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Impact of performing heavy-loaded barbell back squats to volitional failure on lower limb and lumbo-pelvis mechanics in skilled lifters.

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Title

Impact of performing heavy-loaded barbell back squats to volitional exhaustion on lower limb and lumbo-pelvis mechanics in skilled lifters.

Abstract

A common practice in resistance training is to perform sets of exercises at, or close to failure, which can alter movement dynamics. This study examined ankle, knee, hip, and lumbo-pelvis dynamics during the barbell back squat under a moderate-heavy load (80% of 1 repetition maximum (1RM)) when performed to failure. Eleven resistance trained males performed three sets to volitional failure. Sagittal plane movement dynamics at the ankle, knee, hip, and lumbo-pelvis were examined; specifically, joint moments, joint angles, joint angular velocity, and joint power. The second repetition of the first set and the final repetition of the third set were compared. Results showed that while the joint movements slowed ($p < 0.05$), the joint ranges-of-motion were not altered There were significant changes in most mean joint moments ($p < 0.05$), indicating altered joint loading. The knee moment decreased while the hip and lumbo-pelvis moments underwent compensatory increases. At the knee and hip, there were significant decreases ($p < 0.05$) in concentric power output ($p < 0.05$). Whilst performing multiple sets to failure altered some joint kinetics, the comparable findings in joint range-of-motion suggests that technique was not altered. Therefore, skilled individuals appear to maintain technique when performing to failure.

Keywords: fatigue; squat; strength training; kinetics; kinematics.

Introduction

The barbell back squat is a compound exercise frequently used to elicit both strength and power gains in the lower body musculature. When strength gains or hypertrophy are desired, a program consisting of heavy loads (85-100% of one-repetition maximum (1RM)) coupled with a low number of repetitions is recommended (Smilios, Häkkinen, & Tokmakidis, 2010). Conversely, moderate loads (40-60% of 1RM) and a high number of repetitions are employed to optimise muscular endurance and/or power (Farris, Lichtwark, Brown, & Cresswell, 2016). Irrespective of training methods, several sets of exercises are completed close to, or to the point of failure, so as to induce sufficient metabolic and neuromuscular training stimuli (Raeder et al., 2016). While exhaustion is expected when exercising at the completion of such working sets, it can cause changes in movement dynamics and increase the risks of injuries (Vakos, Nitz, Threlkeld, Shapiro, & Horn, 1994; Webster, Austin, Feller, Clark, & McClelland, 2015). Thus, it is important for practitioners to understand and identify any compensatory movement patterns when performing resistance exercises to improve potential injury risk detection, reduce injury incidences, and ensure programs are safely and effectively executed.

Several studies have reported that mechanical stress significantly alters movement patterns during squatting exercises (Hooper et al., 2014; Hooper et al., 2013; Longpré, Acker, & Maly, 2015; Pick & Becque, 2000; Smilios et al., 2010). However, the majority of these studies have examined squatting mechanics following fatigue-inducing protocols. For example, Longpré and colleagues (2015) reported reductions in knee joint loading and vastus lateralis (VL) electromyographic (EMG) activity during squatting exercises after seated knee flexion and extension exercises. Similarly, Smilios and colleagues (2010) observed decreases in VL and vastus medialis (VM) EMG activity during the concentric phase, decreases in concentric external work rates (power), and decreases in concentric movement speeds during squatting exercises immediately after performing four sets of 20 repetitions of squats at 50% of 1 RM. While these findings collectively suggest that injury risks may increase during squatting exercise performed after mechanical stress-inducing protocols, work is needed to examine if these changes are also present during working sets.

The work of Hooper and colleagues (2014) is one of the few studies that examined how squatting mechanics change over the course of working sets. They examined changes during a pyramid scheme (ten repetitions down to one) against an external load. In the early working sets, they observed a reduction in knee flexion coupled with an increase in the degree of trunk flexion. Accordingly, the performance of multiple sets against an external load, with minimal rest in-between, appears to alter squat mechanics, which may have implications for training practice and injury risks (Escamilla, 2001; Potvin, McGill, & Norman, 1991). While the work by Hooper and colleagues (2014) gives insight into changes that can occur when multiple sets are performed, the resistance exercises were performed at moderate loads (i.e., 75% of 1RM), which is not optimal for muscular strength development. A more appropriate protocol is to use a heavier load and perform sets of exercises close to, or to the point of failure (Raeder et al., 2016). To the authors’ knowledge, no study has examined the mechanics of squatting exercises under a heavy external load typically used to optimise strength development.

While previous findings on the impact of mechanical stress on squatting dynamics are insightful (Hooper et al., 2014; Hooper et al., 2013; Longpré et al., 2015; Pick & Becque, 2000; Smilios et al., 2010), there are a number of limiting factors. For example, knee joint dynamics have been the primary focus of most previous studies (Longpré et al., 2015; Pick & Becque, 2000; Smilios et al., 2010), with limited emphasis on other major lower limb joints, such as the ankle and hip, and how these contribute to the external work rates. It is possible that compensatory changes may take place at other lower limb joints which may increase injury risk, particularly during sets performed to, or close, to failure. In addition, previous work has examined the impact of load on the lumbar kinematics and found that increasing load results in significant increases in hyperextension, which in turn increases the compressive stress in the lumbar region (Walsh, Quinlan, Stapleton, FitzPatrick, & McCormack, 2007). However, the impact that fatigue has on lumbar kinematics and subsequent loading has received little attention. Finally, very few studies have examined working sets, particularly those performed to failure, with a heavy external load. While squatting to failure under a heavy external load (i.e., 85% of 1RM) has been reported to alter lower limb dynamics (Pick & Becque, 2000), squatting mechanics were only examined following a single set. Understanding the dynamics of squatting exercises performed to, or in proximity to, failure under moderate-heavy loads across multiple sets is essential as it is common practice for muscular strength and hypertrophic development (Raeder et al., 2016). The purpose of this present study was to examine how performing multiple sets to volitional failure alters ankle, knee, hip, and lumbo-pelvis kinetics and kinematics under a moderate-heavy load (i.e. 80% 1RM). It was hypothesised that performing to volitional failure with result in significant alterations to ankle, knee, hip, and lumbo-pelvis kinetics and kinematics due to compensatory changes.

Materials and methods

Participants

Eleven resistance-trained adult males (age = 26.2 ± 3.8 yrs; mass = 82.4 ± 8.9 kg; height = 1.78 ± 0.08 m; 1RM = 138 ± 19 kg) participated in this study. An inclusion criteria required participants to be uninjured and capable of squatting one and a half times their body weight for 1RM without the use of lifting aids (i.e. weight belt or knee sleeves). According to an a priori sample size calculation, eleven participants was sufficient to generate a statistical power of 80% with an alpha level at 0.05 based on previously collected data (Hooper et al., 2013; Longpré et al., 2015). Procedures undertaken in this study were approved by the Institutional Human Research Ethics Committee and in accordance with the Declaration of Helsinki. All participants were informed of the potential risks and gave written informed consent at the commencement of their involvement.

Procedures

A within-subject repeated measures design was used, consisting of two sessions on two different days. The first session was a familiarisation session and the second was a data collection session. Within both sessions, participants were not permitted to use any lifting aids (i.e. weight lifting shoes, weight belts etc.) and all wore standardised footwear for both sessions.

Within the familiarisation session, participants first undertook a self-selected warm up routine which was noted and standardised across both sessions.

Following the warm up, their 1RM was determined. Participants were instructed to squat as deep as possible whilst using their regular technique (i.e., bar positioning, stance width, foot rotation, and movement speed) to optimise ecological validity (Southwell, Petersen, Beach, & Graham, 2016). Participants had 15 minutes recovery following the 1RM test before they completed a single set of back squats using 80% of 1RM for as many repetitions as possible (AMRAP). The AMRAP test was terminated when a participant could no longer lift the load (concentric failure). The AMRAP test was undertaken during the familiarisation session to ensure participants became familiar with the stress prior to data collection.

Once participants were fully recovered (≥ 2 days) from the familiarisation session, they completed the data collection session. Within this session participants performed three AMRAP tests using 80% of their predetermined 1RM with two minutes of rest given between each AMRAP test. Two minutes was chosen as this has been used previously when examining squatting and fatigue (Smilios et al., 2010).

In the data collection session, participants had retroreflective markers (Figure 1) positioned on anatomical landmarks of their lumbar and lower body (Besier, Sturnieks, Alderson, & Lloyd, 2003; Crewe, Campbell, Elliott, & Alderson, 2013a, 2013b; Vu, Walker, Ball, & Spratford, 2017). Markers were placed over the medial and lateral epicondyles, medial and lateral malleoli, calcaneus, heads of the first and fifth metatarsals, left and right anterior superior iliac spines, and left and right posterior superior iliac spines. Marker clusters consisting of three markers were affixed to the shank and thigh. Markers were also placed over the spinous processes of the first, third, and fifth lumbar vertebrae and 5 cm lateral to the second and fourth lumbar vertebrae. These markers were used to define eight rigid segments being lumbar, pelvis, left and right thighs, left and right shanks, and left and right feet. Locations of the markers were tracked during the AMRAP tests using 10 infra-red Vicon MX-T40S cameras (Oxford Metrics, Oxford, UK). The cameras also tracked two makers positioned on either end of the barbell which allowed bar movement to be measured. Marker data were collected at 250 Hz. Two force plates (AMTI, Watertown, US) were used to collect the ground reaction force data acting on each foot (one foot per force plate). Force plate data were collected at 1000 Hz. All force plate and marker data were collected simultaneously within Vicon Nexus v2.6 (Oxford Metrics, Oxford. UK).

****Figure 1 near here****

Data Processing and Analysis.

Marker trajectory and analogue force plate data were post-processed within Vicon Nexus. All data were filtered using a fourth order low-pass Butterworth filter with a cut-off frequency of 12 Hz, defined following a residual analysis (Winter, 2009). Joint kinetics were calculated using a standard inverse dynamics approach previously described in the literature (Besier et al., 2003; Crewe et al., 2013a, 2013b).

To identify if changes in squat mechanics resulted from completing the three AMRAP sets, data from the second repetition of the first AMRAP test were compared with the last repetition of the third AMRAP test (i.e., final AMRAP test). The second repetition of the first AMRAP test was treated as the baseline (i.e., non-exhausted state) as opposed to the first repetition to ensure stability (Legg, Glaister, Cleather, & Goodwin, 2017). The final complete repetition of the third AMRAP test was the repetition prior to the subject failing to lift the load, which was indicative of a working set, performed to failure.

Sagittal plane dynamics at the ankle, knee, hip, and lumbo-pelvis (defined as a segment between L1 and L5 relative to the pelvis) were examined. Specifically, joint moments, joint angles, joint angular velocity, and joint power were examined. Both moments and power were included as previous work has found that different compensations in these measures can occur at different joints (Farris et al., 2016; Flanagan & Salem, 2008). All joint moment and power data were normalised for system load (Legg et al., 2017). Discrete data points were derived from the time-series data of each leg and averaged to allow comparison between the movement in the second repetition of the first AMRAP and last repetition of the third AMRAP. The average moment during the examined repetitions at ankle, knee, hip, and lumbo-pelvis joints were determined to assess the joint load. The average moments at the aforementioned joints during the concentric phase were also determined to assess for changes in performance of the movement. The average power and joint angular velocity during the concentric phase at the ankle, knee, and hip were also examined to identify if work contributions changed with fatigue. Average power values were chosen over peak power as this is a better indicator of the amount of mechanical work done and the rate it was done at (Farris et al., 2016). To assess for range of motion changes, peak joint (sagittal plane) and bar displacements (all three planes) were determined. The average bar speed during the concentric phase was also examined to identify if there was an overall change in the speed of the movement when fatigued.

Statistical Analyses

The measure of central tendency and dispersion of each dependent variable was reported as mean ± standard deviation. Normality was assessed using the Shapiro-Wilk test with all data found to be normally distributed. Differences in the variables between the two time points were then examined using paired t-tests, with the alpha level set at 0.05. To determine the magnitude of differences between the two time points, effect sizes (ES; Cohen's *d*) were also computed and classified as trivial (0 – 0.19), small (0.20 – 0.49), moderate (0.50 – 0.79), and large (≥0.80) (Cohen, 1988). All statistical analyses were carried out in SPSS v22 (IBM Corp., Armonk, USA).

Results

The average load lifted by the participants during the AMRAP tests was 110 ± 15 kg and the average number of repetitions completed was 11 ± 3 in test one, 7 ± 2 in test two, and 5 ± 2 in test three. Significant difference in mean joint moments were observed at the knee, hip, and lumbo-pelvis. At all three of the aforementioned joints, large effects were detected (Table 1; ES = 0.90 – 1.23). The hip and lumbo-pelvis saw significant increases of 0.07 $Nm.kg^{-1}$ and 0.14 $Nm.kg^{-1}$ respectively. The knee saw a significant decrease of 0.06 $Nm.kg^{-1}$.

Data for the concentric phase of the squat revealed there were a number of significant differences. Mean moments at the hip and lumbo-pelvis were altered (Table 1; $p < 0.05$). A moderate effect was detected at the hip (ES = 0.73) where a significant increase of 0.08 $Nm.kg^{-1}$ was observed. A moderate effect was also detected at the lumbo-pelvis (ES = 0.72) where a significant increase of 0.16 Nm.kg^{-1} was observed. For work rates, only power output at the knee and hip were altered (Table 1; $p < 0.05$). A large effect (ES = 1.67) was detected in the mean hip concentric power output where a significant decrease of 0.15 Watts.kg^{-1} was observed. A large effect was also detected in the mean knee concentric power output where a significant decrease of 0.34 Watts.kg^{-1} was observed.

****Table 1 near here****

There were no significant differences in the range of motion at any joint (Table 1; $p > 0.05$) or in the barbell range of motion (Table 2; $p > 0.05$). While ranges of motion were not significantly altered, there were significant differences in joint angular velocities and in the speed of barbell movement during the concentric phase. Differences in mean joint angular velocity were observed at the hip, knee, and ankle (Table 1; $p < 0.05$). Large effects were detected at all three joints (ES = 1.14 – 1.35) where significant decreases of 0.30 rad.s^{-1}, 0.44 rad.s^{-1}, and 0.14 rad.s^{-1} were observed at the hip, knee, and ankle respectively. For the barbell movement, a large effect was detected in concentric speed (ES = 1.05) where a significant (Table 2; $p < 0.05$) decrease of 0.18 m.s^{-1} was observed.

****Table 2 near here****

Discussion

The aim of this study was to examine the impact of performing heavy back squats (i.e., 80% of 1RM) to failure across multiple sets on squatting dynamics amongst experienced lifters. As has been the case with previous studies that have examined squatting during mechanical stress, performing a back squat exercise to failure across multiple sets significantly altered the movement dynamics of a back squat exercise, possibly due to fatigue. In the current study, dynamics within the final repetition of the third AMRAP were significantly altered at the ankle, knee, hip, and lumbo-pelvis, with a reduction in barbell movement speed, suggesting that compensatory changes occurred. Overall, the findings suggest that some aspects of biomechanical movement patterns during a back squat are altered when undertaken to failure across multiple working sets.

The inability to maintain the barbell movement speed, was not surprising as there were also significant decreases in the angular velocity at the ankle, knee, and hip. Furthermore, others have also observed reductions in movement speed across multiple sets of back squats (Smilios et al., 2010). Given there were significant decreases in joint angular velocity it is not surprising decreases in joint power outputs were also observed as power is the product of the joint's angular velocity and moment (Winter, 2009). Smilios and colleagues (2010) have also observed significant changes to power output with fatigue. In the present study, reductions in power outputs at the knee and hip during the concentric phase were observed. At the knee this was also coupled with a small decrease in mean concentric moment which further explains the reduction in the knee power output. Interestingly however, at the hip the mean concentric moment increased with fatigue indicating that the decrease in joint angular velocity had a larger impact on the power output at the hip than the moment. The increase in hip moment suggests that the hip extensors supersede that of the knee extensors as individuals reach failure across multiple sets during the concentric phase. These biomechanical changes should be considered when prescribing back squat exercises to failure, particularly for individuals prone to hip injuries, or those returning from injuries.

For this cohort, there were significant differences in mean joint moments observed at the knee, hip, and lumbo-pelvis at the conclusion of the third AMRAP, indicating that joint loading was altered. A decrease in knee loading was detected which is in line with the work by Longpré and colleagues (2015) who observed reductions to knee moments during lunging and squatting following a fatiguing protocol. In this current study, the decrease in loading at the knee was coupled with an increase in loading at the hip. This suggests that as the participants fatigued, there may have been a compensatory change undertaken by the musculature surrounding the hip. Changes in muscle activation within these muscles have been observed in the work of others. In a previous study that examined changes during a single set to failure, Pick and Becque (2000) reported that the quadriceps muscle activation was at its greatest in the final repetitions prior to failure. Based on these findings, Pick and Becque (2000) highlighted the importance of prescribing repetition ranges that are at, or close to, to elicit sufficient levels of muscle activation for optimal strength adaptation. While this previous study highlights the importance of including sets performed to failure from a muscle adaptation perspective, it does not examine whether performing this type of activity in training could significantly alter an individual's movement dynamics and impact on injury risk. The results surrounding the mean moments in the current study gives insight into this.

Although joint loading was altered, there was no compromise in the range of motion of the lower limb joints. This finding is of particular importance in the lumbar region as any altered range of motion at this site may result in a loss of spinal stability, thereby increasing injury risk (Schoenfeld, 2010). While the range of motion in the lumbar region remained comparable, there was an increase in lumbo-pelvis loading. This suggests that when approaching failure, greater stabilisation was required from the musculature in this region to maintain posture, which may have implications for injury risks. Thus, practitioners should encourage their athletes to rely on their task-intrinsic cues (e.g., kinaesthetic feedback) during back squats to failure, as visual feedback would be insufficient to detect kinetic alterations in the lumbar region with unaltered kinematics.

As noted above, the lower limb joint ranges of motion at the end of the third AMRAP were comparable with those observed at the start of the first AMRAP. These findings indicate that the participants were consistent with their technique, despite potential attenuation in muscular contractility, and compensatory movements were not induced which can put an individual at an increased injury risk and limit the effectiveness of the exercise (Escamilla, 2001). The non-significant change in joint range of motion conflicts with the findings of others who have examined the impact of fatigue within cohorts skilled in squatting exercises. Hooper and colleagues (2013) observed that fatigue caused a reduction in range of motion at the knee and hip however it should be noted that they examined body weight squats before and after an extreme fatiguing protocol whereas loaded squats were examined in the present study. In subsequent work by Hooper and colleagues (2014), they expanded their investigation to examine how the joint range of motion changed during the squatting component of a fatiguing protocol which consisted of back squats, deadlifts, and bench presses using 75% of 1RM. This work found there was less motion at the knee and a greater degree of trunk flexion at the start of the protocol and suggested this was a demonstration of self-preservation by their participants. This pattern of self-preservation was not observed in the present study, possibly due to the fact that only squats were performed while the fatiguing protocol of the aforementioned study consisted of back squats, deadlifts, and bench presses. The technique changed observed by Hooper and colleagues (2014) are detrimental, due to the reduced knee flexion resulting in less muscle activity and the increased trunk flexion resulting in altered lumbar loading. The findings of this present study however, suggest that performing multiple sets to volitional failure does not appear to alter technique in the same way.

There are a number of limitations that should be considered within this study. A highly skilled cohort was examined, and thus findings may not be inferred to individuals with less experience in resistance training. While this can be seen as a limitation, the findings are highly applicable to practitioners who work with skilled individuals. In addition, the squatting mechanics were examined using a single load of 80% of 1RM. It would be beneficial to examine if dynamics are changed by incorporating varying loads. Future work could also consider examining mechanics throughout the entire working set to identify when technique alterations specifically occur.

Conclusion

The findings of this study indicate that, for experienced lifters, performing multiple sets to volitional failure results in some compensatory changes that could lead to increases in injury risk. Specifically, loading at the knee, hip, and lumbo-pelvis were altered. A reduction in the mean moment was observed at the knee while increases were observed at the hip and lumbo-pelvis. The increase at the hip may be a compensatory change due to the change at the knee while the increase at the lumbo-pelvis loading may lead to an increase the risk of injury and should be considered when prescribing repetition ranges.

While the speed of the movement was reduced at the conclusion of the third set, there were no significant decreases in the joint range of motion which indicates that these individuals were not compromising squat depth. This is important from a strength development standpoint as a reduction in range of motion would result in less muscle activity (Escamilla, 2001). The reduction in movement speed was coupled with reductions in power output at both the knee and hip. This suggests that if practitioners are designating programs where power is of importance, then consideration should be given as to whether later working sets should be performed to volitional failure.

Future work should expand on this study to assess if the changes observed here are also observed when different loads are used and between differing skill levels.

Disclosure statement

The authors report no conflict of interest.

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TABLES

Table 1. Mean (±SD) of the magnitudes of the analysed joint variables in the second and final repetitions of the AMRAP test.

	Second repetition				Final repetition			
	Joint				Joint			
Variable	Hip	Knee	Ankle	Lumbo-pelvis	Hip	Knee	Ankle	Lumbo-pelvis
Mean moment (Nm.kg^{-1}) [ABC]	0.74 (0.09)	0.76 (0.12)	0.21 (0.10)	1.70 (0.14)	0.81 (0.12)	0.70 (0.11)	0.27 (0.10)	1.84 (0.15)
Mean concentric moment (Nm.kg^{-1})[DE]	0.76 (0.12)	0.69 (0.13)	0.23 (0.14)	1.76 (0.22)	0.84 (0.14)	0.62 (0.15)	0.29 (0.13)	1.92 (0.18)
Mean concentric angular velocity (rad.s^{-1})[FGH]	1.09 (0.08)	1.50 (0.25)	0.47 (0.09)	-	0.79 (0.24)	1.06 (0.30)	0.33 (0.12)	-
Mean concentric power (Watts. kg^{-1})[IJ]	0.62 (0.10)	0.89 (0.20)	0.11 (0.07)	-	0.47 (0.13)	0.55 (0.15)	0.10 (0.05)	-
Peak angle (°)	107.34 (9.90)	124.36 (15.88)	37.2 (8.23)	18.60 (4.82)	110.03 (13.97)	127.59 (18.43)	38.50 (7.20)	18.98 (5.83)

[A] Significant increase in mean moment at the hip ($p = 0.01$; ES = 1.08)
[B] Significant decrease in mean moment at the knee ($p = 0.02$; ES = 0.90)
[C] Significant increase in mean moment at the lumbo-pelvis ($p = 0.00$; ES = 1.23)
[D] Significant increase in mean concentric moment at the hip ($p = 0.046$; ES = 0.73)
[E] Significant increase in mean concentric moment at the lumbo-pelvis ($p = 0.049$; ES = 0.72)
[F] Significant decrease in mean concentric angular velocity at the hip ($p = 0.00$; ES = 1.35)
[G] Significant decrease in mean concentric angular velocity at the knee ($p = 0.00$; ES = 1.26)
[H] Significant decrease in mean concentric angular velocity at the ankle ($p = 0.00$; ES = 1.14)
[I] Significant decrease in mean concentric power at the hip ($p = 0.00$; ES = 1.67)
[J] Significant decrease in mean concentric power at the knee ($p = 0.00$; ES = 1.50)

Table 2. Mean (±SD) of the magnitudes barbell displacement and velocity in the second and final repetitions of the AMRAP test.

	Second repetition	Final repetition
Vertical displacement (m)	0.60 (0.08)	0.57 (0.15)
Antero-posterior displacement (m)	0.06 (0.17)	0.08 (0.05)
Medio-lateral displacement (m)	0.02 (0.01)	0.03 (0.01)
Mean concentric velocity ($m.s^{-1}$)[A]	0.48 (0.06)	0.30 (0.13)

[A] Significant decrease in mean barbell velocity during the concentric phase ($p = 0.00$; $d = 1.50$)

FIGURE LIST

Figure 1. Retro-reflective marker set used to define the body as eight rigid segments being lumbar, pelvis, left and right thighs, left and right shanks, and left and right feet. Sagittal plane movement dynamics at the ankle, knee, hip, and lumbo-pelvis were derived from the three-dimensional marker data. Note: some additional markers there are not defined in the text are visible but were not used for any calculations.