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Effect of load positioning on the kinematics and kinetics of weighted vertical jumps

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ABSTRACT.

One of the most popular exercises for developing lower-body muscular power is the weighted vertical jump. The present study sought to examine the effect of altering the position of the external load on the kinematics and kinetics of the movement. Twenty nine resistance trained rugby union athletes performed maximal effort jumps with 0, 20, 40 and 60% of their squat 1RM with the load positioned: 1) on the posterior aspect of the shoulder using a straight barbell (SBJ); and 2) at arms' length using a hexagonal barbell (HBJ). Kinematic and kinetic variables were calculated through integration of the vertical ground reaction force data using a forward dynamics approach. Performance of the HBJ resulted in significantly ($p<0.05$) greater values for jump height, peak force, peak power, and peak rate of force development compared to the SBJ. Significantly ($p<0.05$) greater peak power was produced during the unloaded jump compared to all trials where the external load was positioned on the shoulder. In contrast, significantly ($p<0.05$) greater peak power was produced when using the hexagonal barbell combined with a load of 20% 1RM compared to all other conditions investigated. The results suggest that weighted vertical jumps should be performed with the external load positioned at arms' length rather than on the shoulder when attempting to improve lower-body muscular performance.

Key Words: Ballistic; power; weight-training.

INTRODUCTION

The vertical jump is an important feature of many sports and is frequently incorporated with other explosive body-weight exercises in training aimed at developing muscular power and athletic performance. External resistance can be added to the vertical jump to increase the intensity of the training stimulus (33). The most common methods of applying resistance include the use of barbells, dumbbells, weighted vests and rubber bands. The addition of external resistance to the vertical jump has been shown to increase force whilst concurrently decrease velocity and rate of force development (29). Weighted jumps have become one of the most popular resistance exercises for developing muscular power based on the suggestion that ballistic movements are more effective than the use of traditional resistance exercises such as the squat. It is believed that the primary advantage of ballistic movements is their ability to avoid undesirable deceleration which occurs during the concentric phase of all traditional resistance exercises (23, 30).

Most frequently, weighted jumps are performed by placing a barbell over the posterior aspect of the shoulder (Figure 1). This variation is commonly referred to as the jump squat and requires athletes to lower the body to a chosen depth and then quickly reverse the movement attempting to jump as high as possible. The jump squat has been used extensively by researchers to investigate the load-power relationship (4, 5, 9, 13, 35, 36, 38). The rationale for the extensive study is the thesis that the load which maximises power provides the most effective stimulus for power development (4) Initial results from studies investigating the load-power relationship with the jump squat reported that power was maximized with loads of 30 to 60% 1RM (4, 35, 36, 38). However, more recent studies have consistently shown that power is maximized when vertical jumps are performed unloaded (5, 8, 9, 13). Discrepancies between findings from initial and recent studies are most likely the result of methodological factors such as the procedures used for calculating power (5, 14). Despite efforts to indentify a single load which acutely maximizes power, most researchers currently propose that a range of loads may result in similar long-term improvements depending on factors such as exercise selection, the individual athlete and their recent training history (6, 10, 12, 16).

At present, more information is available on the kinematics and kinetics of weighted jumps performed with a barbell compared to all other methods of providing resistance. The primary advantage of using a barbell is the wide range of loads that can be applied. In contrast, the amount of resistance that can be added with a weighted vest is relatively limited and athletes may find it difficult to stabilize and appropriately position large dumbbells (34). The use of rubber bands provides a pattern of resistance distinct from the aforementioned methods. The external resistance created when using rubber bands changes with displacement of the body and resultant stretch of the resistance material (28). During the bottom portion of the jump the overall stretch of the rubber bands is minimized and therefore less resistance is applied. As the athlete accelerates upwards and raises their centre of mass the bands progressively stretch and increase resistance based on the stiffness of the material (28). Despite anecdotal claims that rubber bands can be used to improve jumping performance (31), research is yet to systematically investigate the effectiveness of the practice.

An additional method of loading the vertical jump which has not been considered in the literature is through the use of a hexagonal barbell (Figure 2). The non-conventional barbell enables athletes to stand within its frame and hold the resistance at arms' length. During weighted jumps the hexagonal barbell applies resistance in a similar manner to that obtained when using dumbbells. However, it is expected that the continuous frame of the hexagonal barbell will provide several advantages over the use of dumbbells, including improved stability and greater capacity to apply a wider range of loads. In a recent study investigating kinematics and kinetics of deadlift variations it was reported that use of a hexagonal barbell produced significantly greater force, velocity and power compared to use of a straight barbell (37). The improved mechanical stimulus created when using the non-conventional barbell was attributed to positioning of the external resistance closer to the bodies' centre of mass, which resulted in favourable changes in the resistance moment arms at the individual joints (37). Other biomechanical studies investigating the effect of changing load position during multi-joint resistance exercises have also demonstrated that kinematics and kinetics can be altered even when the change in load position is minimal (18, 40). Therefore, the purpose of this study was to investigate whether the kinematics and kinetics of the jump squat could be altered by changing the position of the resistance from the shoulders to arms' length through the use of a hexagonal barbell. As the jump squat is considered one of the most effective exercises for developing lower-body power (3), the ability to easily manipulate and potentially augment kinematics and kinetics of such a popular exercise would be of practical significance to many coaches and athletes.

METHODS

Experimental approach to the problem

A cross-sectional, randomized cross-over design was used to compare the kinematics and kinetics of weighted jumps performed with the load positioned on the shoulders and at arms' length. Data were collected for each subject over two sessions separated by one week. The first session was performed in the gymnasium and involved 1RM testing in the squat and hexagonal barbell deadlift. The 1RM squat test was used to set relative intensities for the athletes and match absolute loads for the straight barbell jump (SBJ) and hexagonal barbell jump (HBJ). The 1RM hexagonal barbell test was included to investigate whether similar maximal loads could be applied with both barbells. During the second testing session subjects reported to the laboratory where they performed the SBJ and HBJ with loads equal to 20, 40 and 60% of their predetermined squat 1RM. Kinematics and kinetics were analysed during the second session only.

Subjects

Twenty nine male rugby union athletes (age: 26.3 ± 4.6 yr; stature: 182.4 ± 6.8 cm; mass: 94.5 ± 13.1 kg; 1RM Squat: 153.7 ± 20.3 kg) volunteered to participate in this study. Each of the athletes regularly performed weighted jumps in their training and had prior experience using both straight and hexagonal barbells. The study was conducted eight weeks into the athletes preseason training after a de-load micro-cycle. Prior to experimental testing subjects were notified about the potential risks involved and gave their written informed consent. Approval for this study was provided by the ethical review panel at Robert Gordon University, Aberdeen, UK.

Procedures

During the first session subjects had their 1RM back squat and 1RM hexagonal barbell deadlift tested in a randomized order. All subjects were accustomed to performing multiple 1RM tests in a single session as part of their strength and conditioning provision. To minimize the likelihood of fatigue influencing the results, a 30 minute rest period was allocated between tests (9). Based on a predicted 1RM load subjects performed a series of warm-up sets and up to 5 maximal attempts. A minimum of 2 minutes and a maximum of 4 minutes recovery time was allocated between maximal attempts (2). Within this time frame subjects chose to perform the lifts based on their own perception of when they had recovered. Maximum squat repetitions were performed with an initial eccentric action to a depth where the thighs became parallel with the floor (2). In contrast, the 1RM hexagonal barbell deadlifts were initiated with the load positioned on the ground and required less hip and knee flexion than in the squat. For both movements a lift was deemed successful if the barbell was not lowered at any point during the ascent and upon completion of the movement the body posture was held erect with the knees and hips fully extended.

One week later subjects performed maximum effort unloaded and loaded vertical jumps. The unloaded vertical jump was performed with the arms held stationary at the side of the body. Weighted jumps were performed in a randomized order using both the straight and hexagonal barbell with loads of 20, 40 and 60% of squat 1RM. Subjects performed the downward phase of all vertical jumps to a half-squat position with the hip flexed to approximately 60°. Standardization was applied across conditions to control for potential variation caused by load position or load magnitude during the important preparatory phase of the jump. The half-squat position employed during testing was the same as that used by the athletes during their regular plyometric and weighted jump training. Each trial was visually monitored by the same researcher, with athletes instructed to repeat trials if the half-squat position deviated from the standard. Two vertical jumps were performed for each condition to assess intra-trial reliability. The attempt which resulted in the greatest vertical jump height was selected for further analysis. A minimum 2 minute rest period was allocated between conditions with a longer rest period made available if the subject felt it necessary to produce a maximum performance. All testing was completed between the hours of 17:00 and 20:00 to correspond with the athletes' regular training times. Subjects followed their individual nutritional practices with consumption of water (500 ml) permitted during tests. Room temperature in the gymnasium and laboratory were maintained between 22 and 25° C.

Jumps were performed with a separate piezoelectric force platform (Kistler, Type 9281B Kistler Instruments, Winterthur, Switzerland) under each foot capturing vertical ground reaction force (VGRF) data at 1200 Hz. Force plate data were filtered using a fourth-order, zero-phase lag Butterworh filter with a 50 Hz cutoff. Digital video of each jump was collected using two synchronized video cameras (Basler piA640-210gm, 60Hz) positioned in the frontal and sagittal planes. Kinematic and kinetic data were calculated at the athletes' COM during unloaded trials and at the system COM (athlete + external load) during loaded trials. The kinematic and kinetic variables were calculated using the VGRF-time data and a forward dynamics approach reported previously in the literature (20, 22, 24). Briefly, trials were initiated with subjects standing erect and motionless. Once data acquisition was initiated, subjects were instructed to lower themselves to the standardized depth and then quickly reverse the movement attempting to jump as high as possible. Changes in vertical velocity of the system COM were calculated by multiplying the net VGRF (VGRF recorded at the force plate minus the weight of the athlete and the external resistance) by the intersample time period (1/1200s) divided by the mass of the system. Instantaneous velocity at the end of each sampling interval was determined by summing the previous changes in vertical velocity to the pre-interval absolute velocity, which was equal to zero at the start of the movement. The position change over each interval was calculated by taking the product of absolute velocity and the intersample time period. Vertical position of the system COM was then obtained by summing the position changes. Instantaneous power was calculated by taking the product of the VGRF and the concurrent vertical velocity of the system. Jump height and peak rate of force development were also used to assess kinematics and kinetics. Jump height was calculated from the vertical velocity of the system at take-off (25). Rate of force development was calculated over 5 millisecond intervals from the slope of the VGRF-time curve.

Statistical Analysis.

Intraclass correlation coefficients (ICC's) were calculated to assess intra-trial reliability for each variable analyzed. Data for each dependent variable were determined as normally distributed via the Shapiro-Wilk test for normality. Potential kinematic and kinetic differences obtained during the SBJ and HBJ were analyzed using a 2x3 (barbell 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 16.0, SPSS Inc., Chicago, IL).

RESULTS

Intra-trial reliability for all variables measured was high (ICC = 0.8 to 0.98). Subjects were able to lift a significantly ($p<0.05$) heavier 1RM load in the hexagonal barbell deadlift compared to the back squat (195.4 ± 18.3 kg vs. 153.7 ± 20.3 kg, $p<0.05$). Jump heights for the unloaded and weighted jumps are displayed in figure 3. The addition of resistance significantly increased force ($p<0.05$) and decreased velocity ($p<0.05$) when jumping. Peak rate of force development was significantly ($p<0.05$) greater during unloaded jumps compared with the SBJ. However, similar peak rate of force development values were obtained for unloaded jumps and the HBJ. A load position effect between unloaded and weighted jumps was also found for peak power values. Significantly greater peak power was obtained with the HBJ performed with a 20% 1RM load compared to all other conditions ($p<0.05$). In addition, no significant ($p<0.05$) differences were obtained for peak power produced during unloaded jumps and the HBJ performed with a 40% 1RM load. In contrast, peak power was significantly ($p<0.05$) reduced when resistance was applied using the SBJ. Significant main effects of load position were obtained for peak force, peak power and peak rate of force development ($p<0.05$). For all variables measured there was a trend towards higher values when performing the HBJ (Table 1). No significant interaction effects between load position and load magnitude were found.

DISCUSSION

The results of the current investigation demonstrate that positioning of the external resistance significantly affects the kinematics and kinetics of weighted jumps in experienced weight-trained athletes. Customarily, when athletes perform the weighted jump they use a straight barbell placed across the posterior aspect of the shoulder. The results of the present study demonstrate that if the resistance is moved from the shoulder to arms’ length using a hexagonal barbell the athlete can jump higher and generate greater force, power, velocity and rate of force development. The improved kinematics and kinetics obtained when using the hexagonal barbell most likely result from a change in position of the external resistance from the shoulders to a location closer to the bodies’ centre of mass. It is possible that the change in load position may enable athletes to more closely replicate their unloaded vertical jump technique with a hexagonal barbell as compared with a straight barbell. An important technical aspect of the vertical jump is the posture of the trunk (26, 39). To maximise performance during vertical jumps athletes adopt a trunk position at the bottom of the movement that is substantially inclined from the vertical (39). Research has shown that this posture enables trunk rotation to effectively contribute to jump performance (26) whilst emphasizing torque production at the hip (39). When an external load is positioned on the shoulder the moment arm of the resistance can become large as the trunk is inclined. During squatting where the goal is often to displace a heavy load the torso has to become more vertical to minimise resistive torque and shear force experienced at the lumbar spine (17). When a barbell is positioned across the shoulder to perform the SBJ the potential to create large resistance moment arms may cause athletes to divert from their normal unloaded jump technique and adopt a less effective, more vertical squatting motion. Whilst a segmental biomechanical analysis was not included in this study, review of the video footage illustrated that trunk inclination was substantially less at the conclusion of the downward phase of the SBJ compared to the unloaded vertical jump. The video footage also showed the athletes adopting similar trunk positions across the 20, 40 and 60% 1RM loads, thereby supporting the hypothesis that placement of an external resistance on the shoulder prompts athletes to revert to their back squat technique. This observation is consistent with previous research showing eccentric squat technique to be relatively unchanged across loads of 25 to 100% of an athlete's 3RM (15). In contrast, when athletes perform weighted jumps with the hexagonal barbell the load can be held close to the bodies' centre of mass and moved independently of the torso. These attributes may enable athletes to more closely reproduce their unloaded jump technique when performing the movement with external resistance. Review of the video footage provided support for this theory with greater similarity of gross motor technique demonstrated between the unloaded jump and the HBJ, in particular with regard to the amount of forward torso inclination. A more complete biomechanical analysis should be conducted to investigate potential differences in joint kinematics between jumps and determine whether load position can affect temporal variables or segment coordination.

The kinematic and kinetic improvements obtained when changing load position may also have occurred as a result of differences in the relative intensity created when using the same absolute loads. Performing an exercise with a hexagonal barbell creates less resistive torque at the lower-body joints compared to using a straight barbell positioned further away from the body (37). A reduction in the overall resistance created during the HBJ may have enabled athletes to accelerate the load more effectively and thereby explain the enhanced mechanical profile reported. In the present study, loads used for both forms of weighted jumps were scaled using the athletes' squat 1RM only. Scaling to different maximum strength tests was not used as it was expected there would be differences in movement strategies employed when performing a 1RM deadlift and the HBJ. When lifting maximum loads in the deadlift it has been reported that experienced weightlifters alter their technique and path of the barbell to successfully overcome the sticking region (7, 19, 37). In addition, deadlifts are generally performed from the floor without a preceding lowering phase, whereas, the HBJ is performed with an explosive stretch shortening cycle action with the barbell reaching only approximately knee height. Despite technical complications in scaling the intensity between weighted jumps, the design of the hexagonal barbell and large difference in maximum strength scores obtained in the squat and hexagonal barbell deadlift suggests that a lighter load should be used in the SBJ to equate the overall resistance. Cormie *et al,* (9) have previously shown that as resistance is decreased in the SBJ there is a linear increase in velocity. As a result, equating the overall resistance between weighted jumps may have resulted in similar velocity values. However, Cormie *et al,* (9) also reported that decreasing the resistance in the SBJ results in a linear reduction in the amount of force produced. As the HBJ originally produced significantly greater peak force values, equating the resistance between weighted jumps would increase the disparity in force production, thereby suggesting that at least part of the kinematic and kinetic differences occurred as a result of factors other than the relative intensity of the load.

The results from the present study also demonstrate that positioning of the external resistance can alter the load-power relationship. When using the straight barbell the results coincided with recent studies showing that power is maximized when no external resistance is applied (5, 8, 9, 13). In contrast, when jumps were performed with the hexagonal barbell significantly greater peak power was produced with an external resistance of 20% 1RM compared to all other conditions. No significant difference in peak power was found when comparing the unloaded jump and the HBJ performed with 40% 1RM. To maximize power during any exercise the load selected must provide the best compromise between force and velocity (5). Vertical jumps enable athletes to generate very high velocities with body mass providing enough resistance to produce substantial force output (9). The different load-power relationships of the SBJ and HBJ may be explained by the same mechanisms postulated to affect the associated kinematics and kinetics. If the addition of a barbell on the shoulder unfavourably alters technique during the SBJ then increased force associated with the addition of resistance may not compensate for the simultaneous decrease in velocity. In contrast, if the use of a hexagonal barbell enables athletes to maintain a more effective jumping motion the added resistance and subsequent increased force may outweigh decreases in velocity and explain why high power outputs are maintained to approximately 40% 1RM. Alternatively, an ability to displace heavier loads with the hexagonal barbell may also explain the shift in the load-power relationship. As the maximum load that can be lifted increases, body mass accounts for relatively less resistance and may reach a point where it does not permit production of sufficiently large forces. Under these circumstances an external load could be added to optimise the product of force and velocity. It is important to note, however, that increased peak power obtained during the HBJ in the present study was combined with considerably lower vertical jump heights compared to the unloaded condition. The contrasting mechanical profile occurred as a result of the additional resistance shifting the occurrence of a larger peak force earlier in the concentric phase whilst substantially reducing the velocity of the system centre of mass during the final stages of the movement.

At present, weighted jumps are considered to be among the most effective exercises for the development of lower-body power. McBride *et al,* (27) demonstrated that a short eight week training intervention with the SBJ significantly improved strength, power and agility of recreationally trained men. McBride *et al,* (27) also found that the load the subjects used in training had an effect on adaptations. Subjects performing the SBJ with a light load (30% 1RM) exhibited the greatest improvements during fast velocity tasks, whereas, subjects using a heavy load (80% 1RM) demonstrated greater improvements during slow velocity tasks. Similar velocity-specific improvements in strength and power during weighted jump training have also been reported by Cormie *et al,* (8). Weighted jumps are likely to be effective exercises for developing power based on a number of factors. In the scientific literature peak power values as large as 4750 to 6250 W (≈ 45 to 70 W/kg) have been reported for male athletes performing the SBJ (5, 9, 36). In addition, research comparing exercises used frequently by athletes to develop lower-body power (squat, power clean and SBJ) demonstrated that the SBJ produced the largest power values. (9). Whilst the optimal mechanical stimulus to develop muscular power is at present not fully understood (11), it is likely that performing exercises at fast velocities whilst generating large power outputs provides one of the most effective stimuli (1). It has also been hypothesised that large forces absorbed by skeletal muscles during the landing phase of weighted jumps may also be important for promoting training adaptations (23). In a study conducted by Hori *et al,* (23) an experimental protocol was designed to isolate the effect of landing stress during weighted jumps. Subjects performed the SBJ over an 8 week training period where they landed with the entire load or with just their own bodyweight through the assistance of an electromagnetic braking device. As expected, those that performed weighted jumps without the braking device experienced significantly larger ground reaction forces upon landing. Hori *et al,* (23) found subjects that landed with the entire load demonstrated significantly greater improvements in performance during high velocity tasks. In contrast, subjects that experienced less landing stress through the use of the braking device demonstrated greater improvements during low velocity tasks. In a similar study using hydraulic resistance to control the load during jumps, Hoffman *et al*, (21) reported that over a 6 week period athletes that landed with the entire load experienced greater improvements during low velocity 1RM tests compared with those that landed with bodyweight only. The contrasting results obtained by Hori *et al*, (23) and Hoffman *et al*, (21) can be attributed to a number of methodological differences between the studies. Hoffman *et al*, (21) used a heavier load for the weighted jumps (70 vs. 30% 1RM) and included higher level athletes performing additional strength and power training sessions. Whilst the specific mechanisms and adaptations obtained when landing from weighted jumps are at present unknown, it is evident that the large forces and eccentric loads imposed can provide an additional training stimulus.

Previous attempts have been made to modify weighted jumps to improve kinematics and kinetics. During most forms of weighted jumps athletes are unable to use their arms to contribute to the jumping motion. Specialist equipment has been created that enables athletes to apply substantial resistance whilst allowing arm movement and closer replication of jumping action used in sport. The VertiMax is a commercially available product which features a platform on which athletes can perform sport-specific movements such as the vertical jump. The platform contains bungee cords integrated through a pulley system that can be attached to the athlete's waist, hands and thighs to provide a constant resistance. To investigate the effectiveness of the VertiMax, Rhea *et al,* (32) conducted a study with high school athletes performing periodized strength and plyometric training over a 12 week period. The athletes were randomly allocated between two groups that each performed the same volume of lower-body resistance, sprint and body-weight jumping exercises. In addition to the regular sessions, one group supplemented their training with resisted jump exercises performed on the VertiMax. The group that performed the supplementary exercises experienced significantly greater increases in power over the 12 week period as measured during an unloaded vertical jump test (32). The authors attributed the greater improvement with the inclusion of training on the VertiMax to increased intensity and improved transfer of training due to task specificity. However, the difference reported between groups may be attributable to additional training volume performed by those using the VertiMax. Future research comparing the VertiMax to other forms of weighted jumps is required to determine the extent to which simulating the jumping action influences adaptation.

There have been safety concerns raised over the use of weighted jumps. It has been suggested that large forces produced during the concentric and landing phases may cause injury, which necessitates an extensive warm-up and performance of the exercise in a non-fatigued state to reduce the risks (34). Also, when performing weighted jumps with a barbell positioned on the shoulder there is concern that the load can forcefully impact the cervical vertebrae when landing (34). Positioning the load in the hands during the HBJ avoids this concern and should improve the safety and comfort of performing weighted jumps. To provide the same loading potential as the SBJ athletes performing jumps with the hexagonal barbell must be able to grip the load. In the present study none of the athletes used supportive grip aids beyond chalk and were able to lift a significantly heavier 1RM load in the hexagonal barbell deadlift compared to the back squat. This result demonstrates the stability and large potential range of loads that can be applied when performing the HBJ.

PRACTICAL APPLICATIONS

Weighted jumps have been shown to be an effective exercise for developing lower-body power. Customarily, weighted jumps are performed with the load placed on the posterior aspect of the shoulder. The results of this study demonstrate that improved kinematics and kinetics can be achieved by changing the position of the load from the shoulder to arms' length through the use of a hexagonal barbell. This change in load position may also improve the safety and comfort when performing the exercise. Previous research has shown that improvements in muscular power are greatest when ballistic exercises such as weighted jumps are performed with loads ranging from 0 to 50% 1RM (10). In addition, complete training programs aimed at developing athletes' ability to produce force and power against a range of resistances which may be encountered in sport should also include traditional resistance exercises using heavy loads (8). Based on the results from this study, it is recommended when using weighted jumps as part of a training program to improve muscular performance the exercise should be performed using a hexagonal barbell with loads previously suggested by researchers (i.e., 0 to 50% 1RM).

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Figure Legends.

Figure 1- Straight barbell jump

Figure 2- Hexagonal barbell jump

Figure 3-Mean (+1SD) vertical jump heights across conditions. * Significantly (p < 0.05) different from all other trials. # Significant (p < 0.05) difference between SBJ and HBJ for corresponding load.

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