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TITLE

The effect of footwear on the biomechanics of loaded back squats to volitional exhaustion in skilled lifters

RUNNING HEAD

Effect of footwear on back squat movement dynamics.

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ABSTRACT

This study examined whether footwear influences the movement dynamics of barbell back squats to volitional exhaustion in experienced lifters. Eleven males (1RM = 138 ± 19 kg; 1RM % body weight = 168 ± 18%) performed three sets (5 – 12 ± 4 repetitions per set) of loaded barbell back squats to volitional exhaustion using raised-heel and flat-heel footwear. Barbell motion as well as moments, angles, angular velocity, and power in the sagittal plane at the ankle, knee, hip, and lumbo-pelvis were examined during the second repetition of the first set (T_{second}) and the final repetition of the third set (T_{final}). There were significant reductions ($p < 0.05$) in lower limb concentric angular velocity and power output for both footwear conditions. For the raised-heel condition at T_{final}, hip and knee concentric angular velocity was significantly slower ($p < 0.05$), and knee concentric power output was significantly less ($p < 0.05$) compared to the flat-heel condition. A reduction in barbell velocity was not observed for the raised heel condition despite there being reduction in hip and knee angular velocities. Furthermore, no differences were identified in lower limb joint moments or any of the biomechanical characteristics of the lumbo-pelvis between the footwear conditions. The findings of this study suggest that neither type of footwear reduced joint loading or improved joint range-of-motion.

KEY WORDS

Kinematics; kinetics; strength training; fatigue; squatting; shoes.

INTRODUCTION

The barbell back squat is a common exercise utilized by strength and conditioning coaches to develop lower limb strength and power. Lifters will usually perform repeated sets in training with repetition ranges and loads varying depending on the desired purpose of the training session. A common practice within sessions is to use loads and repetition ranges that result in the lifter working at, or close to, the point of failure to ensure sufficient training stimuli (15). Although performing repetitions under fatigue may provide an important stress to elicit adaptation, it can also perturb the lifter's squatting mechanics (2, 22, 24). Previous work has found that as a lifter fatigues there are reductions in knee joint loading (2, 13) and increases in hip and lumbo-pelvic loading (2). There are also reductions in power output (2, 20), joint range-of-motion (ROM) (9, 10), and movement speed (2, 20). These changes may impair training performance and increase stress on the soft tissues within joints, which may increase the risk of sustaining an injury (9). Previous work has suggested that lifters may be able to reduce the impact of some of these issues by employing ergogenic aids during lifting tasks (3, 8, 12, 27).

Raised-heel shoes have become increasingly popular due to their commercial availability and the variety of selections lifters can choose from to accommodate their training needs. Raised-heel shoes, commonly referred to as weightlifting shoes, are designed with a stiff incompressible sole which will generally have a heel wedge that results in the heel being raised 2.5 cm (17). The incompressible sole of a weightlifting shoe has an advantage over the soft soles of running or athletic footwear, as it does not absorb energy and allows greater vertical force production, which is important to facilitate lifting heavier loads (17).

Several studies (3, 12, 17, 19, 21, 25) have investigated the impact of footwear on barbell back squat movement dynamics, with significant differences reported in both joint kinematics and kinetics between footwear conditions. For example, squatting with a raised-heel resulted in significantly less peak trunk flexion (3, 12, 17, 21) and hip flexion (3, 21), while displaying increased knee flexion (3, 12, 19, 21) and dorsiflexion (12, 21, 25). The increase in knee ROM that a raised-heel elicits may be beneficial as previous work has found that greater knee ROM during squatting increases knee-extensor musculature activity, allowing for greater training stimuli (7). It has also been suggested that lifting with a reduced degree of trunk flexion may reduce shear forces, particularly in the lumbar region, thereby minimising the risk of injury (14).

Considering joint kinetics, squatting with a raised-heel also results in a changes to peak joint moments (21). Southwell and colleagues (21) found that peak knee-extensor moments increased while peak hip-extensor moments decreased when lifters used weightlifting shoes in comparison to barefoot. This finding indicates that there is a greater contribution from musculature surrounding the knee when raised-heel footwear is used. If targeting knee musculature is a focus within training, then this redistribution could be beneficial; however, this could be detrimental for anyone who suffers from knee pathologies as this would also increase knee joint loading. A different pattern of redistribution of peak joint moments has also been reported for raised-heel squatting (12). Legg and colleagues (12) observed that squatting with a raised-heel resulted in an increase in peak sagittal plane ankle moment while the hip and knee moments were not significantly altered. The conflicting findings in the aforementioned studies could be due to the fact that Legg and colleagues (12) compared weightlifting shoes with athletic shoes, whereas Southwell and colleagues (21) examined barefoot and weightlifting shoe conditions.

The aforementioned studies provide insight into how movement changes when squatting with a raised heel. However, these studies only examined a single set with few repetitions, which does not replicate common training practice where back squats are typically performed at or close to the point of volitional exhaustion across multiple sets. Examining the impact a raised-heel has under typical training conditions is important as previous work has found that performing multiple sets to volitional exhaustion results in altered joint dynamics (2). Given that a raised-heel has been previously found to redistribute loading (12, 21), it would be beneficial to examine if exercise-induced stress alters the kinetics and kinematics. Therefore, the aims of this study were:

i. to examine lower limb and lumbo-pelvic kinematics and kinetics during the performance of barbell back squats across multiple sets to volitional exhaustion while wearing raised-heel and flat-heel footwear, and

ii. to compare the barbell back squat lower limb and lumbo-pelvic kinematics and kinetics between raised-heel footwear and flat-heel footwear conditions.

It was hypothesized that that performing barbell back squats to volitional exhaustion with both types of footwear would result in significant alterations in ankle, knee, hip, and lumbo-pelvic kinetics and kinematics due to compensatory changes. It was also hypothesized that the changes in back squat mechanics observed for a raised-heel condition due to volitional exhaustion would be different to that observed for a flat-heel condition.

METHODS

Experimental Approach to the Problem

A within-subject, repeated measures, randomized crossover design was used to examine the biomechanics of loaded barbell squats in flat-heel and raised-heel conditions. For each shoe condition, subjects undertook two familiarization sessions and two experimental sessions (total of four sessions undertaken across four different days) (Figure 1). Subjects were advised to limit lower body training in the 48 hours before each session and to eat and drink as they normally would prior to each session. In each familiarization session, a one repetition maximum test (1RM test) was conducted wearing the assigned shoe condition. This was followed by a test where they performed a set of barbell back squats for as many repetitions as possible (AMRAP test) using 80% of their 1RM. This AMRAP test was conducted during the familiarisation sessions to ensure that subjects were aware of the stress associated with an AMRAP test prior to the experimental sessions. In the two experimental sessions (one per shoe condition), subjects performed three AMRAP tests using the same 80% loads as in their familiarization sessions with two minutes of rest given between each test. Kinematic and kinetic data were collected during the AMRAP tests from which joint level movement dynamics were derived and examined.

Figure 1 near here

Subjects

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; 1RM % body weight = 168 ± 18%) took part in this study. Subjects had been resistance training for a minimum of three years and were training a minimum of three times each week. All were familiar with undertaking strength training in raised-heel and flat-heel footwear. Procedures in this study were approved by the Institutional Human Research Ethics Committee and in accordance with the Declaration of Helsinki. Participation was voluntary and subjects were free to withdraw at any time. All subjects were informed of the potential risks and gave written informed consent. The inclusion criteria required that subjects were able to squat 1.5 times their body weight for at least one full repetition without any form of assistance. An a priori sample size calculation confirmed eleven participants was sufficient to generate statistical power of 80% with an alpha level at 0.05 based on previously collected data (10, 21).

Footwear conditions

For both the raised-heel and flat-heel conditions, the same flat-soled brand of shoe (Anko, Perth, Australia) in a size that suited each individual. The shoe had the insole removed for both conditions and was worn an in-shoe heel wedge (The Wod Life inc, Adelaide, Australia) for the raised-heel condition. A small custom-build piece of timber was added to the bottom of the heel wedge so that when worn, the heel was raised 2.5 cm which is the typical height of a weightlifting shoe (17)(Figure 2). Pilot testing was undertaken to ensure that the fit of the shoe was not affected by the addition of the in-shoe heel wedge. The subjects were not permitted to use any additional lifting aids such as knee sleeves and weight belts to standardize the testing protocols.

Figure 2 near here

Familiarisation sessions

At the commencement of each familiarization session (Figure 1), the subjects undertook their normal warm up routine which was standardized across all sessions. Once adequately warmed up, the subjects then undertook their 1RM test where they were instructed to squat using their regular technique (i.e., bar positioning, stance width, foot rotation, movement speed, and squat depth) to optimise ecological validity (21). Subjects had 15 minutes of recovery following the 1RM test before they completed a single set of back squats using 80% of 1RM for as many as repetitions as possible (AMRAP). Subjects were again instructed to use their regular technique. The AMRAP test was terminated when a subject reached concentric failure.

Experimental sessions

Once the familiarization sessions were complete, two experimental sessions were undertaken (one for each shoe condition; Figure 1). Within these sessions, the subjects performed three AMRAPs with the same load that was used in their familiarization AMRAPs. Two minutes of rest was given between each AMRAP test, which aligns with the length of recovery given in other studies that have examined squatting during exercise-induced stress (2, 20). Within the data collection sessions, subjects had retroreflective markers positioned on the lumbar and lower body anatomical landmarks (1, 5, 6, 23). Marker positions were identical to those described previously by Brice and colleagues (2). Marker locations were used to define eight rigid segments being lumbar, pelvis, left and right thighs, left and right shanks, and left and right feet. Markers were also located on either end of the barbell. All marker locations were tracked using 10 infra-red Vicon MX-T40S cameras (Oxford Metrics, Oxford, UK) sampling at 250 Hz. Two force plates sampling at 1000 Hz (AMTI, Watertown, US) were used to collect the ground reaction force data acting on each foot. Force and marker data were collected within Vicon Nexus v2.6 (Oxford Metrics, Oxford. UK).

Data Processing and Analysis.

Marker trajectory and analogue force plate data were post-processed within Vicon Nexus using the filter methods described previously by Brice and colleagues (2). A standard inverse dynamics approach was used to calculate joint kinetics (1, 5, 6). Data from the second repetition of the first AMRAP test (T_{second}) was compared with the last repetition of the third and final AMRAP test (T_{final}). These two time points were indicative of the extreme ends of the fatigue continuum and comparison between these two points would allow us to identify if changes resulted from squatting to volitional exhaustion. T_{second} was treated as the non-exhausted state, or baseline, and was chosen over the first repetition as the motion in the first repetition can be unstable (12). T_{final} was the repetition immediately prior to the subject failing to lift the load.

Ankle, knee, hip, and lumbo-pelvic sagittal plane dynamics were examined (see Figure 1 for list of all variables). All moment and power data were normalised for system load (12) and data for each leg were averaged. Joint moments were examined to assess how joint loading changed. Power and angular velocity were examined to assess how the work contributions changed. To further assess for ROM and speed of movement changes, barbell displacement in all three planes was determined along with average vertical barbell speed during the concentric phase.

Statistical Analyses

The Kruskal-Wallis test indicated that the dependent measures were departed from the norm, and thus, the measure of central tendency and dispersion of each dependent variable was reported as median and interquartile ranges. Therefore, all analyses were treated with a non-parametric approach. All dependent variables were compared using paired Wilcoxon signed-rank tests. The absolute differences between the outcome measures were compared between T_{second} and T_{final} within the flat-heel and raised-heel conditions, and between the flat-heel and raised-heel conditions at T_{second} and T_{final}. The percentage difference between T_{second} and T_{final} for each outcome measure (%Diff) was also computed for each shoe condition. The %Diff for the two shoe conditions were then compared to further investigate what degree of change resulted when the two types of footwear were worn. These comparisons were undertaken to identify if there were significant differences in the variables elicited by volitional exhaustion for the two conditions, and to assess if there were differences between the shoe conditions. To determine the magnitude of differences, effect sizes (r) were computed using the method described by Rosenthal (16):

$$r = \frac{Z}{\sqrt{N}}$$

where Z is the z-score and N is the number of observations. The effect sizes were classified as trivial (<0.10), small (0.10 – 0.29), moderate (0.30 – 0.49), and large (≥0.50) (4). All statistical analyses were carried out in SPSS v22 (IBM Corp., Armonk, USA), with the alpha level set at 0.05.

RESULTS

When squatting with a raised-heel to volitional exhaustion, there was a significant increase between T_{second} and T_{final} in the mean joint moment observed at the ankle with a large effect being detected ($p = 0.01$; $r = 0.60$; Table 1). There were no significant differences at the other joints examined for the raised-heel condition ($p > 0.05$; Table 1). This was in contrast to the flat-heel condition, where there were increases in mean moments between T_{second} and T_{final} at the hip ($p = 0.01$; $r = 0.58$; Table 2) and lumbo-pelvis ($p = 0.01$; $r = 0.60$; Table 2), and a decrease at the knee ($p = 0.02$; $r = 0.51$; Table 2), all with large effect sizes being detected. There were no significant differences in mean moments between the two shoe conditions at T_{second} or T_{final} ($p > 0.05$; Table 3). Regarding mean moments during the concentric phase, there were no significant changes elicited by volitional exhaustion when squatting with a raised-heel ($p > 0.05$; Table 1), while a number of changes were evident when a flat-heel was used. The flat-heel condition exhibited significant increases between T_{second} and T_{final} in mean concentric moments at the hip where a large effect was detected ($p = 0.02$; $r = 0.80$; Table 2), and lumbo-pelvis where a moderate effect was detected ($p = 0.05$; $r = 0.45$; Table 2). No significant differences were identified in mean concentric moments between the two shoe conditions at any time point for any joint ($p > 0.05$; Table 3).

With respect to the mean work rates during the concentric phase, significant decreases in power output were observed at the hip, knee, and ankle for the raised-heel condition from T_{second} and T_{final} with large effects detected for all three joints ($p = 0.01$ for all; $r = 0.56 – 0.63$; Table 1). However, decreases were only evident at the hip and knee when a flat-heel shoe was used with large effects detected for both ($p = 0.01$ for both; $r = 0.63$ for both; Table 2). When compared between conditions, the work rates at the knee at T_{final} were significantly greater for the flat-heel condition ($p = 0.04$; $r = 0.47$; Table 3). No differences in work rates at the other joints were evident between the shoe conditions ($p > 0.05$; Table 3).

Significant decreases in mean angular velocity between T_{second} and T_{final} were observed at the hip, knee, and ankle for both shoe conditions ($p < 0.001$ – $p = 0.05$; $r = 0.44 – 0.66$; Tables 1 and 2). When the two shoe conditions were compared, the angular velocity at the knee and hip was significantly larger at T_{final} when a flat-heel was used ($p = 0.03$ and $p = 0.04$ respectively; $r = 0.50$ and $r = 0.44$ respectively; Table 3).

When a raised-heel was worn, there were no significant differences in the joint ROM between T_{second} and T_{final} at the lumbo-pelvis, knee, or ankle ($p > 0.05$; Table 1), while at the hip, there was a significant decrease with a large effect observed ($p = 0.02$; $r = 0.51$; Table 1). There were no differences in the joint ROM when a flat-heel was used between T_{second} and T_{final} ($p > 0.05$; Table 2). When the shoe conditions were compared, no differences in joint ROM were evident at T_{second} and T_{final} ($p > 0.05$; Table 3). There were no significant differences in barbell displacement between T_{second} and T_{final} for either shoe condition ($p > 0.05$; Table 4). However, there were significant reductions between T_{second} and T_{final} in the mean barbell velocity during the concentric phase for both footwear conditions, with large effects detected for both (p = 0.00 and p = 0.01 for raised-heel and flat-heel respectively; *r* = 0.66 and *r* = 0.63 for raised-heel and flat-heel respectively; Table 4). When the velocities of the shoe conditions were compared, there were no significant differences in movement velocity detected at T_{second} and T_{final} (p > 0.05; Table 5). While shoe conditions had no impact on movement velocity (p > 0.05; Table 4), the vertical, antero-posterior, and medio-lateral displacements were larger when the raised-heel was worn at both T_{second} and T_{final} (p = 0.00 – 0.05; *r* = 0.44 – 0.66; Table 5).

When the degree of change between the shoe conditions was assessed by comparing %Diff for the two shoe conditions, there were significant differences in concentric angular velocity at the hip and knee. No other significant differences were observed (p > 0.05; Table 3 and 5). The angular velocity %Diff for the raised-heel at both the hip and knee was significantly larger than the %Diff for the flat-heel (p = 0.04 and p = 0.05 for the hip and knee respectively, *r* = 0.46 and *r* = 0.44 for the hip and knee respectively; Table 3).

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

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

****Table 3 near here****

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****Table 5 near here****

DISCUSSION

The first aim of this study was to examine how movement dynamics of experienced lifters changed while performing back squats to volitional exhaustion for multiple sets when wearing raised-heel and flat-heel footwear. The second aim was to examine if the changes to dynamics as a result of volitional exhaustion were significantly different for the two shoe conditions.

According to our results, performing back squats to exhaustion perturbed several lower body and trunk mechanics during both footwear conditions. Furthermore, the changes induced by volitional exhaustion varied between the footwear conditions. For the raised-heel condition, mean moment increased at the ankle, mean concentric power and angular velocity decreased at all joints, and hip ROM decreased. For the flat-heel condition, mean moment increased at the hip and lumbo-pelvis and decreased at the knee, mean concentric power decreased at the hip and knee, and mean concentric angular velocity decreased at all joints. Despite there being differences in how the movements perturbed, between shoe comparisons revealed there were minimal differences between the footwear types and neither type increased joint loading or improved joint ROM.

When examining mean moments at the ankle, knee, hip, and lumbo-pelvis, the mean moment significantly increased at the ankle with volitional exhaustion when the raised-heel was worn. Alternatively, the mean moment increased at the hip and lumbo-pelvis, and decreased at the knee during the flat-heel condition. This finding for the flat-heel condition aligns with what we have previously reported (2) and indicates that compensatory changes may be taking place as the knee musculature is physically stressed. Thus, the way in which the squat dynamics changed with exhaustion appears to differ based on the type of footwear. Despite this, when the mean moments were compared between the two shoe conditions, there were no significant differences at T_{second} and T_{final}, or in the degree of change between T_{second} and T_{final} (i.e. comparison of %Diff data).

Mean moment is a measure of joint loading and the lack of difference in the mean moments of the shoe conditions suggests that neither footwear has an advantage when it comes to reducing loading. If joint loading is reduced then stress to the structures within the joint will be less which may lower the risk of acquiring an injury (2, 22, 24). It has been suggested that using a raised-heel may assist in reducing injury, particularly in the lower back region (17). However, our findings suggest this may not be the case as there were no differences in joint loading and more work is needed to investigate further whether a raised-heel does in fact reduce injury risk. To our knowledge, previous studies have only focused on examining how footwear affects moments when squatting in a non-fatigued state and the findings of these studies conflict with what we observed here. Legg and colleagues (12) observed that moments at the ankle were significantly larger when experienced lifters wore weightlifting shoes, compared with when they wore an athletic shoe. While we did observe that the raised-heel ankle mean moment was larger than the flat-heel at T_{second} (%Diff = 11.83%; $p > 0.05$, $r = 0.125$), there were no significant differences. The findings of our study also conflict with those of Southwell and colleagues (21), who observed that using a raised-heel resulted in an increase in knee moment and a decrease in hip moment. We observed no significant differences in mean moments at the knee or hip at T_{second}, suggesting that these measures were comparable between flat-heel and raised-heel conditions prior to exercise-induced stress. In both aforementioned studies, subjects were able to wear their own footwear and differences in the makes and models may have resulted in a different loading pattern due to varying heel heights and levels of stability (21). It is also possible that the differences between our findings and Legg and colleagues' (12) may be due to the fact that we did not standardize squat depth. However, this does not explain the differences between our findings and Southwell and colleagues' (21) as they too did not standardize squat depth.

There was very little impact on the joint ROM when squatting to volitional exhaustion. There were no significant differences in ROM between T_{second} and T_{final} within the flat-heel condition, while for the raised-heel, there was a decrease in the hip ROM between T_{second} and

T_{final}. This finding for hip ROM aligns with the work of Hooper and colleagues (10), who also examined fatigue effects on squatting and suggested that the reductions in ROM are not unexpected given that a deeper squat requires a larger amount of muscle force to ascend and as a subject fatigues, their ability to generate adequate force may be altered. Despite there being a difference in how joint ROM changed with volitional exhaustion for the two shoe conditions, there were no significant differences in the magnitudes of the ROM for the two shoe conditions at T_{second} and T_{final}, or in %Diff which suggests that footwear type did not significantly alter the movement. Results of previous studies that compared lower limb and lumbo-pelvic ROM for different footwear conditions are varied. For example, Southwell and colleagues (21) found that when raised-heel footwear was worn while squatting with a load of 80% of 1RM, the ROM at the knee was greater and ROM at the ankle and hip was reduced. As has already been discussed, Southwell and colleagues (21) allowed their subjects to use their own makes and models of shoes and noted that there may have been differences in the heel heights and arch supports. Not standardizing their footwear, may explain the discrepancy between findings. One study that standardized footwear was that of Sinclair and colleagues (19), who examined a skilled group of lifters performing with a load of 70% of 1RM. In their study, there were no significant differences in ROM at any joint when a raised-heel was compared with a barefoot inspired shoe. This aligns with our findings and supports the suggestion that there are no differences in joint ROM between the two footwear conditions. This conflicts with what many believe is a key benefit of using a raised-heel during squats. It is commonly believed that using a raised heel results in a reduction in trunk and lumbo-pelvic flexion (12, 17). Our findings supports the growing amount of evidence that conflicts with this (11, 19, 21, 25). However, it should be noted that rasied-heel footwear may have other benefits that were not examined in this study or the studies of others.

Despite there being a significant reduction in hip ROM between T_{second} and T_{final} when the raised-heel was used, this did not translate to a significant decrease in the vertical barbell displacement. This may be due to the slight increases in ROM at both the knee and hip which may have compensated for the reduction at the hip. There were also no significant changes in vertical barbell displacement for the flat-heel condition, or anterior-posterior and medio-lateral displacement between T_{second} and T_{final} for both shoe conditions. When the footwear conditions were compared, there were a number of differences in the barbell motion. At both T_{second} and T_{final}, anterior-posterior and medio-lateral motions were greater when the raised-heel was worn as was the vertical displacement at T_{final}. Our findings suggest that the flat-heel provided a more stable base as there were less anterior-posterior and medio-lateral displacements, which aligns with what others have suggested and observed for flat-heel or barefoot inspired footwear (18). This finding should be considered if a lifter appears to have stability issues when performing barbell squats, especially when moderate-heavy loads are being used. The larger amount of antero-posterior barbell displacement when the raised-heel was used, particularly at T_{final}, may explain why there was an increase in the mean ankle moment at T_{final} when the raised-heel was worn. It is possible that as the lifters fatigued, they were required to counter the larger amount of anterior-posterior motion through greater contraction of the plantar flexors, which others suggest can assist with resisting anterior barbell displacement (28).

Although there were no significant changes in barbell ROM between T_{second} and T_{final}, there was a significant reduction in the barbell's vertical movement speed during the concentric phase for both shoe conditions. Not surprisingly, the reduction in barbell movement speed was coupled with a number of significant reductions in lower limb joint angular velocities. For both shoe conditions, mean concentric angular velocity at the hip, knee, and ankle were significantly slower at T_{final}, which has previously been observed when multiple back-to-back sets of barbell back squats were performed (2, 20). Considering differences in movement speed between the shoe conditions, previous work has suggested that while a flat-heel shoe may aid with stability, it can impact on performance measures such as velocity (18). This was not the case for barbell velocity in our study, as there were no significant differences in barbell velocity between the shoe conditions. Conversely, footwear type did impact on lower limb mean concentric joint angular velocity. When the raised-heel was worn, concentric angular velocities at both the hip and knee was significantly slower at T_{final} and the relative decrease in angular velocities between T_{second} and T_{final} (%Diff) were greater. This indicates that, while there were differences in the lower limb movement speed between the shoe conditions, this did not translate to a difference in barbell movement speed. The discrepancy may be due to some other type of compensatory change taking place at a site in the body that was not examined in this study. These findings may be of interest to those who participate in sports like CrossFit™, where activity is timed and performance of fast repetitions is beneficial. Footwear may not be as crucial with explosive strength training, as overall barbell movement speed under a moderate-heavy load appears to not be impacted by footwear.

When squatting with a raised-heel, power output decreased between T_{second} and T_{final} at all three lower limb joints. When squatting with a flat-heel, power output decreased between T_{second} and T_{final} at the hip and knee, which aligns with what we have previously reported for a flat-heel shoe condition (2). When the shoe conditions were compared, we found that concentric power output at the knee was significantly less at T_{final} during the raised-heel condition. This could partly be explained by the significantly slower mean knee angular velocity at T_{final} when the raised-heel was worn, since power output is the product of the joint's angular velocity and moment (26). To the authors' knowledge, no previous work has examined joint level power output for different shoe conditions while squatting. The one study that did have a power measure examined centre of mass power (18), and the findings of that study conflict with what we observed here. Shorter and colleagues (18) found that centre of mass power is reduced when barefoot inspired footwear are used during back squats, while our observations suggest that it was the raised-heel that resulted in lower power output at the knee. However, it should be noted that Shorter and colleagues (18) compared barefoot inspired footwear with an athletic shoe, with performance of partial squats in a non-fatigued state, which could explain the difference in findings.

The final measure to consider was the mean moments during the concentric phase at the ankle, knee, hip, and lumbo-pelvis. When the raised-heel was worn, there were no significant differences in mean concentric moments between T_{second} and T_{final}. However, when the flat-heel was used there were significant increases in both the hip and lumbo-pelvic mean concentric moments which aligns with previous findings (2). Although squat mechanics changed with volitional exhaustion, when the two shoe conditions were compared, the magnitudes of the moments were not significantly different. This further supports our conclusion that neither type of footwear gave the wearer an advantage.

There were a number of limiting factors that should be considered within this study. Firstly, we only examined two shoe conditions, even though athletics footwear is another common type of footwear worn while strength training. Therefore, future work should consider examining what changes volitional exhaustion elicits when athletic footwear is worn. It is important to note that, while only two types of footwear were examined, the shoe conditions were standardized, which is a strength of our study. Despite this, it could be argued that standardizing footwear may have impacted ecological validity as the footwear may have felt unfamiliar and resulted in the subjects performing differently. We attempted to minimize this by including familiarization sessions. A second limiting factor was that only one load was used, and future work should consider examining if similar changes in dynamics occur when other loads are used. A third limiting factor was that we instructed our subjects to use their regular squatting technique and did not standardize squat depth, foot positioning, or movement speed. We chose to do this to enhance ecological validity and replicate real-world training practices. A fourth limiting factor was our sample size, although our a priori power analysis indicated that 11 was a sufficient sample size. Finally, only skilled male lifters were examined, which may limit transferability of our findings to females lifters, lesser-skilled lifters, recreational lifters, or beginners. Nonetheless, our strict inclusion criteria optimised homogeneity of our sample, a novelty of our study, which makes our findings highly applicable to competitive athletes and practitioners alike.

PRACTICAL APPLICATIONS

The findings of our study revealed that when skilled lifters perform barbell back squats to volitional exhaustion using 80% of their 1RM, the way their movement altered when they became fatigued differed depending on whether they wore raised-heel and flat-heel footwear. Despite this observation, between shoe comparisons showed that although there may have been differences in how the movements perturbed, there were no significant differences in the joint moments or joint ROM. The comparable joint moments, an indicator of joint loading, suggests that footwear type is not crucial for skilled lifters when a reduction in joint loading sought. The comparable joint ROM and barbell vertical ROM suggests that neither footwear type resulted in a greater squat depth. Significant differences were seen in lower-limb movement speed and power output where values were lower for the raised-heel. This did not translate to lower barbell vertical velocity which further supports the notion that footwear type does not impact on the performance of skilled lifters when they became exhausted. We did observe that when a flat-heel was worn, this provided the lifters with a more stable base as there was less barbell movement in the anterior-posterior and medio-lateral directions. This finding should be noted for those who have stability issues. Flat-heel footwear should be used by these individuals, particularly when squatting under moderate-heavy loads or when working at or close to volitional exhaustion.

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FIGURE LEGENDS

Figure 1: Schematic showing the testing procedure where the shoe conditions were flat-heel and raised-heel (condition order was randomized). A minimum of 2 days was allowed between sessions to ensure subjects were fully recovered.

Figure 2: Customised in-shoe heel wedge used for the raised-heel condition.

TABLES

Table 1. Median and inter-quartile ranges of the magnitudes of the analyzed joint variables at the second (T_{second}) and final (T_{final}) repetition, and the percentage difference (Diff%) between T_{second} and T_{final} for the raised-heel condition.

Joint	Repetition	Mean moment ($Nm.kg^{-1}$)	Mean concentric moment ($Nm.kg^{-1}$)	Mean concentric angular velocity ($rad.s^{-1}$)	Mean concentric power ($W. kg^{-1}$)	Peak angle (°)
Hip	T_{second}	0.74 (0.63 – 0.84)	0.75 (0.65 – 0.90)	1.06 (1.01 – 1.86)[B]	0.59 (0.53 – 0.78)[E]	107.40 (95.33 – 113.01)[H]
	T_{final}	0.77 (0.68 – 0.87)	0.80 (0.66 – 0.90)	0.63 (0.39 – 0.81)[B]	0.37 (0.26 – 0.50)[E]	109.99 (94.70 – 122.70)[H]
	Diff%	3.94 (-5.43 – 17.41)	-4.40 (-10.76 – 23.11)	-43.24 (-63.21 – -31.90)	-44.54 (-51.51 – -16.07)	2.72 (0.13 – 3.86)
Knee	T_{second}	0.76 (0.65 – 0.84)	0.67 (0.55 – 0.74)	1.55 (1.36 – 1.74)[C]	0.89 (0.65 – 1.16)[F]	118.20 (113.10 – 134.20)
	T_{final}	0.70 (0.60 – 0.80)	0.61 (0.48 – 0.74)	0.80 (0.51 – 1.66)[C]	0.41 (0.27 – 0.55)[F]	128.82 (117.22 – 142.28)
	Diff%	-10.26 (-16.73 – 0.81)	-13.73 (-24.28 – 13.00)	-45.40 (-62.50 – -31.90)	-51.77 (-70.21 – -38.78)	2.77 (-016 – 8.34)
Ankle	T_{second}	0.21 (0.15 – 0.30)[A]	0.27 (0.19 – 0.38)	0.54 (0.42 – 0.59)[D]	0.14 (0.10 – 0.18)[G]	42.37 (32.98 – 44.46)
	T_{final}	0.28 (0.18 – 0.37)[A]	0.30 (0.12 – 0.42)	0.26 (0.15 – 0.36)[D]	0.08 (0.04 – 0.13)[G]	42.22 (28.90 – 43.15)
	Diff%	21.77 (-3.67 – 50.36)	13.91 (-18.19 – 47.50)	-49.15 (-64.29 – -37.93)	-43.91 (-77.35 – -19.64)	-1.42 (-10.58 – 1.99)
Lumbo-pelvis	T_{second}	1.70 (1.49 – 1.83)	1.74 (1.59 – 1.95)	-	-	18.70 (15.23 – 20.88)
	T_{final}	1.78 (1.61 – 1.94)	1.81 (1.60 – 1.98)	-	-	19.10 (16.45 – 21.39)
	Diff%	6.75 (1.29 – 19.45)	2.78 (-8.78 – 27.43)	-	-	2.44 (-12.62 – 11.03)

[A] Significant increase in mean moment at the ankle ($p = 0.01$; $r = 0.60$)
[B] Significant decrease in mean concentric angular velocity at the hip ($p < 0.01$; $r = 0.66$)
[C] Significant decrease in mean concentric angular velocity at the knee ($p < 0.01$; $r = 0.66$)
[D] Significant decrease in mean concentric angular velocity at the ankle ($p < 0.01$; $r = 0.66$)
[E] Significant decrease in mean concentric power at the hip ($p = 0.01$; $r = 0.60$)
[F] Significant decrease in mean concentric power at the knee ($p = 0.01$; $r = 0.63$)
[G] Significant decrease in mean concentric power at the ankle ($p = 0.01$; $r = 0.56$)
[H] Significant increase in peak angle at the hip i.e. reduction in the overall ROM ($p = 0.02$; $r = 0.51$)

Table 2. Median and inter-quartile ranges of the magnitudes of the analyzed joint variables in the second (T_{second}), final (T_{final}) repetition, and the percentage difference (Diff%) between T_{second} and T_{final} for the flat-heel condition.

Joint	Repetition	Mean moment (Nm.kg^{-1})	Mean concentric moment (Nm.kg^{-1})	Mean concentric angular velocity (rad.s^{-1})	Mean concentric power (W. kg^{-1})	Peak angle (°)
Hip	T_{second}	0.74 (0.65 – 0.90)^{A}	0.74 (0.67 – 0.85)^{D}	1.08 (1.04 – 1.14)^{F}	0.61 (0.55 – 0.72)^{I}	106.46 (98.61 – 115.84)
	T_{final}	0.81 (0.72 – 0.89)^{A}	0.81 (0.71 – 0.93)^{D}	0.81 (0.61 – 0.85)^{F}	0.45 (0.40 – 0.62)^{I}	110.48 (96.42 – 119.39)
	Diff%	7.74 (4.03 – 14.21)	10.58 (1.70 – 19.49)	-31.03 (-41.23 – -11.46)	-22.36 (-33.86 – -16.00)	2.07 (-1.52 – 5.42)
Knee	T_{second}	0.78 (0.65 – 0.86)^{B}	0.71 (0.57 – 0.77)	1.46 (1.30 – 1.66)^{G}	0.88 (0.74 – 1.07)^{J}	121.28 (109.83 – 140.56)
	T_{final}	0.74 (0.63 – 0.78)^{B}	0.65 (0.54 – 0.76)	1.00 (0.82 – 1.34)^{G}	0.50 (0.45 – 0.74)^{J}	134.57 (109.51 – 144.00)
	Diff%	-7.87 (-14.88 – 0.50)	-2.60 (-19.66 – 8.99)	-30.07 (-44.61 – -11.45)	-37.39 (-55.98 – -20.56)	1.68 (-1.48 – 4.06)
Ankle	T_{second}	0.18 (0.15 – 0.27)	0.20 (0.15 – 0.37)	0.47 (0.40 – 0.56)^{H}	0.10 (0.07 – 0.15)	38.32 (30.26 – 41.73)
	T_{final}	0.26 (0.18 – 0.33)	0.29 (0.17 – 0.40)	0.27 (0.26 – 0.41)^{H}	0.09 (0.05 – 0.14)	38.47 (31.53 – 44.05)
	Diff%	18.65 (-13.03 – 48.50)	7.38 (-19.86 – 32.63)	-39.53 (-47.06 – -12.77)	-40.00 (-60.42 – 22.22)	0.38 (-2.06 – 9.59)
Lumbo-pelvis	T_{second}	1.67 (1.58 – 1.83)^{C}	1.73 (1.56 – 1.99)^{E}	-	-	18.00 (15.96 – 21.58)
	T_{final}	1.84 (1.72 – 1.93)^{C}	1.94 (1.76 – 1.21)^{E}	-	-	18.11 (16.30 – 20.60)
	Diff%	8.89 (2.85 – 14.10)	13.29 (1.13 – 20.44)	-	-	2.36 (-5.90 – 8.07)

[A] Significant increase in mean moment at the hip (p = 0.01; *r* = 0.58)
[B] Significant decrease in mean moment at the knee (p = 0.02; *r* = 0.51)
[C] Significant increase in mean moment at the lumbo-pelvis (p = 0.01; *r* = 0.60)
[D] Significant increase in the mean concentric moment at the hip (p = 0.02; *r* = 0.80)
[E] Significant increase in mean concentric moment at the lumbo-pelvis (p = 0.05; *r* = 0.45)
[F] Significant decrease in mean concentric angular velocity at the hip (p = 0.05; *r* = 0.44)
[G] Significant decrease in mean concentric angular velocity at the knee (p < 0.001; *r* = 0.66)
[H] Significant decrease in mean concentric angular velocity at the ankle (p = 0.01; *r* = 0.60)
[I] Significant decrease in mean concentric power at the hip (p = 0.01; *r* = 0.63)
[J] Significant decrease in mean concentric power at the knee (p = 0.01; *r* = 0.63)

Table 3. Median and interquartile ranges of the differences between raised-heel and flat-heel in the second (T_{second}) and final (T_{final}) repetition, and the difference between raised-heel and flat-heel percentage differences (Diff%). A positive value indicates that the raised-heel was larger than the flat-heel magnitude.

Joint	Repetition	Mean moment (Nm.kg^{-1})	Mean concentric moment (Nm.kg^{-1})	Mean concentric angular velocity (rad.s^{-1})	Mean concentric power (W. kg^{-1})	Peak angle (°)
Hip	T_{second}	0.02 (-0.02 – 0.05)	0.03 (-0.03 – 0.09)	0.02 (-0.07 – 0.10)	-0.01 (-0.12 – 0.08)	-1.21 (-4.16 – 1.76)
	T_{final}	-0.05 (-0.11 – -0.03)	-0.10 (-0.12 – -0.02)	-0.21 (-0.30 – 0.10)[A]	-0.11 (-0.18 – 0.03)	-0.10 (-2.37 – 2.09)
	Diff%	-0.50 (-16.10 – 7.95)	-6.48 (-27.31 – 11.54)	11.66 (2.33 – 20.72)[B]	8.12 (-14.40 – 33.18)	1.60 (-0.88 – 3.99)
Knee	T_{second}	0.06 (0.02 – 0.13)	-0.01 (-0.09 – 0.03)	0.03 (-0.07 – 0.17)	0.01 (-0.08 – 0.09)	2.08 (-8.35 – 4.36)
	T_{final}	0.02 (-0.08 – 0.07)	0.00 (-0.12 – 0.07)	-0.28 (-0.42 – 0.04)[C]	-0.13 (-0.25 – 0.01)[E]	1.61 (-7.33 – 5.93)
	Diff%	2.37 (-9.21 – 12.96)	4.00 (-13.83 – 24.31)	13.99 (-3.44 – 31.30)[D]	12.49 (-4.59 – 28.16)	0.31 (-3.18 – 5.85)
Ankle	T_{second}	0.01 (-0.04 – 0.09)	0.01 (0.00 – 0.14)	0.03 (-0.03 – 0.07)	0.03 (0.00 – 0.08)	4.01 (-3.91 – 8.25)
	T_{final}	-0.04 (-0.07 – 0.06)	-0.03 (-0.12 – 0.09)	-0.07 (-0.17 – 0.01)	-0.01 (-0.05 – 0.01)	2.98 (-9.57 – 7.54)
	Diff%	11.83 (-50.38 – 48.91)	11.90 (-21.28 – 58.58)	12.97 (-1.08 – 33.53)	9.80 (-12.78 – 37.27)	1.10 (-1.67 – 6.89)
Lumbo-pelvis	T_{second}	-0.02 (-0.11 – 0.21)	-0.01 (-0.14 – 0.28)	-	-	-0.53 (-1.15 – 0.67)
	T_{final}	-0.09 (-0.21 – 0.08)	-0.10 (-0.29 – 0.09)	-	-	-0.69 (-2.32 – 1.52)
	Diff%	0.11 (-17.67 – 8.04)	-2.93 (-32.79 – 8.60)	-	-	1.09 (-4.73 – 8.15)

[A] Raised-heel mean concentric angular velocity at the hip is significantly less than flat-heel angular velocity at T_{final} ($p = 0.05$; $r = 0.44$)
[B] Raised-heel Diff% in concentric angular velocity at the hip is significantly greater than flat-heel %Diff ($p = 0.04$; $r = 0.46$)
[C] Raised-heel mean concentric angular velocity at the knee is significantly less than flat-heel angular velocity at T_{final} ($p = 0.03$; $r = 0.50$)
[D] Raised-heel Diff% in concentric angular velocity at the knee is significantly greater than flat-heel %Diff ($p = 0.05$; $r = 0.44$)
[E] Raised-heel mean concentric power at the knee is significantly less than flat-heel power at T_{final} ($p = 0.04$; $r = 0.47$)

Table 4. Median and interquartile ranges of the magnitudes barbell displacement and concentric velocity in the second (T_{second}) and final (T_{final}) repetition, and the percentage difference (Diff%) between T_{second} and T_{final} for both shoe conditions.

	Raised-heel			Flat-heel		
Repetition	T_{second}	T_{final}	Diff %	T_{second}	T_{final}	Diff %
Vertical (m)	0.63 (0.50 – 0.68)	0.66 (0.53 – 0.70)	2.94 (0.00 – 6.00)	0.62 (0.50 – 0.67)	0.64 (0.46 – 0.68)	-1.45 (-6.25 – 2.90)
Anterior-posterior (m)	0.11 (0.07 – 0.11)	0.13 (0.10 – 0.19)	58.33 (-9.09 – 100.00)	0.06 (0.05 – 0.07)	0.07 (0.05 – 0.11)	20.00 (-28.57 – 57.14)
Medio-lateral (m)	0.04 (0.03 – 0.08)	0.05 (0.04 – 0.10)	25.00 (-14.29 – 66.67)	0.02 (0.01 – 0.03)	0.03 (0.02 – 0.04)	50.00 (-50.00 – 150.00)
Concentric velocity ($m.s^{-1}$)	0.50 (0.45 – 0.53)[A]	0.29 (0.22 – 0.37)[A]	-40.00 (-51.11 – -26.00)	0.47 (0.43 – 0.52)[B]	0.30 (0.19 – 0.39)[B]	-35.59 (-63.46 – -22.64)

[A] Significant decrease in mean barbell velocity during the concentric phase for the raised-heel ($p < 0.001$; $r = 0.66$)
[B] Significant decrease in mean barbell velocity during the concentric phase for the flat-heel ($p = 0.01$; $r = 0.63$)

Table 5 Median and interquartile ranges of the differences in barbell displacement and concentric velocity between raised-heel and flat-heel in the second (T_{second}) and final (T_{final}) repetition, and the difference between raised-heel and flat-heel percentage differences (Diff%). A positive value indicates that the raised-heel was larger than the flat-heel magnitude.

	Difference between shoe conditions		
Repetition	T_{second}	T_{final}	Diff%
Vertical (m)	0.01 (0.00 – 0.02)	0.02 (0.00 – 0.08)[C]	-0.02 (-3.44 – 3.39)
Anterior-posterior (m)	0.04 (0.02 – 0.05)[A]	0.03 (0.02 – 0.07)[D]	-17.14 (-38.96 – 75.00)
Medio-lateral (m)	0.03 (0.02 – 0.06)[B]	0.04 (0.01 – 0.07)[E]	-37.50 (-125.00 – 33.33)
Concentric velocity ($m.s^{-1}$)	0.01 (-0.03 – 0.05)	-0.03 (-0.05 – 0.06)	3.36 (-17.22 – 10.68)

[A] Significantly larger antero-posterior displacement at T_{second} for the raised-heel ($p = 0.01$; $r = 0.66$)
[B] Significantly larger medio-lateral displacement at T_{second} for the raised-heel ($p = 0.01$; $r = 0.62$)
[C] Significantly larger vertical displacement at T_{final} for the raised heel ($p = 0.05$; $r = 0.44$)
[D] Significantly larger antero-posterior displacement at T_{final} for the raised-heel ($p < 0.001$; $r = 0.66$)
[E] Significantly larger medio-lateral displacement at T_{final} for the raised-heel ($p = 0.01$; $r = 0.56$)