch the individual if the COM is moved beyond the base of support. Both the powerlifting squat and the box squat as it is commonly known are now popular exercises used by athletes other than powerlifters to develop strength and power (6, 19). However, some researchers and practitioners have questioned the safety and effectiveness of both exercises (4, 6). To date, only a limited number of studies have quantified biomechanical variables during the powerlifting squat or box squat. Multiple investigators have collected data from squats performed during powerlifting competitions (10, 14, 21). However, research has established that techniques used by individual powerlifters are varied and that some choose not to restrict anterior displacement of the knee (14). Much less information is available regarding the biomechanics of the box squat. McBride et al. (19) compared kinetic and electromyographic data of powerlifters performing the box squat and what was described as a standard squatting movement. The authors reported only minimal differences in peak force and muscle activity measured at the thigh. The experimental protocol utilized by Mc Bride et al. (19) did not calculate joint specific data or provide kinematic information regarding the movement strategies used by the powerlifters to perform each exercise. Due to the limited information available at present, coaches and athletes are unable to make informed judgements regarding the appropriateness of the powerlifting squat or box squat. Therefore, it was the principal aim of this study to provide a detailed kinematic and kinetic comparison of each exercise with additional analysis of the traditional squat to provide a reference. In fulfilling this aim, the study objectives included data collection for each exercise over a range of loads performed with the intent to overcome the resistance as fast as possible to simulate the training protocols used frequently to develop muscular strength and power.

METHODS

Experimental Approach to the Problem. A cross-sectional, repeated measures design was used to quantify and compare kinematics and kinetics of the traditional squat, powerlifting squat and box squat. The experimental approach provided original information regarding movement strategies used to perform each exercise and comparative data to assist practitioners in exercise instruction and training prescription. The subjects comprised well-trained powerlifters with extensive experience in performing each exercise. Data were collected for each subject over two sessions separated by one week. Session 1 was performed in the gymnasium and involved one-repetition maximum (1RM) testing in the squat. Session 2 was performed in the laboratory where subjects performed maximum speed repetitions for each exercise using loads of 30, 50 and 70% of their recorded 1RM. Kinematics and kinetics were analysed during session 2 only.

Subjects. Twelve male powerlifters participated in the study (age: 27.2 ± 4.2 yr; stature: 180.3 ± 4.8 cm; mass: 100.2 ± 13.1 kg; squat 1RM: 220.2 ± 36.2 kg; resistance training experience: 9.2 ± 3.1 yr). All subjects had a minimum of 3 yrs experience performing each exercise. 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. Subjects were notified about the potential risks involved and gave their written informed consent to be included. Prior approval was given by the ethical review panel at Robert Gordon University, Aberdeen, UK.

1RM testing. All subjects chose to perform the squat 1RM test using the powerlifting technique they used in competition. No supportive aids beyond the use of a weightlifting belt were permitted during the test. Based on a 1RM load predicted from performance in recent training sessions subjects performed a series of warm-up sets and up to 5 maximum attempts. A minimum of 2 minutes and a maximum of 4 minutes recovery time was allocated between attempts (2). Within this time frame subjects chose to perform the lifts based on their own perception of when they had recovered. All repetitions were performed to a depth where the thighs became parallel with the floor (2). Each attempt was deemed successful if the appropriate depth was reached and the barbell was not lowered at any point during the ascent phase.

Squat variation testing. Prior to performing maximum speed repetitions subjects engaged in their own specific warm-up. Generally, this began with 3 to 5 sets of light squats (e.g., < 40% 1RM) for 6 to 10 repetitions. All subjects then performed a series of maximum speed repetitions prior to any data collection. Once suitably prepared, subjects performed all three exercises with loads of 30, 50, and 70% of their predetermined 1RM. One trial comprising two repetitions was performed for each load and condition to assess intra-trial reliability. The nine trials were performed in a randomized order with a minimum 2 minute rest period allocated. A longer rest period of up to 4 minutes was made available if the subject felt it necessary to produce a maximum performance. For the traditional squat subjects were instructed to allow the knee to travel past the toes during the descent phase. For the powerlifting squat and box squat subjects were instructed to move the hip posteriorly and try to maintain as vertical a shin position as possible. During the box squat subjects were permitted to displace the COM behind the base of support during the final portion of the descent and were instructed to pause for a minimum of 1 second on the box. Instructions were given to perform the concentric portion of each repetition with maximum effort attempting to lift the load as fast as possible whilst maintaining contact with the ground throughout the movement. For each trial the repetition that produced the greatest peak barbell velocity 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 and room temperature was maintained between 22 and 25°C. Consistent verbal encouragement was provided during both testing sessions with subjects frequently reminded to lift each load as fast as possible.

Biomechanical instrumentation. A marker was placed on each of the following bony landmarks: spinous process of the 7th cervical vertebra, spinous process of the 10th cervical vertebra, 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 center 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 nine-camera motion analysis system (Vicon MX, Vicon Motion Systems, Oxford Metrics, UK). Marker position and ground reaction force (GRF) data were captured at 200 and 1200Hz respectively.

Data processing and reduction. 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 6 Hz. A three-dimensional lower body model (16) and upper body model (13) were used to calculate joint positions and angles of the torso, hip, knee and ankle, as well as the position of the 5th lumbar vertebra. Linear and angular velocities were calculated by differentiating position data with a Lagrangian five point differentiation scheme. Joint moments were calculated using inverse dynamics and anthropometric data with Vicon Nexus 1.7 processing software (Oxford Metrics, Oxford, UK). The moment arm created by the external resistance was also calculated for each joint. This was computed by measuring the horizontal distance from the geometric center of the barbell to the respective joint centers. Kinematics and kinetics for the hip, knee and ankle were calculated for both left and right sides and then averaged to obtain single values. Squatting technique was assessed by using quantitative and qualitative means. Quantitatively, technique was assessed by measuring joint angles during the first frame of the concentric movement. For qualitative analyses representative joint angle-time curves were selected and compared across techniques. Similar quantitative and qualitative analyses have been used previously to describe techniques used to perform the squat (10, 12). Peak power and rate of force development (RFD) were also measured to assess the external performance of each squat. Instantaneous power values were calculated as the product of the vertical GRF and corresponding vertical barbell velocity. RFD was calculated from the slope of the vertical GRF-time curve extending from the transition between eccentric and concentric phases to the maximum value of the first peak.

Statistical Analysis. Intra-trial reliability for each variable analysed was assessed by intraclass correlation coefficient (ICC). As recommended by Baumgartner (3), ICCs were calculated with a correction factor for number of repetitions performed per trial (n=2) and number of repetitions used in the criterion score (n=1). Intra-trial reliability for all variables reported was above 0.88. Potential differences in kinematic and kinetic variables measured during the squats were analyzed using a 3x3 (squat type x load) repeated measures ANOVA. Significant main effects were further analyzed with Bonferroni adjusted pair-wise comparisons. Statistical significance was accepted at $P < 0.05$. All statistical procedures were performed using the SPSS software package (SPSS, Version 17.0, SPSS Inc., Chicago, IL).

RESULTS

Linear Kinematics. The powerlifting squat and box squat were performed with a significantly wider stance than the traditional squat (89.6 ± 4.9cm, 92.1 ± 5.1cm, 48.3 ± 3.8cm, respectively). Linear displacements of the barbell and joint centers in the anterior-posterior direction revealed differences across techniques (Table 1). The largest effects were noted during the eccentric phase where greater posterior hip displacements and reduced anterior knee displacements occurred during the powerlifting squat and box squat compared to the traditional squat. These differences were reflected in the overall displacement of the system COM. During the eccentric phase the system COM was displaced anteriorly during the traditional squat and posteriorly during the powerlifting squat and box squat.

Angular Kinematics. Potential differences in squatting posture were primarily assessed by recording segmental angles during the first frame of the concentric phase. The values were averaged across loads as the external resistance was found to have minimal effect (Table 2). Similar torso angles were obtained for the traditional squat and powerlifting squat. However, at the start of the concentric phase a significantly more upright torso was recorded for the box squat. Angular differences across the exercises were observed at all three joint axes of the hip. The wide stance squats (powerlifting and box) displayed significantly greater abduction angles than the traditional squat. In addition, significantly greater hip flexion and internal rotation was recorded during the powerlifing squat compared with the other exercises. Significant differences were also obtained for the knee and ankle, with greater flexion angles obtained at both joints during the traditional squat.

A qualitative assessment of the lifting technique adopted for each exercise was obtained by selecting representative joint angle-time curves. Comparatively homogenous traces were obtained for the traditional squat (Figure 2). The results illustrate that the hip and knee flex and extend together with similar magnitudes. Also, similar patterns of flexion then extension were observed for the torso and ankle during the traditional squat. Assessment of the joint angle-time curves for the powerlifting squat and box squat revealed subjects selected one of two distinct techniques to perform the movement (Figures 3 and 4 illustrate representative curves for the distinct patterns used in the powerlifting squat). The first technique exhibited similar flexion and extension angles for the hip and knee as observed during the traditional squat (Figure 3). However, the movement also included substantially more rotation of the femur around the vertical and anterior-posterior axes than observed during the traditional squat. The second technique observed exhibited two distinct phases during the eccentric portion of the movement (Figure 4). Initially, movement was isolated in the sagittal plane at the hip joint. Upon reaching a critical hip flexion angle the knee and ankle simultaneously flexed along with concurrent abduction and internal rotation of the femur. Whilst the same overall movement patterns were observed for the powerlifting squat and box squat, the actual magnitude of torso inclination and ankle flexion during the eccentric phase were reduced when the box was introduced.

Angular Kinetics. Peak joint moments and moment arms are displayed in Table 3. Moment arms were calculated relative to the barbell center and correspond with the time interval of the peak joint moment. Positive values indicate the barbell was anterior to the joint center and negative values indicate a posterior barbell location. Significant differences were obtained for all joint moments and moment arms across the exercises. The greatest differences in peak joint moments were recorded at the spine and ankle. At both joints, the largest peak moments were produced during the traditional squat, followed by the powerlifting squat, then box squat. The addition of a box resulted in significant changes to a number of moment arms and peak joint moments. In particular, the use of a box decreased peak extension moments at the spine and hip and increased peak extension moments at the knee.

External Kinematics and Kinetics. The external stimulus of each exercise was assessed through measurement of the GRF, velocity, power and RFD. The vertical GRF maintained an overall similar profile for each exercise across loads. However, it was observed that as the external load increased the vertical GRF-time curve became more bimodal, with an increase in the relative size of the second peak. The group average vertical GRF-time curves performed with a load of 70% 1RM are displayed in Figure 5. The greatest differences in vertical GRF were observed during the box squat. There were no sharp increases in force production during the transition between eccentric and concentric phases as was evident with the other exercises. In addition, as the individual sat and paused there was a gradual transfer of load from the system to the box resulting in a substantial reduction in force production. Across the loading conditions, significantly greater peak vertical GRF was obtained for the traditional squat and powerlifting squat compared to the box squat (Table 4). Significant differences were also obtained for peak velocity, peak power and RFD. The greatest differences were obtained for RFD where 3- to 4-fold larger values were obtained for the box squat.

DISCUSSION

The results of the present study reveal significant biomechanical differences between the traditional squat and two of its most popular variations, the powerlifting squat and box squat. One of the most significant technical differences noted was the stance width used for each exercise. All of the athletes in the present study self-selected a narrow stance for the traditional squat and a wide stance for the powerlifting squat and box squat. Previous research investigating the effects of stance width on squatting biomechanics has reported a number of findings similar to the results obtained here (10). Using video data collected during a powerlifting competition, Escamilla et al. (10) reported that athletes performing wide stance squats exhibited greater hip flexion and smaller plantarflexion angles than those performing narrow stance squats. These results correspond with the significant differences in joint angles recorded in the present study between the narrow stance traditional squat and the wide stance powerlifting squat. In addition, Escamilla et al. (10) reported similar effects of stance width on hip and ankle moments. In particular, wide stance squats were found to produce significantly larger hip extension moments and smaller ankle extension moments (10). In contrast to the findings of the present study, Escamilla et al. (10) reported that overall joint-time curves for the torso and lower body were similar between narrow and wide stance squats. However, data collected by Escamilla et al. (10) were recorded during an active competition and the authors were unable to influence the lifting techniques employed; whereas, in the present study athletes were instructed to let the knee travel past the toes during the traditional squat and to maximize posterior displacement of the hip during the powerlifting squat and box squat. These instructions resulted in different movement strategies beyond alterations to stance width. The joint-time curves for the traditional (narrow stance) squat were consistent across subjects and featured simultaneous flexion then extension of the hip and knee, with greater range of motion obtained at the knee joint (Figure 2). During the powerlifting squat and box squat (wide stance) two distinct techniques were observed. The first technique also featured simultaneous flexion then extension of the hip and knee. However, the movement was combined with significantly greater ab/adduction and int/external rotation of the femur compared to that measured during the traditional squat (Figure 3). The second technique observed during wide stance squats featured two distinct phases during the eccentric portion of the movement (Figure 4). The first phase consisted of isolated hip flexion to approximately 40 degrees. Upon reaching this point, the second phase of the movement was initiated and comprised rapid flexion of the knee and ankle, combined with substantial abduction and internal rotation of the femur. The different movement strategies selected were clearly influenced by the stance width adopted. When attempting to displace the knees past the toes a narrow stance may have been selected to facilitate tracking of the patella over large knee flexion angles. In contrast, a wide stance was most likely adopted when attempting to maximize posterior displacement of the hip in order to decrease the height of the system COM and increase overall stability.

When discussing the advantages and potential risks associated with each type of squat, researchers and practitioners have generally focused on the kinetics associated with the exercise (6). Based largely on research conducted by Fry et al. 2003 (12), it is commonly believed that squats which minimize anterior displacement of the knee produce greater muscular forces at the hip and require a more horizontal torso position to remain balanced. Importantly, it is believed that this torso position results in larger forces and moments experienced at the lumbar spine, which increases the risk of developing lower back injuries. The results from the present study support claims that greater muscular forces are generated at the hip when attempting to maintain a more vertical shin position (6). This conclusion is based on significant differences in peak joint moments measured between the traditional squat and powerlifting squat. In contrast to the findings of Fry et al. (12) the results obtained here demonstrate that positioning of the torso is not dependent on the amount of anterior knee displacement. In addition, the largest peak moments at the L5/S1 joint in the present study were measured during performance of the traditional squat and not the powerlifting squat as would have previously been expected. Collectively, the results contradict previous suggestions that there is a greater risk of developing lower back injuries when performing variations such as the powerlifting squat. Contrasting results may be due to a number of methodological differences between the studies. Subjects recruited by Fry et al. (12) were recreationally trained and attempted to adopt similar movement strategies when performing the traditional squatting technique and the variation with restricted anterior knee displacement. Conversely, subjects in the present study were competitive powerlifters with enough experience in both exercises to select different movement strategies. Based on consistent technical features adopted by all athletes in the present study, it is clear that maintaining a relatively upright torso position whilst restricting anterior displacement of the knee is best achieved by adopting a wide stance and achieving significant range of motion at the hip joint in all three planes of motion. This may have implications for individuals who wish to perform the powerlifting squat or restrict anterior displacement of the knee but have limited movement capabilities at the hip joint.

Differences in peak joint torques recorded for each exercise were largely a result of the relative displacements of the barbell and joint centers. Performance of the traditional squat created relatively large anterior displacements of the barbell, knee and system COM during the eccentric phase (Table 1). In contrast, use of the box enabled individuals to maximize posterior displacement of the hip which resulted in an overall posterior displacement of the barbell. Visual observation of box squat repetitions revealed that many of the powerlifters displaced the system COM behind the base of support during the final stages of the eccentric movement. The use of the box to safely maximize posterior displacement created an ordered succession of squatting motions with the traditional squat situated at one end of the spectrum and the box squat at the other. A number of peak joint moments analyzed in the present study reflected this ordered succession. At the ankle joint, peak extension moments were greatest during the traditional squat, followed by the powerlifting squat, then box squat. Differences in peak moments measured at the ankle would have been caused by variation in the displacement of the system COM. The larger anterior displacements created during the traditional squat would have resulted in an increased joint moment to compensate for the greater total resistance (28). Based on the results of previous research (12, 28) and large differences noted across techniques for anterior knee displacement, a similar ordered effect was expected for peak moments developed at the knee joint. However, the results showed that the largest peak moments were obtained during the box squat, with similar smaller values obtained during the traditional squat and powerlifting squat. For each exercise the peak knee extension moment was developed during the initial stage of the concentric movement. As individuals maintained a more upright torso position when performing the box squat, the greater resistance moment arm created explains the larger peak moment recorded. The magnitude of the resistance moment arm created at the knee joint was similar between the traditional squat and powerlifting squat. As a result, no significant difference for the peak knee extension moment was measured between the two exercises. This result contradicts findings from previous research reporting reduced knee moments when maintaining a more vertical shin position (12). However, previous results were associated with an increased forward lean of the torso which did not occur in the present study. It is also important to note, that the overall mechanical stress experienced at the knee may not be adequately described by the peak moment alone. Research has shown that compressive and shear forces at the knee increase with larger flexion angles and greater displacement of the femur relative to the tibia (11, 24, 28). As a result, it is expected that greater overall stress at the knee joint will occur during the traditional squat.

Significant kinetic differences were also obtained at the hip joint. Across exercises, the largest peak moment was obtained during performance of the powerlifting squat. This result may be due to a number of biomechanical and physiological factors. The increased forward lean of the torso during the powerlifting squat in comparison to the box squat would have created a larger resistance moment arm at the hip, which would explain the difference in peak extension moment found. However, a significant difference was also obtained between the powerlifting squat and traditional squat despite both exercises creating a similar resistance moment arm. The difference may have been caused by variation in recruitment of the muscles surrounding the hip joint. Researchers have previously commented that powerlifters intentionally emphasise hip extension when performing wide stance squats (28). Support for this claim can be found in multiple studies which have reported increased muscle activity of the gluteus maximus when squats are performed with wider stance widths (20, 22). In addition to creating the largest extension moment at the hip, the powerlifting squat also produced the largest peak abduction and peak axial rotation moments. These larger kinetic values corresponded with greater frontal and transverse rotations of the femur during the powerlifting squat compared to the other exercises. Recently, there has been interest in altering the position of the femur during squatting exercises to target specific muscle groups (11, 23, 25). Anecdotally, it is believed that performing the squat with the hip in external rotation increases muscle activity of the quadriceps and hip abductors (25). Research conducted thus far has failed to demonstrate changes in quadriceps activity with altered rotation of the femur (11, 25); however, data exists to suggest that muscle activity of the hip abductors can be influenced (23). Previous studies have attempted to control the position of the femur by fixing the orientation of the foot. However, during the present study significant axial rotation was measured despite the foot remaining still. For each exercise the movement was initiated with the foot abducted and the hip externally rotated. As the movement progressed, foot position remained fixed as the hip moved in and then out of internal rotation. Results from other kinematic studies incorporating 3D motion capture systems have reported similar results for athletes performing the squat (9, 29). This observation may have implications for potential injuries at the knee joint. Research has previously shown that hip adduction combined with internal rotation of the femur during knee flexion exercises is associated with increased valgus stress and repetitive injuries such as anterior cruciate ligament strain, iliotibial band friction syndrome and patellofemoral pain syndrome (15, 18). During the bottom portion of the squat where internal rotation of the femur was at its greatest, the athletes in the present study were able to maintain appropriate alignment of the femur and tibia through substantial abduction of the hip. During the powerlifting squat where internal rotation and hip flexion is maximized, untrained individuals and those with restricted movement capabilities may be unable to maintain hip abduction. This may lead to those individuals descending into an adducted and internally rotated posture which could create large stresses at the knee.

In order to obtain a more complete understanding of the biomechanical stimulus presented by an exercise, recent research has focused on the external kinematics and kinetics created (7, 17, 30). Most frequently, variables such as force, velocity, power and RFD have been measured (1). The data obtained has also been used to rank exercises based on the belief that those which acutely maximize the production of each variable provide the best stimulus for longitudinal improvement. To ensure the biomechanical stimulus is maximized for each variable, repetitions in the present and previous studies were performed with the intention to lift the load as fast as possible (7, 17, 30). The results obtained here demonstrate that large forces can be produced in all three squatting exercises even when light resistances are displaced with maximum velocity. Across the 30 to 70% 1RM loads, peak vertical GRF for the group was approximately 2.1 to 2.8 times body weight. The largest effects of squat variation on force and all other external kinematics and kinetics recorded were obtained during the box squat. Group average force-time curves showed reduced peak values and changes to the overall profile with the box squat compared to the other exercises (Figure 5). During the traditional squat and powerlifting squat a large increase in force was measured during the transition period between eccentric and concentric phases. However, during the box squat, athletes were able to decrease force production during this transition period and use the box to partially slow the system COM. Following a sustained reduction in force as the athletes paused on the box, force was then rapidly increased during the concentric phase. A similar reduction in peak force when performing the box squat was reported in a recent study conducted by McBride et al. 2010 (19) The authors suggested that lower forces produced during the box squat compared to a standard squatting movement was the result of reduced stretch-shortening activity from pausing on the box. The powerlifters in the present study were instructed to follow their individual practices regarding the length of time paused on the box, as long as a minimum period of one second was adhered to. On average, the group paused for 1.7 seconds with times ranging from 1.3 to 2.3 seconds. Research has shown that as duration between eccentric and concentric phases increases there is a progressive reduction in contribution from the stretch shortening cycle (27). The long pauses obtained during the box squat are therefore likely to explain the reductions in force, velocity and power in comparison to the other exercises studied. However, the largest effect of squat variation observed was an increase in RFD during the box squat. The results showed 3 to 4-fold greater values in RFD when squats were performed with the box. As RFD and the squat exercise are both considered important elements of training for athletic improvement (8), the finding that significantly larger RFD values can be obtained when using the box could have important implications for training prescription. Whilst it remains unclear which training practices are most effective for long-term improvements in RFD, many believe that performing explosive resistance exercises that create high RFD values will be successful (8). The large disparity in RFD values obtained between the exercises may provide researchers with an effective model to study RFD using movements that are transferable to many sporting actions.

PRACTICAL APPLICATIONS

The squat is widely regarded as one of the most effective exercises for improving strength and athletic performance. Most often, the exercise is performed with a narrow stance and the knee is permitted to travel past the toes. In many instances, strength and conditioning coaches will attempt to manipulate the exercise to target particular areas of the body or simply to provide variation in training. Traditionally, strength and conditioning coaches have manipulated the biomechanics of the squat by altering the position of the barbell to perform either the front squat or overhead squat. However, the results of this study show that the biomechanical stimulus of the squat can be altered by employing different movement strategies and by using a box to modify the transition between eccentric and concentric phases. By instructing individuals to maximize posterior displacement of the hip as is required during the powerlifting squat, it is possible to increase the stress placed on the hip joint in all three planes. This squatting style requires a wide stance to remain stable and if performed correctly may decrease the stress placed at the ankle and lumbar region in comparison to the traditional squat. In addition, performance of the powerlifting squat may be beneficial for individuals who have sufficient movement capabilities at the hip but lack range of motion at the ankle joint and therefore are unable to descend to sufficient depth with appropriate body positioning. Coaches and athletes should be aware that correct performance of the powerlifting squat may require substantial mobility at the hip joint and practice to co-ordinate the segments of the body. We recommend that the box squat be used as a training tool to improve competency in performing the powerlifting squat. Initially, a relatively tall box may be used to teach the exercise and progressed by gradually decreasing the height as proficiency increases. In addition, the very large RFD values produced during the box squat suggest it could be an effective exercise to develop explosive strength and athleticism. Based on current paradigms used in the training of athletes it is recommended that multiple sets of 3 to 6 repetitions be performed to develop these qualities.

Acknowledgments

The results of the present study do not constitute endorsement by the authors or the NSCA.

Conflicts of interest: None

Sources of funding: None

Figure Captions.

Figure 1-Traditional Squat (top), Powerlifting Squat (middle) and Box Squat (bottom).

Figure 2-Representative joint angle-time curve for the traditional squat.

Dashed line indicates transition from eccentric to concentric

Figure 3-Representative joint angle-time curve for a distinct movement pattern observed during the powerlifting squat.

Dashed line indicates transition from eccentric to concentric

Figure 4- Representative joint angle-time curve for a second distinct movement pattern observed during the powerlifting squat.

Dashed line indicates transition from eccentric to concentric

Figure 5-Group average force time curves obtained with a 70% 1RM load.

Circles indicate transition between phases of the squat (eccentric/concentric) and (eccentric/box/concentric)

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Table 1. Anterior-posterior displacements calculated across the eccentric and concentric phases (mean ± SD)

	Traditional	Powerlifting	Box
Eccentric			
30% 1RM			
Bar (cm)	9.5 ± 2.1*†	5.1 ± 2.2*‡	-6.8 ± 6.0†‡
COM (cm)	3.2 ± 2.8*†	-6.8 ± 3.1*	-8.4 ± 3.5†
Hip (cm)	-15.5 ± 2.6*†	-21.1 ± 3.2*‡	-28.7 ± 5.1†‡
Knee (cm)	22.4 ± 4.3*†	16.4 ± 3.3*‡	13.9 ± 2.7†‡
50% 1RM			
Bar (cm)	8.4 ± 1.8*†	4.1 ± 2.2*‡	-7.1 ± 6.4†‡
COM (cm)	3.5 ± 2.7*†	-4.2 ± 3.0*	-7.9 ± 4.0†
Hip (cm)	-15.6 ± 1.8*†	-18.1 ± 2.9*‡	-25.3 ± 6.2†‡
Knee (cm)	20.7 ± 3.1†	17.3 ± 4.1‡	14.4 ± 3.5†‡
70% 1RM			
Bar (cm)	7.4 ± 1.8*†	3.8 ± 1.9*‡	-5.9 ± 2.9†‡
COM (cm)	4.1 ± 3.4*†	-2.8 ± 2.4*	-3.7 ± 3.2†
Hip (cm)	-15.1 ± 2.7†	-16.0 ± 6.2‡	-23.6 ± 6.0†‡
Knee (cm)	19.9 ± 2.6†	18.2 ± 5.0‡	13.7 ± 3.9†‡
Concentric			
30% 1RM			
Bar (cm)	-5.8 ± 2.1†	-4.2 ± 2.2‡	9.4 ± 4.1†‡
COM (cm)	-2.5 ± 1.2*†	6.7 ± 2.3*‡	10.6 ± 2.9†‡
Hip (cm)	18.1 ± 3.4†	20.2 ± 2.8‡	29.0 ± 3.3†‡
Knee (cm)	-21.6 ± 4.1*†	-18.2 ± 3.1*‡	-13.1 ± 2.5†‡
50% 1RM			
Bar (cm)	-6.2 ± 1.9*†	-3.6 ± 2.4*‡	10.8 ± 3.7†‡
COM (cm)	-2.0 ± 0.8*†	7.6 ± 1.6*‡	11.3 ± 2.2†‡
Hip (cm)	16.2 ± 3.1*†	19.2 ± 1.9*‡	29.0 ± 3.4†‡
Knee (cm)	-22.8 ± 4.2*†	-18.3 ± 3.2*‡	-13.3 ± 2.3†‡
70% 1RM			
Bar (cm)	-6.1 ± 1.9†	-3.7 ± 2.7‡	9.9 ± 4.0†‡
COM (cm)	-2.0 ± 0.8*†	8.4 ± 5.0*	9.5 ± 1.8†
Hip (cm)	14.7 ± 3.3†	17.5 ± 2.0‡	26.6 ± 3.1†‡
Knee (cm)	-20.3 ± 3.6†	-19.2 ± 3.2‡	-13.7 ± 3.4†‡

* Significant difference between traditional and powerlifting ($p < 0.05$).

† Significant difference between traditional and box ($p < 0.05$).

‡ Significant difference between powerlifting and box ($p < 0.05$).

Table 2. Joint angles at the start of the concentric phase (mean ± SD)

	Traditional	Powerlifting	Box
Torso (flexion °)	33.5 ± 4.6†	33.1 ± 4.5‡	26.9 ± 3.8†‡
Hip (flexion °)	104.3 ± 4.9*	112.6 ± 5.8*	105.7 ± 5.6
Hip (abduction°)	28.0 ± 5.5*†	38.4 ± 4.7*	37.5 ± 2.2†
Hip (int rotation °)	19.3 ± 3.3*	27.4 ± 4.1*‡	20.9 ± 2.1‡
Knee (flexion °)	121.1 ± 3.4*†	112.1 ± 4.3*‡	103.8 ± 5.2†‡
Ankle (flexion °)	37.2 ± 3.9*†	26.7 ± 5.1*‡	14.4 ± 4.2†‡
Shank (horizontal°)	53.2 ± 3.1*†	68.9 ± 4.1*‡	76.3 ± 3.8†‡

* Significant difference between traditional and powerlifting ($p < 0.05$).
† Significant difference between traditional and box ($p < 0.05$).
‡ Significant difference between powerlifting and box ($p < 0.05$).

Table 3. Peak joint moments and corresponding moment arms (mean ± SD)

	Traditional	Powerlifting	Box
30% 1RM			
Moment arms (cm)			
L5/S1	23.5 ± 3.0†	22.9 ± 2.6‡	18.2 ± 2.3†‡
Hip	26.6 ± 2.7†	26.1 ± 2.1‡	21.1 ± 2.2†‡
Knee	- 9.1 ± 1.8*†	- 7.5 ± 1.2*‡	- 13.9 ± 1.9†‡
Ankle	10.1 ± 2.0*†	5.3 ± 1.0*‡	2.5 ± 1.7†‡
Moments (Nm)			
L5/S1 (ext)	266 ± 36*†	222 ± 21*	203 ± 19†
Hip (ext)	200 ± 26*	222 ± 29*‡	193 ± 28‡
Hip (abd)	58 ± 18*	75 ± 25*	64 ± 28
Hip (int rotation)	35 ± 16*	48 ± 18*‡	26 ± 10‡
Knee (ext)	166 ± 28†	161 ± 24‡	197 ± 28†‡
Ankle (ext)	82 ± 15*†	56 ± 8*‡	41 ± 11†‡
50% 1RM			
Moment arms (cm)			
L5/S1	22.6 ± 2.3†	21.9 ± 2.2‡	18.3 ± 2.6†‡
Hip	25.9 ± 2.5†	25.8 ± 2.4‡	21.3 ± 2.8†‡
Knee	- 10.5 ± 1.9*†	- 8.0 ± 1.4*‡	- 14.7 ± 2.1†‡
Ankle	9.5 ± 1.8*†	5.6 ± 1.5*	2.5 ± 2.1†
Moments (Nm)			
L5/S1 (ext)	320 ± 42*†	261 ± 30*	233 ± 21†
Hip (ext)	240 ± 29†	253 ± 33‡	213 ± 35†‡
Hip (abd)	63 ± 29*	84 ± 27*	69 ± 35
Hip (int rotation)	42 ± 24	50 ± 19‡	26 ± 17‡
Knee (ext)	188 ± 32†	176 ± 27‡	221 ± 29†‡
Ankle (ext)	93 ± 17*†	64 ± 16*	58 ± 15†
70% 1RM			
Moment arms (cm)			
L5/S1	22.1 ± 2.5†	22.4 ± 2.3‡	19.7 ± 2.8†‡
Hip	25.2 ± 2.9	26.2 ± 2.1‡	23.3 ± 3.0‡
Knee	- 10.1 ± 1.1*†	- 8.1 ± 0.8*‡	- 15.2 ± 2.8†‡
Ankle	9.9 ± 2.2†	5.6 ± 1.6	2.4 ± 2.1†
Moments (Nm)			
L5/S1 (ext)	354 ± 49*†	308 ± 39*	279 ± 35†
Hip (ext)	256 ± 35*†	281 ± 32*‡	230 ± 37†‡
Hip (abd)	70 ± 30*	94 ± 26*	79 ± 35
Hip (int	43 ± 24	55 ± 22	38 ± 28

rotation)			
Knee (ext)	201 ± 39	192 ± 36	229 ± 39
Ankle (ext)	104 ± 20*†	78 ± 10*	71 ± 14†

* Significant difference between traditional and powerlifting ($p < 0.05$).
† Significant difference between traditional and box ($p < 0.05$).
‡ Significant difference between powerlifting and box ($p < 0.05$).

Table 4. External kinematics and kinetics (mean ± SD)

	Traditional	Powerlifting	Box
30% 1RM			
Peak Vertical Force (N)	2166 ± 194	2165 ± 182	2080 ± 280
Peak Velocity (ms^{-1})	1.68 ± 0.15†	1.61 ± 0.19‡	1.44 ± 0.12†‡
Peak Power (W)	2901 ± 293†	2825 ± 315‡	2472 ± 288†‡
RFD (Ns^{-1})	4801 ± 1572†	4963 ± 1542‡	16390 ± 4204†‡
50% 1RM			
Peak Force (N)	2448 ± 295†	2400 ± 270‡	2265 ± 306†‡
Peak Velocity (ms^{-1})	1.39 ± 0.14	1.34 ± 0.13	1.31 ± 0.11
Peak Power (W)	2702 ± 114	2695 ± 161	2589 ± 307
RFD (Ns^{-1})	5319 ± 1334†	5333 ± 1443‡	16980 ± 3199†‡
70% 1RM			
Peak Force (N)	2680 ± 309†	2685 ± 301‡	2528 ± 302†‡
Peak Velocity (ms^{-1})	1.18 ± 0.16	1.16 ± 0.12	1.12 ± 0.09
Peak Power (W)	2637 ± 137	2589 ± 135	2484 ± 301
RFD (Ns^{-1})	5083 ± 1227†	5868 ± 1972‡	14537 ± 3612†‡

* Significant difference between traditional and powerlifting ($p < 0.05$).
† Significant difference between traditional and box ($p < 0.05$).
‡ Significant difference between powerlifting and box ($p < 0.05$).