The effect of weightlifting shoes on the kinetics and kinematics of the back squat

Hayley S Legg[1], Mark Glaister[1], Daniel J Cleather[1] and Jon E Goodwin[1]

[1]School of Sport, Health and Applied Science, St. Mary's University, Twickenham, UK

In Press at: Journal of Sport Sciences, Volume xx, Pages x-x

DOI:10.1080/02640414.2016.1175652

Corresponding author

Hayley Legg

St. Mary's University, Waldegrave Road, Twickenham. TW1 4SX United Kingdom

Email: Hayley.legg@hotmail.com / Hayley.legg@stmarys.ac.uk

ABSTRACT

Weightlifting shoes (WS) are often used by athletes to facilitate their squat technique, however the nature of these benefits is not well understood. In this study, the effects of footwear and load on the mechanics of squatting were assessed for 32 participants (age: 25.4 ± 4.4 yr; mass 72.87 ± 11.35 kg) grouped by sex and experience. Participants completed loaded and unloaded back squats wearing both WS and athletic shoes (AS). Data was collected utilising a 3D motion capture system synchronised with a force platform and used to calculate kinematic and kinetic descriptors of squatting. For both load conditions, WS gave significantly ($P < 0.05$) reduced ankle flexion and increased knee flexion than AS, as well as a more upright trunk and greater knee moment for the unloaded condition. In addition, the experienced group experienced a significantly greater increase in knee and hip flexion with WS than the novices when unloaded. These results are consistent with the idea that WS permit a more knee flexed, upright posture during squatting, and provide preliminary evidence that experienced squatters are more able to exploit this effect. Decisions about footwear should recognise the effect of footwear on movement and reflect an athlete's movement capabilities and training objectives.

Keywords: joint moments, strength training, footwear, sex, experience

INTRODUCTION

Weightlifting shoes (WS) are considered to be one of the most important pieces of equipment used for weightlifting training and competition (Dreschler, 1998; Kono, 2001). Beyond the sport of weightlifting, many individuals utilise WS for strength and power training. WS are thought to provide lifters with additional support (Stiggins & Allsen, 1982) and to protect the feet, ankles and knees during the squat (Dunn et al., 1984). WS are designed with a raised heel, which is often made of wood, to offer strength, durability and increased stability (Dreschler, 1998; Kono, 2001). It has been suggested that the elevation created by the solid heel allows the athlete to maintain a neutral pelvic tilt when descending into a deep squat (Kono, 2001). In addition, it has been proposed that a higher heel will facilitate the maintenance of a more upright torso with a neutral curvature of the spine (Charniga, 2006; Dreschler, 1998; Sato Fortenbaugh & Hydock, 2012) and in doing so potentially reduce loading on the spine and hip (Fairchild, Hill, Ritchie, & Socher, 1993; Lander, Bates, & Devita, 1986; List, Gülay, Stoop, & Lorenzetti, 2013; McLaughlin, Lardner, & Dillman, 1978; Neitzel & Davies, 2000). A more upright trunk posture has also been associated with forward knee translation (Fry, Smith, & Schilling, 2003; List et al., 2013; Lorenzetti et al., 2012) and forward translation of the knees in relation to the toes has been demonstrated as typical of skilled squatters (McKean, Dunn & Burkett, 2010a). Despite this, the National Strength and Conditioning Association (NSCA; Chandler & Stone, 1991) suggest that this outcome should be avoided. It would thus appear useful to demonstrate the extent to which knee translation is associated with reduced trunk lean when WS are utilised to highlight whether knee translation, or some other mechanism, underpins the trunk angle changes seen with WS (Sato et al. 2012). In particular, this would answer the question as to whether a degree of anterior knee translation may be required for athletes in order to reduce loading on the spine (by facilitating a more upright trunk position).

Both experience (Chandler & Stone, 1991; Dunn et al., 1984; McLaughlin, Dillman & Lardner, 1977, McLaughlin et al., 1978) and sex (Fry, Housh, Hughes & Eyford, 1988; Fry, Kraemer, Bibi & Eyford, 1991; Lynn & Noffal, 2012; McKean et al., 2010a; McKean, Dunn & Burkett, 2010b) have been demonstrated to influence squat technical models, and also responses to loading (McKean et al., 2010a). With this in mind it would seem unlikely that WS would offer the same outcome for all athletic groups. As such, it seems necessary to differentiate outcomes for a range of populations.

This short review has thus identified a number of factors that may be influenced by the use of WS when squatting. The aim of this study was to investigate these by exploring the influence of WS versus AS on the mechanics of the back squat.

METHODS

Participants

32 participants (Table 1) volunteered to participate in the study. Participants were grouped according to sex and experience. To be considered experienced, participants were required to have a minimum of 12 months training history utilising the back squat on a regular basis. The novice group were participants who had no background of utilising the barbell squat and were

participating in recreational physical activity. All participants in the experienced group participated in competitive sports (rugby n = 11, athletics n = 1, rowing n = 2, cycling n = 1 cricket n = 1). All participants were free from lower limb injury in the 6 months preceding data collection. All participants provided written informed consent. The study was approved by the St Mary's University Ethics Committee prior to commencement.

Table 1: Subject characteristics (mean ± standard deviation).

	Novice		Experienced	
	Female	Male	Female	Male
N	8	8	8	8
Age (years)	26.5 ± 2.0	27.1 ± 3.6	25.4 ± 5.7	22.9 ± 5.7
Weight (kg) ‡	62.4 ± 3.8	73.2 ± 5.7	71.2 ± 13.6	84.6 ± 7.3
Height (cm)	164.9 ± 5.6	179.5 ± 7.6	167.2 ± 8.2	182.4 ± 7.0
Experience (years)	N/A	N/A	4.3 ± 2.4	5.0 ± 3.6
Weekly activity (hours) †	5.3 ± 2.9	6.6 ± 4.2	13.2 ± 6.9	8.1 ± 2.5
1 RM (kg) as a % of Bodyweight	N/A	N/A	86 ± 19	154 ± 24

† Significant difference ($p < 0.05$) when comparing experience
‡ Significant difference ($p < 0.001$) when comparing gender
RM = Repetition Maximum

Procedures

A schematic of the experimental procedures is shown in Figure 1. Prior to the warm up, the novice group were shown a video of an experienced squatter wearing WS performing a deep barbell back squat with a load of 20 kg. The deep squat was categorised by knee flexion angles greater than 100° and contact between the posterior thigh and shank (Escamilla, 2001). The video demonstrated five squats in the sagittal plane and five squats in the frontal plane. The video was played on a continuous loop and each novice participant could view it as often as they required throughout the warm up. No verbal guidance or feedback was given to the participants. All participants completed a standardised warm up. For the unloaded bodyweight sets, a wooden dowel was used to replicate a barbell. Under the loaded condition, the experienced participants lifted a load equal to 75% of their self-reported 1 RM, the novice group lifted a load equal to 25% of their bodyweight.

Participants completed five squat repetitions in each of four experimental conditions. Two footwear conditions (1. their own AS and 2. WS) were utilised in random order and within each of these, participants completed first unloaded and then loaded squat sets. Between each repetition the participants were required to pause for one second in order to provide distinction between repetitions. Force data was recorded from the right foot only. During data collection experienced participants were permitted to use a stance, foot position, and movement speed that they would normally use in training. No instructions were given regarding foot placement or movement speeds to the novice participants beyond the video observation. To ensure the same foot placement across all trials, the participants' self-selected stance and foot position were marked on the platform. A minimum rest period of three minutes between conditions was imposed. Data collection took approximately 90 minutes and was completed in a single session.

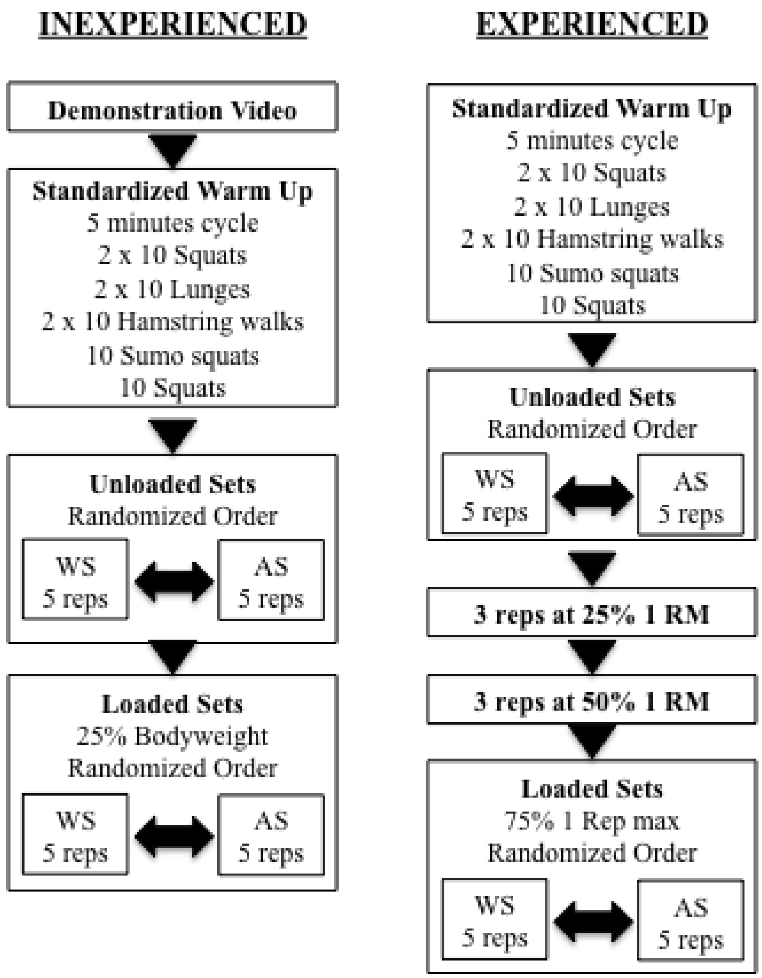

Figure 1: Schematic of experimental approach. WS = weightlifting shoe, AS = athletic shoe.

The laboratory set up is detailed in Figure 2. An 11 camera motion analysis system (MX 3+ Vicon Motion Systems, Oxford, UK) was used to capture three-dimensional kinematic data (200 Hz). Force data was collected at 400 Hz from a single Kistler force platform (Kistler 9286AA 400 mm x 600 mm, Kistler Instruments Ltd, London, UK). The force plate was synchronised with the motion capture system. Reflective markers were placed on the anatomical locations highlighted in Table 2, with an additional two markers on the distal aspects of the bar. The 3-D positional data was filtered using a Woltring filter, and reconstruction and inverse dynamic analysis was performed using the PlugIn gait model within Vicon Nexus software (Vicon Motion Systems, Oxford, UK).

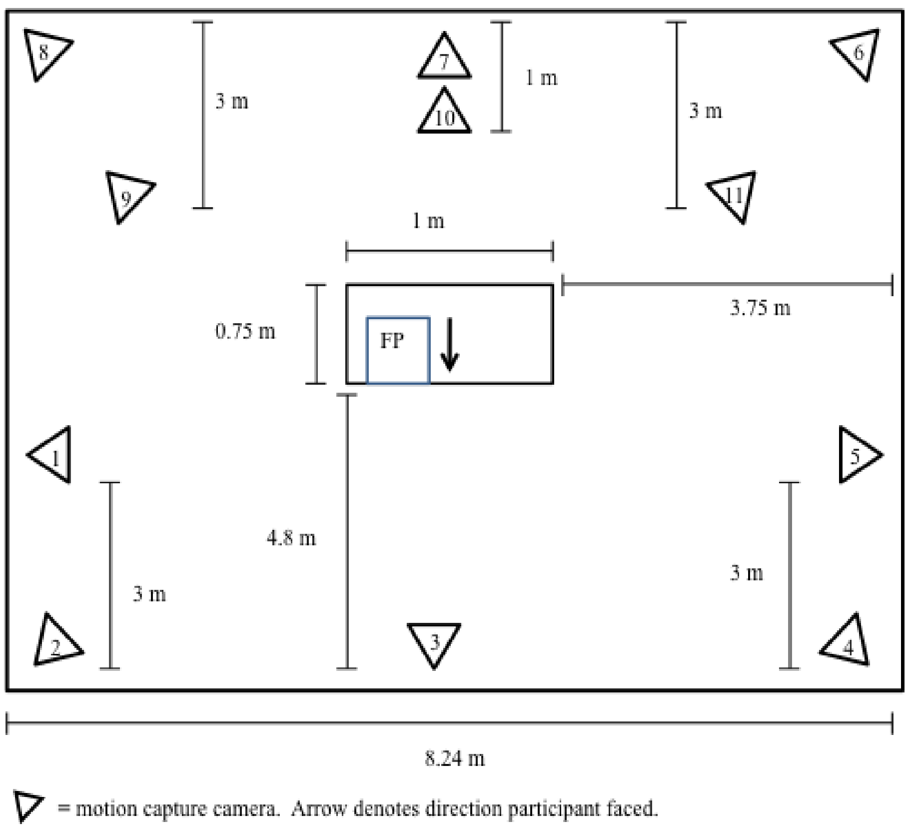

Figure 2: Overhead view of experimental set-up. Cameras 1-8 were 2.5 m from the floor, whereas cameras 9-11 were 1 m from the floor. FP = Force plate.

Table 2: Reflective marker placement.

Reflective Marker	Placement
Lifting bar	Distal aspects
ASIS	Directly over corresponding spinous process
PSIS	Directly over corresponding spinous process
Thigh	Lateral aspect of the thigh
Knee	Lateral aspect of the knee joint, level with the joint centre
Tibia	Lateral aspect of the shank
Ankle	Lateral malleoli
Heel	On footwear in line with the calcaneus
Toe	On footwear over the second metatarsal head

ASIS = anterior superior iliac spine, PSIS = posterior superior iliac spine.

Data from the first and fifth repetitions were neglected, allowing participants to be evaluated during more stable mid-set repetitions. For all variables the mean value from repetitions two to four was recorded. In order to define each individual squat cycle, the vertical linear displacement of the bar was used, and the bottom of the squat was defined as the moment when the bar reached its lowest point. In the bottom position, the sagittal joint angles and the distance through which the knees (centre of rotation) moved anteriorly in relation to the toes were calculated in three dimensions (Figure 3). The trunk angle was calculated relative to the horizontal using the distal bar marker in relation to the posterior superior iliac spine marker. The peak sagittal joint moments of the ankle, knee, and hip of each squat were calculated and normalised to system load. The level of variability in centre of pressure for both the anterior-posterior ($VCOP_x$) and medio-lateral ($VCOP_y$) planes was used to establish each participant's level of stability during the squat. A variability index was used to quantify the magnitude of the participant's centre of pressure movement throughout the entire squat cycle. To achieve this the centre of pressure location was differentiated twice, and the resulting acceleration values were summed over time for the entire squat cycle (Equation 1). To allow for comparisons, each squat was normalised to the squat cycle duration.

Equation 1:

$$\frac{\int \left\| COPk''(t) \right\|^2 dt}{t}$$

t = time

k = plane of movement (anterior-posterior ($VCOP_x$) and medio-lateral ($VCOP_y$)

Statistical analysis

The mean peak values of each set were used for statistical analysis. All statistical analyses were conducted using Predictive Analytics Software Statistics (Version 18; SPSS: IBM Company, New York, NY) software. Repeated measures ANOVAs were used to assess any differences in the bottom position of the squat due to footwear, experience and sex. The unloaded data was analysed using a 3 way ANOVA (footwear x experience x sex). The loaded data was separated according to experience and two separate 2 way ANOVAs (footwear x sex) were conducted for each dependant variable. The respective significant interactions were followed-up using *post hoc* tests with Bonferroni adjustments for multiple comparisons. The above analyses provided 95% confidence limits for all estimates. A significance level of $P<0.05$ was set.

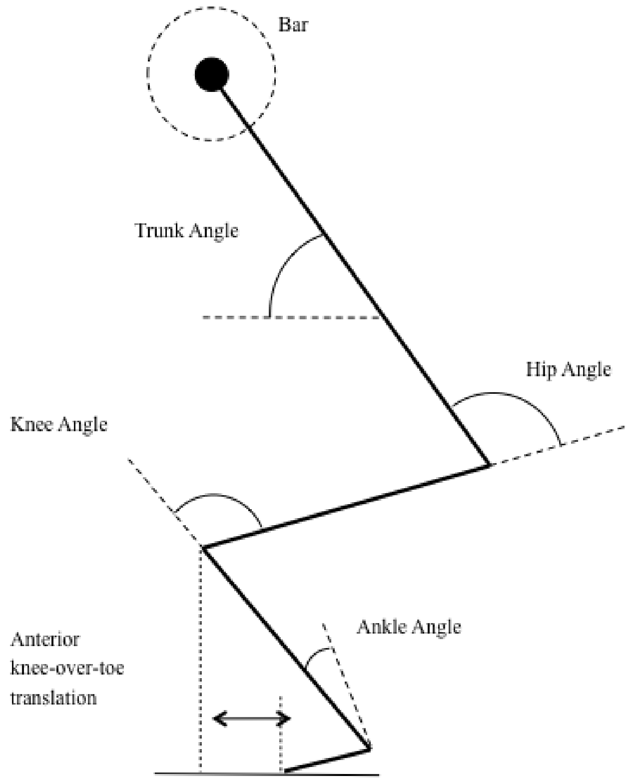

Figure 3: Free body diagram of the barbell back squat demonstrating the segmental angles and anterior knee translation positions. Free body diagram segmental angles and anterior knee translation

RESULTS

Unloaded

The results of the unloaded trials are shown in Table 3. When comparing footwear there was a significant effect at the ankle angle ($F_{(1,28)} = 32.79$; $P = 0.00$), knee angle ($F_{(1,28)} = 19.81$; $P =$

0.00), trunk angle ($F_{(1,28)} = 16.12$; $P = 0.00$), and knee moment ($F_{(1,28)} = 6.93$; $P = 0.01$). The significant differences show that when utilising the WS compared to the AS there is a reduction in ankle flexion (mean difference: 3.61°; 95% likely range 2.32 – 4.90°), a greater degree of knee flexion (mean difference: 3.32°; 95% likely range 1.79 – 4.84°) and a more upright trunk (mean difference: 2.39°; 95% likely range 1.16 – 3.58°). In addition, the WS exhibits a significantly greater knee joint moment than the AS (mean difference: 0.05 N.m.kg; 95% likely range 0.01 – 0.10 N.m.kg). An effect due to experience was seen at the hip angle ($F_{(1,28)} = 7.66$; $P = 0.01$), knee angle ($F_{(1,28)} = 12.47$; $P = 0.00$) and $VCOP_x$ ($F_{(1,28)} = 4.82$; $P = 0.04$). The experienced group exhibited significantly greater hip (mean difference: 7.26°; 95% likely range 1.89 – 12.63°) and knee (mean difference: 17.65°; 95% likely range 7.41 – 27.89°) flexion than the novice, demonstrating a greater squat depth. The experienced group also had significantly greater $VCOP_x$ variability compared to the novice (mean difference: 8.58×10^{12} mm^2s^{-5}; 95% likely range 0.57×10^{12} mm^2s^{-5} – 16.58×10^{12} mm^2s^{-5}). A significant footwear × experience interaction was present for the ankle angle ($F_{(1,28)} = 6.38$; $P = 0.02$); *post hoc* comparisons were unable to identify where those differences were. The only significant effect due to sex was seen at the hip ($F_{(1,28)} = 5.27$; $P = 0.03$), with females displaying a greater degree of flexion compared to the males (mean difference: 6.02°; 95% likely range 0.65 – 11.40°). No significant effects were shown in knee translation for any of the independent variables.

Loaded - Novice

Table 4 displays the results from the novice-loaded trials. A main effect for footwear was shown at the ankle angle ($F_{(1,14)} = 20.44$; $P = 0.00$), knee angle ($F_{(1,14)} = 10.97$; $P = 0.01$), knee moment ($F_{(1,14)}$ = 8.04; P = 0.01) and $VCOP_y$ ($F_{(1,14)}$ = 6.94; P = 0.02). The effect of footwear on the trunk was not significant for this group (P = 0.059, mean difference: 2.27°; 95% likely range -0.10 – 4.64°). The significant differences indicated a reduction in ankle flexion (mean difference: 2.49°; 95% likely range 1.31 – 3.67°), a greater degree of knee flexion (mean difference: 3.46°; 95% likely range 1.22 – 5.70°), an increase in knee moment (mean difference: 0.96 N.m.kg; 95% likely range 0.01 – 0.07 N.m.kg) and a reduction in $VCOP_x$ (mean difference: 4.51 x 10^6 mm^2s^{-5}; 95% likely range 0.84 x 10^6 mm^2s^{-5} - 8.18 x 10^6 mm^2s^{-5}) when using the WS. A footwear × sex interaction was shown for the knee moment ($F_{(1,14)}$ = 8.40, P = 0.01). *Post hoc* comparisons were unable to identify where those differences were. No significant differences were seen in the effect of footwear on the anterior knee translation. There were no significant effects due to sex for any of the novice dependent variables under load.

Loaded - Experienced

The experienced-loaded results are presented in Table 5. An effect of footwear was seen at the ankle ($F_{(1,14)}$ = 8.21; P = 0.01), knee ($F_{(1,14)}$ = 13.06; P = 0.00), ankle moment ($F_{(1,14)}$ = 7.09; P = 0.02) and $VCOP_x$ ($F_{(1,14)}$ = 4.64; P = 0.05). The statistical differences demonstrated a reduction in ankle flexion (mean difference: 1.99°; 95% likely range 0.50 – 3.49°), a greater degree of knee flexion (mean difference: 2.57°; 95% likely range 1.05 – 4.10°), an increase in ankle moment (mean difference: 0.03 N.m.kg; 95% likely range 0.01 – 0.06 N.m.kg), and an decrease in $VCOP_x$ (mean difference: 6.24 x 10^{11} mm^2s^{-5}; 95% likely range 12.4 x 10^{11} – 0.03 x 10^{11} mm^2s^{-5}), when utilising the WS compared to the AS. A significant effect due to sex was demonstrated at the knee ($F_{(1,14)}$ = 11.47; P = 0.00), ankle moment ($F_{(1,14)}$ = 18.13; P = 0.00)

Table 3: Unloaded squat kinematic and kinetic parameters (means ± standard deviations) for each footwear, experience and gender condition.

	Beginners				Experienced			
	Males		Females		Males		Females	
	AS	WS	AS	WS	AS	WS	AS	WS
Joint Angle (Degrees)								
Ankle *◊	27.68 ± 7.71	26.82 ± 8.29	35.53 ± 7.79	32.36 ± 6.81	37.11 ± 6.12	30.61 ± 4.23	32.77 ± 6.55	28.86 ± 7.72
Knee *†	98.49 ± 20.12	104.41 ± 20.32	110.29 ± 7.97	112.67 ± 7.05	125.56 ± 11.44	127.57 ± 10.40	120.20 ± 16.87	123.14 ± 13.39
Hip †‡	100.19 ± 8.05	99.70 ± 9.73	104.96 ± 8.73	107.02 ± 7.65	107.83 ± 6.25	106.63 ± 5.98	113.00 ± 5.85	113.46 ± 7.90
Trunk *	37.36 ± 16.56	39.99 ± 16.79	39.45 ± 10.98	41.94 ± 10.27	42.73 ± 9.11	46.14 ± 9.81	41.61 ± 7.23	42.56 ± 5.6
Knee Translation (mm)	15.27 ± 56.83	13.95 ± 57.22	58.96 ± 47.68	53.75 ± 31.80	32.22 ± 29.87	26.85 ± 25.44	46.58 ± 38.87	39.57 ± 37.49
Peak Moment (N.m.kg)								
Ankle	0.39 ± 0.11	0.38 ± 0.11	0.53 ± 0.13	0.47 ± 0.11	0.50 ± 0.24	0.56 ± 0.24	0.51 ± 0.15	0.48 ± 0.08
Knee *	1.10 ± 0.20	1.12 ± 0.16	1.10 ± 0.21	1.13 ± 0.17	1.19 ± 0.27	1.28 ± 0.23	0.87 ± 0.40	0.94 ± 0.36
Hip	1.07 ± 0.18	1.10 ± 0.25	1.31 ± 0.21	1.31 ± 0.23	1.33 ± 0.28	1.22 ± 0.26	1.25 ± 0.27	1.20 ± 0.26
VCOP								
VCOP x †	7.44 ± 5.99	7.22 ± 5.46	7.62 ± 6.30	7.73 ± 5.98	10.66 ± 6.42	9.50 ± 5.46	20.58 ± 18.15	23.58 ± 21.37
VCOP y	5.27 ± 6.04	4.33 ± 4.20	4.00 ± 3.68	3.69 ± 3.02	6.60 ± 5.67	6.48 ± 6.41	6.40 ± 4.01	6.68 ± 5.79

VCOP: Centre of pressure variability in the anterio-posterior plane (VCOPx, mm^2s^{-5} x 10^{12} ± mm^2s^{-5} x 10^{12}) and the medio-lateral plane (VCOPy, mm^2s^{-5} x 10^7 ± mm^2s^{-5} x 10^7).

* Significant difference ($p < 0.05$) when comparing footwear

† Significant difference ($p < 0.05$) when comparing experience

‡ Significant difference ($p < 0.05$) when comparing gender

◊ Significant interaction ($p < 0.05$) between footwear and experience and hip moment ($F_{(1,14)}$ = 5.53; P = 0.03). The males had a significantly greater degree of knee flexion compared to females (mean difference: 18.92°; 95% likely range 6.94 – 30.89°), in addition, the males had higher joint moments at the ankle (mean difference: 0.27 N.m.kg; 95% likely range 0.13 – 0.40 N.m.kg), and the hip (mean difference: 0.28 N.m.kg; 95% likely range 0.02 – 0.53 N.m.kg), when compared to the females. Finally, no significant effects of footwear or sex were observed at the trunk, knee moment, the knee translation or the $VCOP_y$.

Table 4: Novice group loaded squat kinematic and kinetic parameters (means ± standard deviations) for each footwear and gender condition.

		Males		Females	
		AS	WS	AS	WS
Joint Angle (Degrees)					
	Ankle *	30.90 ± 8.43	28.77 ± 8.28	32.48 ± 7.81	29.64 ± 7.17
	Knee *	104.09 ± 17.70	108.73 ± 16.38	109.87 ± 5.24	112.14 ± 5.69
	Hip	100.20 ± 9.40	101.16 ± 10.77	105.04 ± 9.24	106.81 ± 9.64
	Trunk	42.71 ± 14.24	45.10 ± 15.88	41.96 ± 5.73	44.11 ± 5.14
Knee Translation (mm)		26.04 ± 64.78	25.29 ± 56.69	47.51 ± 38.75	53.34 ± 30.66
Peak Moment (N.m.kg)					
	Ankle	0.53 ± 0.08	0.51 ± 0.10	0.52 ± 0.11	0.55 ± 0.11
	Knee *♯	0.83 ± 0.33	0.92 ± 0.31	1.00 ± 0.19	1.00 ± 0.15
	Hip	1.33 ± 0.33	1.28 ± 0.31	1.39 ± 0.20	1.43 ± 0.16
VCOP					
	VCOP x	4.64 ± 4.15	4.09 ± 3.23	5.47 ± 3.84	4.73 ± 3.81
	VCOP y*	3.39 ± 3.44	2.72 ± 2.70	2.92 ± 2.61	2.69 ± 2.29

VCOP: Centre of pressure variability in the anterio-posterior plane (VCOPx, $mm^2s^{-5} \times 10^{12} \pm mm^2s^{-5} \times 10^{12}$) and the medio-lateral plane (VCOPy, $mm^2s^{-5} \times 10^7 \pm mm^2s^{-5} \times 10^7$).
* Significant difference ($p < 0.05$) when comparing footwear
♯ Significant interaction ($p < 0.05$) between footwear and gender

Table 5: Experienced group loaded kinematic and kinetic parameters (means ± standard deviations) for each footwear and gender condition.

	Males		Females	
	AS	WS	AS	WS
Joint Angle (Degrees)				
Ankle *	30.10 ± 6.38	28.80 ± 6.46	27.81 ± 4.61	25.13 ± 4.91
Knee *‡	128.17 ± 13.77	131.77 ± 11.38	110.28 ± 9.67	111.83 ± 9.72
Hip	112.34 ± 7.89	112.83 ± 8.01	112.07 ± 8.10	112.46 ± 7.72
Trunk	46.63 ± 4.13	47.54 ± 4.21	42.92 ± 7.65	40.89 ± 6.42
Knee Translation (mm)	32.50 ± 38.99	38.37 ± 27.34	12.23 ± 25.87	16.73 ± 32.03
Peak Moment (N.m.kg)				
Ankle *‡	0.75 ± 0.13	0.77 ± 0.15	0.47 ± 0.11	0.51 ± 0.12
Knee	0.99 ± 0.25	1.03 ± 0.27	0.86 ± 0.12	0.85 ± 0.12
Hip ‡	1.61 ± 0.19	1.63 ± 0.21	1.35 ± 0.29	1.34 ± 0.25
VCOP				
VCOP x *	2.26 ± 1.61	1.76 ± 1.16	6.78 ± 7.82	6.04 ± 6.63
VCOP y	2.07 ± 2.02	2.13 ± 2.14	2.70 ± 2.09	2.51 ± 2.62

VCOP: Centre of pressure variability in the anterio-posterior plane (VCOPx, mm^2s^{-5} x 10^{12} ± mm^2s^{-5} x 10^{12}) and the medio-lateral plane (VCOPy, mm^2s^{-5} x 10^7 ± mm^2s^{-5} x 10^7).
* Significant difference ($p < 0.05$) when comparing footwear
‡ Significant difference ($p < 0.05$) when comparing gender

DISCUSSION

The WS affected the kinematics of the squat movement compared to the AS. The current findings support the general coaching contention that utilising a WS allows a lifter to squat to a greater depth, through increased knee flexion (Charniga, 2006; Dreschler, 1998; Kono, 2001), by reducing the demand for ankle dorsiflexion (Sato et al., 2012; Schoenfeld, 2010; Stiggins & Allsen, 1982), allowing the peak hip angle to remain unchanged and promoting an upright trunk (Sato et al., 2012). Across all trials, the WS elicited a reduction in ankle dorsiflexion and an increase in knee flexion. It has been previously shown that when ankle range is restricted, the knee is unable to flex maximally without assistance from a decline surface (Zwerver, Bredeweg & Hof, 2007). The decline generated by the WS was sufficient to reduce the demand at the ankle joint.

Contrary to previous research (Sato et al., 2012) the WS allowed for a deeper squat position to be achieved, providing greater levels of knee flexion with similar hip angles. Sato et al. (2012) stipulated a thigh to parallel squat position, which would account for the differences in findings. In the present study, by not instructing the participants to achieve a predetermined depth, it was assumed they were able to move without restriction and within their natural range of motion capabilities under each condition (McKean et al., 2010a). Several sources have identified that anatomical factors influence squat movement (Fry et al., 1988 and Fry et al., 1991) and the depth that individuals are able to squat (Myer et al., 2014). In addition, it has been suggested that in order to attain a greater squat depth, an athlete may require improvements in hip flexibility (Schoenfeld, 2010). Increasing an athlete's squat depth, or utilising a deep back squat does not increase the athlete's risk of injury, providing sufficient technique and progressions are utilised (Hartmann, Wirth & Klusemann, 2013). The alterations in kinematics generated by WS may: first, provide an acute strategy to permit increased squat depth prior to achievement of improved hip mobility; and secondly, provide an aid to those limited by their anthropometry.

When unloaded, the trunk was in a more upright position when wearing WS. This trend was also evident when the novice group was loaded, although the effect was not significant. A reduction in anterior trunk lean due to WS has been shown in previous research (Sato et al., 2012). Additionally, the findings of the present study confirm the theoretical notion put forward by the coaching community that utilising a heel lift elicits a more upright trunk during a deep squat (Charniga, 2006; Dreschler, 1998). In contrast, the absence of differences in trunk position due to footwear for the experienced group under load is not in agreement with previous work (Sato et al., 2012). It would seem likely the lighter loads and restrictions on depth used by Sato et al. (2012) would explain differences from the findings presented here. Further, the experienced group studied here appeared able to maintain a similar trunk angle at a greater squat depth whilst wearing WS, suggesting this group has an established trunk movement pattern under load. The present findings suggest that WS could be a suitable tool to assist increases in squat depth without compromising trunk position.

During the unloaded trials, and novice loaded trials, the kinetic data demonstrated that when using WS there is an increase in flexion at the knee joint, placing further emphasis on the knee extensors. It has been shown that squatting on a decline surface increases the knee joint moment due to the posterior shift of the line of force in relation to the knee joint axis; however, this has been seen on decline surfaces much greater than that created by the WS (Kongsgaard et al., 2006; Zwerver et al., 2007). The posterior shift in force generated by the WS heel lift coupled with the decrease in trunk flexion caused by the WS, explains the increase in the demand at the knee joint. Moreover, a reduction in trunk lean has previously been demonstrated to shift the line of force towards the knee joint and away from the hips and trunk (Lorenzetti et al., 2012). Under load, the experienced group did not exhibit an increase in knee joint moment; however, there was an increase in ankle joint moment in the WS condition. In accordance with the kinematic changes brought about by the WS, the increased knee flexion with similar trunk angles would suggest the distal and proximal segments of the thigh and trunk become comparatively closer on the sagittal plane, leading to a shortening of the moment arms of the knee and hip. This may explain the similarities between joint moments under the two footwear conditions. The increase in ankle moment, coupled with the increased movement in $VCOP_x$, would suggest that experienced lifters adopt a strategy to resist the anterior movement of the body's centre of mass, by utilising the ankle and plantar flexor muscle group to control their balance during the squat cycle (Zwerver et al., 2007). During the squat it is important to establish an optimal kinetic environment for all the joints involved (Fry et al., 2003). Although significant, the magnitudes of the changes in knee and ankle joint moments were relatively small between the two footwear conditions. These alterations elicited by WS should be assessed in conjunction with the athlete attaining the appropriate lifting technique to ensure that training outcomes are being met.

The WS did not elicit significant changes to the anterior translation of the knees relative to the toes. Only one previous study has documented anterior knee translation with respect to the toe position (McKean et al., 2010a). In agreement with this previous work the knees moved anteriorly beyond the toes during the squat movement when depth and knee movement were unrestricted. This study also demonstrated a large variability in knee displacement, further supporting the notion that anterior translation is highly individual (McKean et al., 2010a), and may explain the lack of significant differences in anterior knee translation within the present findings. Limiting or restricting anterior knee translation results in compensatory movements at the hip and trunk (Fry et al., 2003; List et al., 2013; Lorenzetti et al., 2012; McKean et al., 2010a). Coaches should consider that anterior translation of the knees might be a necessary component of the squat movement for some individuals, in order to prevent undesirable compensatory kinematic and kinetic adaptions from occurring (Fry et al., 2003; McKean et al., 2010a).

For strength gains to be elicited most effectively, it has been suggested that a stable surface is required (Cressey, West, Tiberio, Kraemer & Maresh, 2007; McBride, Cormie & Deane, 2006). AS have been suggested to be an inappropriate footwear choice for squatting, due to the compressible nature of the sole (Charniga, 2006; Dreschler, 1998; Kono, 2001). When unloaded there were no differences in the VCOP variability between the AS and WS, suggesting that AS do not generate an unstable surface under those conditions. However, under load, it appears that WS were more stable with significantly lower VCOP variability in the $VCOP_y$ for the novice and the $VCOP_x$ for the experienced when compared with AS. The current findings suggest that WS may be a more suitable choice of footwear during the squat if maximal strength gains are the primary objective of the exercise.

There were differences in squat kinematics between the experienced and novice groups. When unloaded, the experienced group demonstrated a deeper squat position, as reflected by greater hip and knee flexion. Despite the differences in squat depth there were similar ankle and trunk angles between the two groups. It has been suggested that novice lifters will attempt to restrict their anterior knee movement during the squat (Fry et al., 2003). Consequently, a trunk lean strategy is necessary to maintain their centre of mass over their base of support to avoid falling, a common error observed in novice populations during the squat (Chandler & Stone, 1991; Dunn et al., 1984; McLaughlin et al., 1977). The differences in squat kinematics suggest that the novice group may adopt a trunk lean strategy at a reduced squat depth when compared to experienced lifters. When unloaded, the experienced group exhibited more VCOP variability in the anterior-posterior plane than the novice group. This may imply that the experienced group were able to manage the changes in VCOP variability effectively during their squat pattern to achieve the outcome. In contrast, the reduced variability coupled with a restricted squat depth in the novice group potentially indicates a strategy of minimising variance to avoid a loss of balance during the squat. Utilising coaching strategies to manage VCOP, and subsequently balance, may be of benefit to novice lifters. An increase in stability during the squat cycle may allow novice athletes to explore the available ranges of movement within the boundaries of the base of support.

Differences in squat movement and coordination patterns between sexes have previously been shown (Lynn & Noffal, 2012; McKean et al., 2010a; McKean et al., 2010b). When unloaded, females had more hip flexion; this difference has also been shown to occur during a single leg squat (Zeller, McCory, Kibler & Uhl, 2003). The differences in hip anatomy and flexibility between the sexes may account for this (McKean et al., 2010b); however, an understanding of the variations at the hip are yet to be fully explained (Lynn & Noffal, 2012; McKean et al., 2010a; Zeller et al., 2003) and is a topic for future research. In the current study, experienced males displayed larger ankle and hip moments and greater degrees of knee flexion when under load compared to experienced females. This is in agreement with previous literature, with differences in knee flexion and joint moments being demonstrated between sexes in an experienced population (McKean et al., 2010a). It has been suggested that the variability in joint moments between sexes may be due to different strategies utilised by males to absorb and transfer forces through the lower limb joints and muscles (McKean et al., 2010a). In contrast, there were no differences due to sex in the novice group; further investigation is warranted to establish the kinematic and kinetic deviations between different populations and skill levels. The findings of this study add to the current literature that demonstrates differences in squatting strategies utilised between the sexes, which need to be examined in greater detail to establish the underlying mechanisms for these differences and the associated practical implications.

There are a few limitations that should be considered when evaluating the outcomes of the present study. The order of the unloaded and loaded conditions was not randomised, and as such, there is an associated risk of a practice effect occurring, particularly in the novice group. Further, whilst the loaded condition was designed to present a safe but moderate challenge, the different loads utilised between the novice and experienced groups meant that it was not possible to compare the effects of WS under load between the two groups. There is also likely to have been some variation in the relative effort demanded by the loaded condition within both groups since the novices were prescribed by percentage bodyweight rather than strength, and the experienced group 1 RM was self-reported. This outcome was accepted for safety reasons in the novice group, and is believed to be a minor issue for the experienced group who were all considered familiar with their level of performance due to training regularly using maximal and near maximal loads. Finally, there were no restrictions applied to the participants' stance, speed, or depth during the squat movement. It was assumed that they were able to move freely and to the limits of their range of motion. Although representing a reduced level of control, this choice was made to promote athletes using their preferred pattern of movement in all cases, which was deemed to offer the best level of ecological validity.

CONCLUSIONS

Wearing weightlifting shoes whilst performing the back squat elicits changes to an athlete's squat movement. Athletes who are limited in their squat depth and cannot meet the increased hip flexion, knee flexion and ankle dorsiflexion requirements of the movement may benefit from utilising WS when squatting. The use of WS may allow an athlete to achieve a greater squat depth whilst promoting an upright posture. Due to the non-compressible nature of WS, they may be a suitable footwear choice to aid stability and as such might facilitate strength increases. The introduction of WS use into a novice athletes training regime, alongside appropriate coaching strategies, may be a suitable approach to expedite technical progression and achievement of squat range. Although increases in knee and ankle joint moments between the two footwear conditions are evident, the magnitudes are relatively small. The decision regarding an athlete's footwear choice during the squat exercise needs to consider the alterations in joint kinematics and kinetics generated by each footwear option, alongside the athlete's movement capabilities and training objectives.

REFERENCES

Chandler, T. J., & Stone, M. (1991). H. The squat exercise in athletic conditioning: A position statement and review of the literature. *National Strength and Conditioning Association Journal*, *13*, 51-58.

Charniga, A. C. (2006). Why Weightlifting Shoes? Livonia: Sportivny Press.

Cressey, E. M., West, C. A., Tiberio, D. P., Kraemer, W. J., & Maresh, C. M. (2007). The effects of ten weeks of lower-body unstable surface training on markers of athletic performance. *Journal of Strength and Conditioning Research, 21,* 561-567.

Dreschler, A. J. (1998) The Weightlifting Encyclopedia. A guide to World Class Performance. New York: A is A Communications.

Dunn, B., Klein, K., Kroll, B., McLaughlin, T., O'Shea, P., & Wathen, D. (1984). Coaches roundtable: The squat and its application to athletic performance. *Strength and Conditioning Journal, 6*, 10-19.

Escamilla, R. F. (2001). Knee biomechanics of the dynamic squat exercise. *Medicine and Science in Sports and Exercise, 33,* 127–141.

Fairchild, D., Hill, B., Ritchie, M., & Socher, D. (1993). Common technique errors in the back squat. *Strength and Conditioning Journal, 15*, 20-27.

Fry, A. C., Housh, T. J., Hughes, R. A., & Eyford, T. (1988). Stature amd flexibility variables as discriminators of foot contact during the squat exercise. *Journal of Applied Sports Science Research, 2,* 24-26.

Fry, A. C., Kraemer, W. J., Bibi, K. W., & Eyford, T. (1991). Stature variables as discriminators of foot contact during the squat exercise in untrained females. *Journal of Applied Sports Science Research, 5*, 77-81.

Fry, A. C., Smith, C., & Schilling, B. K. (2003). Effect of knee positions on hip and knee torques during the barbell squat. *Journal of Strength and Conditioning Research, 17*, 629-633.

Hartmann, H., Wirth, K., & Klusemann, M. (2013). Analysis of the load on the knee joint and vertebral column with changes in squatting depth and weight load. *Sports Medicine, 43,* 993-1008.

Kongsgaard, M., Aagaard, P., Roikjaer, S., Olsen, D., Jensen, M., Langberg, H., & Magnusson, S. P. (2006). Decline eccentric squats increases patella tendon loading compared to standard eccentric squats. *Clinical Biomechanics, 21,* 748-745.

Kono, T. (2001). Weightlifting Olympic Style. Aiea, HI: Hawaii Kono Company.

Lander, J. E., Bates, B. T., & Devita, P. (1986). Biomechanics of the squat exercise using a modified center of mass bar. *Medicine and Science in Sports and Exercise, 18,* 469-478.

List, R., Gülay, T., Stoop, M., & Lorenzetti, S. (2013). Kinematics of the trunk and lower extremities during restricted and unrestricted squats. *Journal of Strength and Conditioning Research, 27*, 1529-1538.

Lorenzetti, S., Gülay, T., Stoop, M., List, R., Gerber, H., Schellenberg, F., & Stüssi, E. (2012). Comparison of the angles and corresponding moments in the knee and hip during restricted and unrestricted squats. *Journal of Strength and Conditioning Research, 26*, 2829-2836.

Lynn, S. K., & Noffal, G. J. (2012) Lower extremity biomechanics during a regular and counterbalanced squat. *Journal of Strength and Conditioning Research, 26*, 2417-2425.

McBride, J. M., Cormie, P., & Deane, R. (2006). Isometric squat force output and muscle activity in stable and unstable conditions. *Journal of Strength and Conditioning Research, 20*, 915-918.

McKean, M. R., Dunn, P. K., & Burkett, B. J. (2010). Quantifying the movement and the influence of load in the back squat exercise. *Journal of Strength and Conditioning Research, 24*, 1671-1679.

McKean, M. R., Dunn, P. K., & Burkett, B. J. (2010). The lumbar and sacrum movement pattern during the back squat exercise. *Journal of Strength and Conditioning Research, 24*, 2731-2741.

McLaughlin, T. M., Dillman, C. J., & Lardner, T. J. (1977). A kinematic model of performance in the parallel squat by champion powerlifters. *Medicine and Science in Sports and Exercise, 9*, 128-133.

McLaughlin, T. M., Lardner, T. J., & Dillman, C. J. (1978). Kinetics of the parallel squat. *Research Quarterly, 49*, 175-189.

Myer, G. D., Kushner, A. M., Brent, J. L., Schoenfeld, B. J., Hugentobler, J., Lloyd, R., Vermeil, A., Chu, D. A., Harbin, J., & McGill, S. M. (2014). The back squat: A proposed assessment of functional deficits and technical factors that limit performance. *Journal of Strength and Conditioning Research, 36,* 4-27.

Neitzel, J. A., & Davies, G. J. (2000). The benefits and controversy of the parallel squat in strength training and rehabilitation. *Strength and Conditioning Journal, 22,* 30-37.

Sato, K., Fortenbaugh, D., & Hydock, D. S. (2012). Kinematic changes using weightlifting shoes on barbell back squat. *Journal of Strength and Conditioning Research, 26*, 28-33.

Schoenfeld, B. J. (2010). Squatting kinematics and kinetics and their application to exercise preformance. *Journal of Strength and Conditioning Research, 24*, 3497-3506.

Stiggins, C., & Allsen, P. (1982). Exercise methods notebook 2: Squats. *NSCA Journal, 4,* 61.

Zeller, B. L., McCory, J. L., Kibler, B., & Uhl, T.L. (2003). Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *American Journal of Sports Medicine, 31*, 449-456.

Zwerver, J., Bredeweg, S. W., & Hof, A. L. (2007). Biomechanical analysis of a single-leg decline squat. *British Journal of Sports Medicine, 41*, 264-268.