EFFECTS OF FOOTWEAR ON SAGITTAL PLANE KINEMATICS AND CENTRE OF PRESSURE EXCURSION DURING THE BARBELL BACK SQUAT

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Footwear has been proposed to alter squat performance whereby flat soles may reduce foot-floor proprioception and raised heels may decrease joint range of motion. This study aimed to investigate the effects of footwear on centre of pressure excursion (CPE) and sagittal plane kinematics during the back squat. Seven males performed squats during five different footwear conditions (barefoot, weightlifting shoe, running shoe, minimal shoe, flat-soled shoe) while sagittal plane kinematics and CPE were recorded. Results showed no significant difference in CPE between any footwear conditions. Peak knee flexion was significantly greater for running shoes and weightlifting shoes compared to barefoot. Peak shank angle was significantly greater when wearing weightlifting shoes compared to minimal footwear. This suggests footwear which increases heel height may increase peak joint angles to allow for a deeper squat.

KEY WORDS: Squat, footwear, kinematics, centre of pressure.

INTRODUCTION: The back squat is one of the most popular weightlifting exercises and is commonly used by strength and conditioning coaches, athletes and recreational lifters (Fry et al., 2003). Executing the back squat with incorrect technique increases the risk of injury, which can be a result of weak musculature and decreased flexibility of the lower body (Butler et al., 2010). The knee joint has been reported to be at greater risk of injury during the squat movement compared to the hip and ankle joints since it experiences the greatest external moments and undergoes the greatest degree of movement (Butler et al., 2010). Additionally, technique can be severely compromised due to ankle inflexibility and a subsequent inability to dorsiflex which may cause lifters to struggle to lower their hips below the line of the knee, which may result in compensatory movements such as an increased shank angle relative to vertical, greater knee valgus movement and greater forward flexion of the torso, the latter of which has been proposed as a risk factor for lumbar spine injury (Fortenbaugh et al., 2010). A raised heel has been proposed to decrease the flexibility required of the ankle joint during a squat which can result in reduced knee valgus movement (Bell et al., 2008). Purdam et al., (2004) examined the effects of squatting with a raised heel and found knee pain was significantly decreased when compared to squatting on a flat surface. As a result, it would be reasonable to suggest that footwear with a raised heel would provide the greatest benefit during a squat.

Weightlifting shoes are specifically suited to squatting and incorporate a raised wooden heel and straps over the midline of the foot. Therefore they may contribute to an improved squat technique by raising the heel, decreasing instability of the foot floor interface and reducing potential mediolateral movement of the foot within the shoe (Shorter et al., 2011; Fortenbaugh et al., 2010). Similarly, minimal-soled footwear are purported to be beneficial to squat technique due to the non-compressible sole, providing greater stability which increases direct force transfer in the direction of movement (Shorter et al., 2011). Despite running shoes having a raised heel, the instability provided due to the thick and soft sole of the shoe has been reported to negate any potential benefits (Sato et al., 2012). For example, Sato et al., (2012) found that weightlifting shoes allowed for more advantageous joint and segment angles during a squat compared to running shoes and Behm et al., (2002) found that although antagonistic muscle activation was greater when wearing running shoes, the overall force output was 20.2% lower, owing to the unstable conditions. Whilst a number of previous studies have examined the effects of up to three different footwear conditions on either body kinematics or measures of stability, no study has analysed a broad spectrum of available footwear on both kinematic and centre of pressure excursion variables during the squat movement. Therefore the aim of the study was to investigate the effects of footwear on lower limb kinematics and centre of pressure excursion during the back squat in recreationally trained male athletes.

METHODS: Following institutional ethical approval, seven healthy male subjects (age = 23.0 ± 1.5; height = 1.76 ± 0.05 m; mass = 76.0 ± 6.1 kg) were recruited for the study. All subjects were experienced in performing the back squat exercise and had no serious injuries in the 12 months preceding testing. Subjects were given a detailed briefing of the testing procedure and then signed an informed consent form.
The subjects were required to attend two testing sessions. Upon arrival to the laboratory on the first visit, the subjects' height and body mass were measured. The subjects were required to wear comfortable footwear that they would usually wear to perform squatting exercises. Each subject was asked to complete a self-selected warm up before beginning a five repetition maximum (RM) test. The 5RM test protocol began with 12 repetitions with an unloaded Olympic bar (20 kg) within a squat rack, followed by eight repetitions at 40 kg and five repetitions at 60 kg. After this point, the subject was required to complete five repetitions at incrementing weights for up to five sets, with three minute rest periods in between each set. The test was terminated when the subject could not perform five repetitions at a given weight with satisfactory technique. Using the Brzycki formula, each subject's 5RM value was assumed to be 86% of their theoretical 1RM.
Upon the second visit to the laboratory, subjects were required to complete a standardised warm-up of 20 bodyweight squats followed by dynamic stretching of the quadriceps, hamstring, gluteus maximus and gastrocnemius. Subjects were then required to perform barbell back squat exercises to their self-determined typical depth during five different footwear conditions; barefoot, weightlifting shoes (Do-Win 2010), minimal shoes (New Balance 625 Sn20), running shoes (New Balance MR100) and flat soled shoes (Converse All Star). The order in which each of the footwear conditions was assigned to each subject was randomized. Subjects were recorded using a digital video camera (Canon IXUS 240HS, Canon Inc., Tokyo, Japan) placed on a stationary tripod at right angles to the sagittal plane sampling at 60 Hz. A pressure mat (FootScan, RsScan, Suffolk, UK) was placed inside the squat rack to measure the centre of pressure, also sampling at 60 Hz. For each footwear condition, subjects performed five repetitions of a back squat at 60% of the subject's pre-determined theoretical 1RM. Subjects were instructed to perform each repetition at a consistent speed, with a controlled eccentric phase and a moderately-paced concentric phase (lasting approximately 1 second) and were given three minutes rest between footwear conditions.
Of the five repetitions of the squat exercise performed for each subject during each of the footwear conditions, only the second, third and fourth repetitions were used for subsequent analysis. For centre of pressure excursion, peak anterior movement, peak posterior movement, peak left movement, peak right movement were calculated for each repetition. Videos were analysed using Kinovea motion analysis software (version 8.15) to measure peak hip flexion, peak knee flexion, peak ankle dorsiflexion, peak torso angle and peak shank angle. One-way repeated measures analysis of variance (ANOVA) was conducted to analyse the effects of the different footwear conditions on each of the centre of pressure excursion and sagittal plane kinematic dependent variables measured.

RESULTS: There was no significant difference in centre of pressure excursion between any of the footwear conditions ($p > 0.05$) (Table 1). Knee flexion was significantly greater during the running shoe condition ($p = 0.001$) and the weightlifting shoe condition ($p = 0.014$) compared to the barefoot condition. Also, shank angle was significantly greater ($p = 0.038$) during the weightlifting shoe condition compared to the minimal footwear condition (Table 2). All other kinematic dependent variables were not significantly different between the footwear conditions.

Table 1. Centre of pressure excursion during the five footwear conditions during a back squat (mean ± standard deviation).

	Barefoot	Running shoes	Weightlifting shoes	Minimal footwear	Flat-soled shoes
Peak anterior movement (mm)	65.8 ± 25.0	84.0 ± 12.3	82.8 ± 37.0	85.2 ± 26.5	81.1 ± 21.9
Peak posterior movement (mm)	44.5 ± 13.8	53.0 ± 16.8	47.8 ± 24.6	47.2 ± 16.7	46.3 ± 17.9
Peak left movement (mm)	80.1 ± 50.6	97.9 ± 51.6	68.3 ± 22.0	90.0 ± 49.2	70.3 ± 30.2
Peak right movement (mm)	70.8 ± 69.3	81.2 ± 30.4	63.3 ± 26.3	74.2 ± 35.1	62.0 ± 15.3

Table 2. Sagittal plane kinematics during the five footwear conditions during a back squat (mean ± standard deviation).

	Barefoot	Running shoes	Weightlifting shoes	Minimal footwear	Flat-soled shoes
Hip flexion (^{o})	118 ± 6	118 ± 9	122 ± 12	121 ± 9	120 ± 7
Knee flexion (^{o})	103 ± 15[1,2]	107 ± 14[1]	113 ± 12[2]	106 ± 15	106 ± 16
Ankle plantar(+)/dorsiflexion (-) (^{o})	-5 ± 6	-6 ± 5	-5 ± 4	-8 ± 6	-8 ± 6
Torso angle (^{o})	44 ± 7	42 ± 8	43 ± 7	44 ± 8	45 ± 7
Shank angle (^{o})	27 ± 7	31 ± 6	32 ± 6[3]	28 ± 5[3]	28 ± 8

[1]: significant difference in knee flexion between barefoot and running shoes (p = 0.001).
[2]: significant difference in knee flexion between barefoot and weightlifting shoes (p = 0.014).
[3]: significant difference in shank angle between weightlifting shoes and minimal footwear (p = 0.038).

DISCUSSION: The results showed centre of pressure excursion was not significantly different between footwear conditions, however, some sagittal plane kinematic variables were significantly influenced by footwear conditions. The use of running shoes was shown to significantly increase peak knee flexion in comparison to barefoot. This is consistent with work by Sato et al. (2013) who found a difference of 8.59% in knee flexion between these conditions which is similar to the 5.6% difference found in the present study. The increased knee flexion suggests a greater depth of squat, which could potentially be attributed to the raised heel of the running shoe (Sato et al., 2012). Additionally, Sato et al. (2013) found further significant differences in trunk, thigh and hip angles, which were not observed in the present study. Weightlifting shoes also displayed significantly greater peak knee flexion compared to barefoot, with a percentage difference of 16.1%, which is greater than the difference between barefoot and running shoes. Fortenbaugh et al. (2010) demonstrated similar findings, showing that knee flexion at the bottom of the squat whilst wearing weightlifting shoes and running shoes was not significantly different.

Weightlifting shoes produced significantly greater (14.1%) peak shank angle than in the minimal footwear condition. This finding would suggest that weightlifting shoes cause the knees to move more anteriorly in the minimal footwear condition, potentially causing an increased risk of knee injury. However, even if the knees were to move over the toes, McKean et al. (2010) stated that this is a natural movement in many squatters. There was no significant difference in ankle angle between weightlifting shoes and minimal footwear, which would support this.

Since torso angle was not found to change across any of the conditions showing subjects maintained a consistent upright torso regardless of the footwear condition. This would imply that even though shank angle was greater when wearing weightlifting shoes, the subjects were able to maintain a similar torso angle compared to the other footwear conditions, which may suggests no increased risk of lower back injury (Fortenbaugh et al., 2010).

No significant difference between footwear conditions was found for centre of pressure excursion therefore it could be suggested that all footwear conditions provide similar stability. However, there was a general trend in the data for the running shoe condition to display greater centre of pressure excursion, particularly in the mediolateral direction, suggesting that this condition may not be as suitable for performing squat exercises as the other conditions. Additionally, with no significant difference found between barefoot and minimal footwear conditions, this may have implications for recreational lifters since the use of minimal footwear is growing in the fitness setting (Sato et al., 2013) and barefoot squatting would appear to be a more cost-effective option than minimal footwear.
Whilst the results of the present study provide some evidence that different footwear alters sagittal plane kinematics, future research should utilise 3D motion analysis to capture movement in all three planes of motion and analyse joint moments and powers. Also future research should investigate a range of intensities as differences between footwear conditions may be more pronounced when lifting weights closer to a lifter's 1RM.

CONCLUSION: The findings of the present study suggest that a raised heel may alter lower limb kinematics during the squat movement so that a lifter may be able to perform a lower squat movement. However, the general trend in the data for greater centre of pressure excursion while wearing the running shoe suggest that the compressible sole of the shoe may result in less stability during squatting. Therefore it is recommended that weightlifting shoes should be worn when performing back squat exercises to ensure lower limb joints are able to move through their full range of motion whilst maintaining stability.

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