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AQ1 ORIGINAL ARTICLE

The influence of different footwear on 3-D kinematics and muscle activation during the barbell back squat in males

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Abstract
The barbell back squat is commonly used by athletes participating in resistance training. The barbell squat is typically performed using standard athletic shoes, or specially designed weightlifting footwear, although there are now a large number of athletes who prefer to squat barefoot or in barefoot-inspired footwear. This study aimed to determine how these footwear influence 3-D kinematics and muscle activation potentials during the barbell back squat. Fourteen experienced male participants completed squats at 70% 1 rep max in each footwear condition. 3-D kinematics from the torso, hip, knee and ankle were measured using an eight-camera motion analysis system. In addition, electromyographical (EMG) measurements were obtained from the rectus femoris, tibialis anterior, gastrocnemius, erector spinae and biceps femoris muscles. EMG parameters and joint kinematics were compared between footwear using repeated-measures analyses of variance. Participants were also asked to subjectively rate which footwear they preferred when performing their squat lifts; this was examined a chi-squared test. The kinematic analysis indicated that, in comparison to barefoot the running shoe was associated with increased squat depth, knee flexion and rectus femoris activation. The chi-squared test was significant and showed that participants preferred to squat barefoot. This study supports anecdotal evidence of athletes who prefer to train barefoot or in barefoot-inspired footwear although no biomechanical evidence was found to support this notion.

Keywords: Biomechanics, kinesiology, training

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Introduction

The barbell back squat is commonly used by athletes participating in resistance training, or during the rehabilitation of lower extremity injuries (Chandler & Stone, 1991; Gullett, Tillman, Gutierrez, & Chow, 2009). As such, this exercise has received considerable attention, in strength and conditioning research, in terms of kinetics, kinematics and electromyographical (EMG) potentials.

The barbell squat originates from an upright position, with maximal extension of the hip and knee joints and the ankle in a neutral position. The squat movement is initiated through flexion of the hip and knee joints and dorsiflexion of the ankle. When the necessary squat depth is attained the lifter subsequently extends the hip and knee joints and plantarflexes the ankle in order to reverse the direction of the squat and return to the standing position (Schoenfeld, 2010). The barbell squat recruits many of the lower extremity muscles, with predominant activation of the quadriceps, ham- strings, tibialis anterior, gastrocnemius and lumbar muscles (Schoenfeld, 2010). There is also significant isometric recruitment of the supporting musculature such as the abdominals, trapezius and rhomboids to promote postural control in the trunk during the squat.

It is common for the barbell squat to be performed using standard athletic shoes, or specially designed weightlifting footwear (Panariello, Backus, & Parker, 1994; Sato, Fortenbaugh, Hydock, & Heise, 2013). These specialist footwear encompass a rigid midsole, heel angulation and outsole with a high coefficient of

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University's Code of Conduct for Research can be found at the following web address:http://www.uclan.ac.uk/information/research/research_degrees/ethics_research_governance.php. AQ4

friction (Davis, 2012). Whilst weightlifting and athletic footwear have habitually been the footwear of choice for those who regularly undertake the back squat, barefoot squatting is increasing in popularity, and being employed in strength and conditioning programmes. An increasing number of athletes are now utilising barefoot and barefoot-inspired foot- wear, such as Vibram five-fingers, during training. It is perceived that such methods aid in increasing lower limb proprioception. The rationale behind this concept is that barefoot squatting may provide increased lower limb stability and force generation (Shorter, Lake, Smith, & Lauder, 2011). A cush- ioned midsole in athletic footwear is proposed to negatively affect the body's centre of balance. Vertical displacement under the foot, as a result of the cushioning under load, creates a less stable base, potentially compromising squatting potential and safety throughout the exercise (Kilgore & Rippetoe, 2006).

Barefoot training, and squatting in particular, is AQ5 believed to increase the strength of the intrinsic musculature of the foot and ankle and also increase ankle joint freedom of movement (Sato et al., 2013). Brown (2013) proposed that these alterations improve balance and ankle range of motion during the lift, thus providing the lifter with greater capab- ility to produce the desired movement pattern. Until recently, however, many of the proposed benefits of barefoot squatting were anecdotal and there was little scientific evidence to support these claims. Recent research has, however, considered the effi- cacy of the barefoot squat.

Shorter et al. (2011) examined power production during the back squat whilst wearing trainers, bare- foot-inspired footwear and without shoes. They found at 80% of 1 rep max that the barefoot-inspired shoe was associated with the lowest peak and average power performance in comparison to the shod and barefoot conditions. Sato et al. (2013) examined the differences in squat kinematics performed barefoot and in running shoes. Sagittal plane kinematics were obtained for the thigh and trunk segments in addi- tion to angulation profiles of the hip, knee and ankle joints. Their findings were contrasted against the National Strength and Conditioning Association position statement regarding the squat (Chandler & Stone, 1991). It was observed that greater trunk flexion was present during the barefoot squat, and that it was also more challenging for lifters to attain the desired parallel position in this condition when compared to the shod condition. Both of these observations were deemed to be unfavourable as they compromised squat technique. However, the barefoot condition was associated with seven degrees less knee flexion in comparison to the running shoe. It was hypothesised that this may be beneficial in reducing the knee torque experienced during squat lifts.

Despite the wealth of published information exam- ining the squat, in addition to more recent evidence concerning the efficacy of squatting barefoot and in barefoot-inspired footwear, there has yet to be an investigation which has examined the simultaneous 3-D kinematics and muscle activation parameters with weightlifting shoes, athletic trainers, barefoot- inspired footwear and barefoot squatting itself. There- fore, the aim of the current study was to investigate the influence of these footwear on 3-D kinematics and muscle activation potentials during the barbell back squat. This study tested the hypothesis that both 3-D kinematic and muscle EMG patterns would be significantly influenced by the athletic footwear con- ditions examined in this investigation.

Methods

Participants

Fourteen male participants completed the study, the mean and standard deviation characteristics of the participants were: age = 19.14 ± 0.71 years; height = 1.74 ± 6.38 cm; body mass = 69.75 ± 6.38 kg. Participants were all practiced in squat lifting with a minimum of 5 years of experience in performing barbell back squats. All were free from musculoske- letal pathology at the time of data collection, and provided written informed consent. The procedure used for this investigation was approved by the University of Central Lancashire, School of Sport Tourism and Outdoor ethical committee, in accord- ance with the principles outlined in the Declaration of Helsinki.

Procedure

One week prior to data collection, each participant attended the laboratory where their one repetition maximum (RM) back squat weight was taken with a certified NSCA strength and conditioning trainer. These results would be used to calculate the 70% of their 1RM, which was selected as being representat- ive of loads used for a 12RM work out (Brzycki, 1993). Participants completed five back squat repeti- tions in each footwear AQ7 condition using their normal squat technique.

3-D kinematic information was collected using an eight-camera optoelectric motion capture system using Qualisys track manager software (Qualisys Medical AB, Goteburg, Sweden) with a sampling frequency of 250 Hz. The calibrated anatomical sys- tems technique (CAST) was utilised to quantify joint kinematics (Cappozzo, Catani, Croce, & Leardini, 1995). To define the anatomical frames of the pelvis,

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right foot, shank, thigh and torso, retroreflective were positioned onto the calcaneus, first metatarsal heads, medial and lateral malle- oli, medial and lateral femoral epicondyles, anterior (ASIS) and posterior (PSIS) superior iliac spines, xiphoid process, greater trochanter, acromion pro- cess and iliac crests. The hip joint centre was determined using regression equations based on the separation between ASIS markers (Sinclair, Taylor, Currigan, & Hobbs, 2013). Rigid carbon-fibre track- ing clusters comprising of four non-linear retro- reflective markers were positioned onto the pelvis, thigh and shank segments and securely positioned using tape. The foot was tracked using the calcaneus, first and fifth metatarsal markers. Retroreflective markers were attached using strong double-sided tape. A carbon-fibre tracking cluster was also secured onto shank segment using a cohesive band- age. Static calibration trials (not normalised to standing posture) were obtained with the participant in the anatomical position in order for the positions of the anatomical markers to be referenced in relation to the tracking clusters/markers. Separate static trials were obtained for each footwear condition.

Surface EMG activity was obtained at a capture frequency of 1000 Hz from the rectus femoris (RF), tibialis anterior (TA), gastrocnemius (GM), erector spinae (ES) and biceps femoris (BF) muscles. Bipo- lar electrodes with an inter-electrode distance of 19 mm were utilised. In accordance with the guidelines outlined by SENIAM, the electrodes were placed on the muscle bellies in line with the muscle pennation angle (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). Prior to data collection, the skin was shaved and primed with abrasive paper and cleaned with an ethanol wipe to reduce surface impedance (Cram & Rommen, 1989).

The order, in which the participants completed their squats in each footwear condition, was rando- mised. Upon conclusion of the data collection, participants were asked to subjectively indicate which shoe condition that they preferred for squat- ting. All data were collected on the same day.

Data processing

Dynamic trials were digitised using Qualisys Track Manager in order to identify anatomical and tracking markers then exported as C3D files. 3-D kinematics were quantified using Visual 3-D (C-Motion Inc, Germantown, MD, USA) after marker displacement data were smoothed using a low-pass Butterworth fourth-order zero-lag filter at a cut-off frequency of 6 Hz (Winter, 1990). 3-D kinematics were calculated using an XYZ cardan sequence of rotations (where X represents sagittal plane; Y represents coronal plane and Z represents transverse plane rotations) markers (Sinclair, Taylor, Edmundson, Brooks, & Hobbs, and fifth 2012). All kinematic waveforms were normalised to 100% of the squat movement phase then processed trials were averaged. Discrete 3-D kinematic mea- sures from the hip, knee, ankle and torso which were extracted for statistical analysis were (1) peak angle during the squat movement, (2) relative range of motion (representing the angular displacement from initiation of movement to peak angle) and (3) squat depth. These variables were extracted from each of the five trials for each joint in all the three planes of rotation, and the data were then averaged within subjects for comparative statistical analysis.

The EMG signals from each muscle were full- wave rectified and filtered using a 20-Hz Butter- worth zero-lag low-pass fourth-order filter to create a linear envelope. Mean and peak EMG amplitude from each muscle were obtained and normalised to a maximum voluntary contraction (MVC). This was obtained by performing an isometric squat hold using a reversed squat rack. Participants were asked to push to maximum effort.

Footwear

The footwear conditions used in the current invest- igation consisted of a Do-Win (Gong Lu II) weight lifting shoe, Vibram five-fingers (M105) barefoot- inspired footwear, Saucony (pro grid guide II) conventional running training shoe and no footwear (barefoot). The footwear were the same for all participants and differed in size only (sizes 7-9 in men's shoe UK sizes).

Statistical analyses

Means and standard deviations of the 3-D kinematic and EMG parameters were calculated for each footwear condition. Differences between footwear were examined using one-way repeated-measures analysis of variance (ANOVA) with significance accepted at the $p < 0.05$ level. Post hoc pairwise comparisons were utilised using a Bonferroni adjust- ment to control for type I error. Effect sizes were calculated using partial eta^2 (η_p^2). If the sphericity assumption was violated then the degrees of freedom were adjusted using the Greenhouse-Geisser correc- tion. The data were screened for normality using a Shapiro-Wilk which confirmed that the normality assumption was met. A chi-square (χ^2) test was utilised to test the assumption that an equal number of participants would subjectively favour each of the four footwear conditions. All statistical procedures were conducted using SPSS version 21.0 (SPSS Inc., Chicago, IL, USA).

Results

Favoured footwear and squat depth

Results of the chi-square test were significant (χ^2 = 4.14, $p < 0.05$) indicated a significant difference between the reported and expected number of respondents for each footwear preference, with the majority preferring barefoot squatting (barefoot n = 7, barefoot-inspired n = 3, weightlifting shoe n = 2 and running shoe n = 2). A significant main effect ($\eta^2_p = 0.36$) was also observed for the magnitude of squat depth. Post hoc pairwise comparisons revealed that squat depth in the running shoe (0.51 ± 0.07 m) was significantly greater than when squatting bare- foot (0.47 ± 0.06 m). No significant differences ($p > 0.05$) were shown between the weightlifting (0.49 ± 0.06 m) and barefoot-inspired footwear (0.48 ± 0.06 m).

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3-D kinematics

Torso

No significant ($p > 0.05$) differences in torso kinematics were found between the footwear condi- tions (Table I).

Hip

No significant ($p > 0.05$) differences in hip joint kinematics were found between the footwear condi- tions (Table I).

Knee

Significant main effects were found in the sagittal plane for peak flexion ($p < 0.05$, $\eta^2_p = 0.21$) and relative range of motion ($p < 0.05$, $\eta^2_p = 0.46$), respectively. Post hoc pairwise comparisons showed that both peak angle and relative range of motion were significantly greater in the running shoe com- pared to the barefoot condition (Table I).

Ankle

Significant main effects were found for peak dorsi- flexion ($p < 0.05$, $\eta^2_p = 0.21$) and relative range of motion ($p < 0.05$, $\eta^2_p = 0.41$). Post hoc pairwise comparisons showed that both peak angle and relative range of motion were significantly greater in the running shoe and weightlifting footwear compared to the barefoot condition. There was also a significant main effect found for peak angle in the

Table I. Angular kinematic parameters (°) as a function of footwear

	Barefoot	Barefoot inspired	Weightlifting shoes	Running shoes
Torso				
Peak flexion	–16.49 ± 22.76	–12.61 ± 22.92	–15.57 ± 17.90	–11.31 ± 17.24
Peak left tilt	–5.11 ± 4.46	–4.27 ± 5.00	–5.12 ± 4.29	–5.66 ± 3.94
Peak left rotation	–4.03 ± 4.66	–2.84 ± 3.60	–5.58 ± 4.24	2.93 ± 1.68
Relative ROM X	21.43 ± 15.45	17.99 ± 15.85	18.57 ± 10.29	17.41 ± 9.68
Relative ROM Y	4.27 ± 4.95	4.03 ± 5.01	4.41 ± 4.29	4.27 ± 4.64
Relative ROM Z	2.58 ± 1.98	2.47 ± 1.98	3.89 ± 2.26	2.93 ± 1.68
Hip				
Peak flexion	87.91 ± 17.19	89.44 ± 17.40	86.98 ± 16.72	88.91 ± 17.56
Peak adduction	9.14 ± 4.55	10.14 ± 4.64	9.33 ± 4.55	8.40 ± 4.75
Peak internal rotation	15.19 ± 12.69	15.43 ± 13.46	12.63 ± 9.05	13.49 ± 10.92
Relative ROM X	76.76 ± 14.34	76.91 ± 14.26	73.55 ± 17.19	75.36 ± 17.94
Relative ROM Y	1.54 ± 1.24	1.36 ± 0.86	1.75 ± 1.09	1.96 ± 2.07
Relative ROM Z	3.29 ± 3.03	2.82 ± 3.13	1.82 ± 1.30	3.56 ± 4.97
Knee				
Peak flexion	101.45 ± 12.64	102.87 ± 11.59	107.55 ± 12.73	105.75 ± 12.94A*
Peak adduction	3.20 ± 5.86	3.06 ± 5.89	3.38 ± 6.38	1.93 ± 4.70
Peak internal rotation	1.80 ± 5.27	2.30 ± 4.84	2.38 ± 5.11	4.33 ± 5.40
Relative ROM X	94.60 ± 12.25	94.38 ± 11.01	98.03 ± 12.11	105.75 ± 12.94
Relative ROM Y	5.37 ± 6.72	5.29 ± 6.62	5.86 ± 7.14	5.06 ± 5.28
Relative ROM Z	3.23 ± 3.33	4.24 ± 3.24	4.65 ± 3.71	5.22 ± 4.72
Ankle				
Peak dorsiflexion	26.14 ± 4.75	26.70 ± 7.12	29.29 ± 5.22A	28.43 ± 4.27A*
Peak eversion	–8.19 ± 4.32	–6.90 ± 5.06	–0.50 ± 4.10A	–1.58 ± 4.13A*
Peak internal rotation	7.34 ± 6.54	5.73 ± 6.48	1.03 ± 7.82	2.66 ± 5.67
Relative ROM X	25.96 ± 4.70	26.35 ± 4.89	29.27 ± 3.61	27.80 ± 3.47
Relative ROM Y	8.50 ± 0.52	6.79 ± 0.85	0.63 ± 0.54	1.15 ± 1.28
Relative ROM Z	8.33 ± 4.22	6.55 ± 3.74	5.96 ± 3.69	6.20 ± 4.16

A, significantly different from barefoot; X, sagittal plane; Y, coronal plane; Z, transverse plane. *Significant main effect.

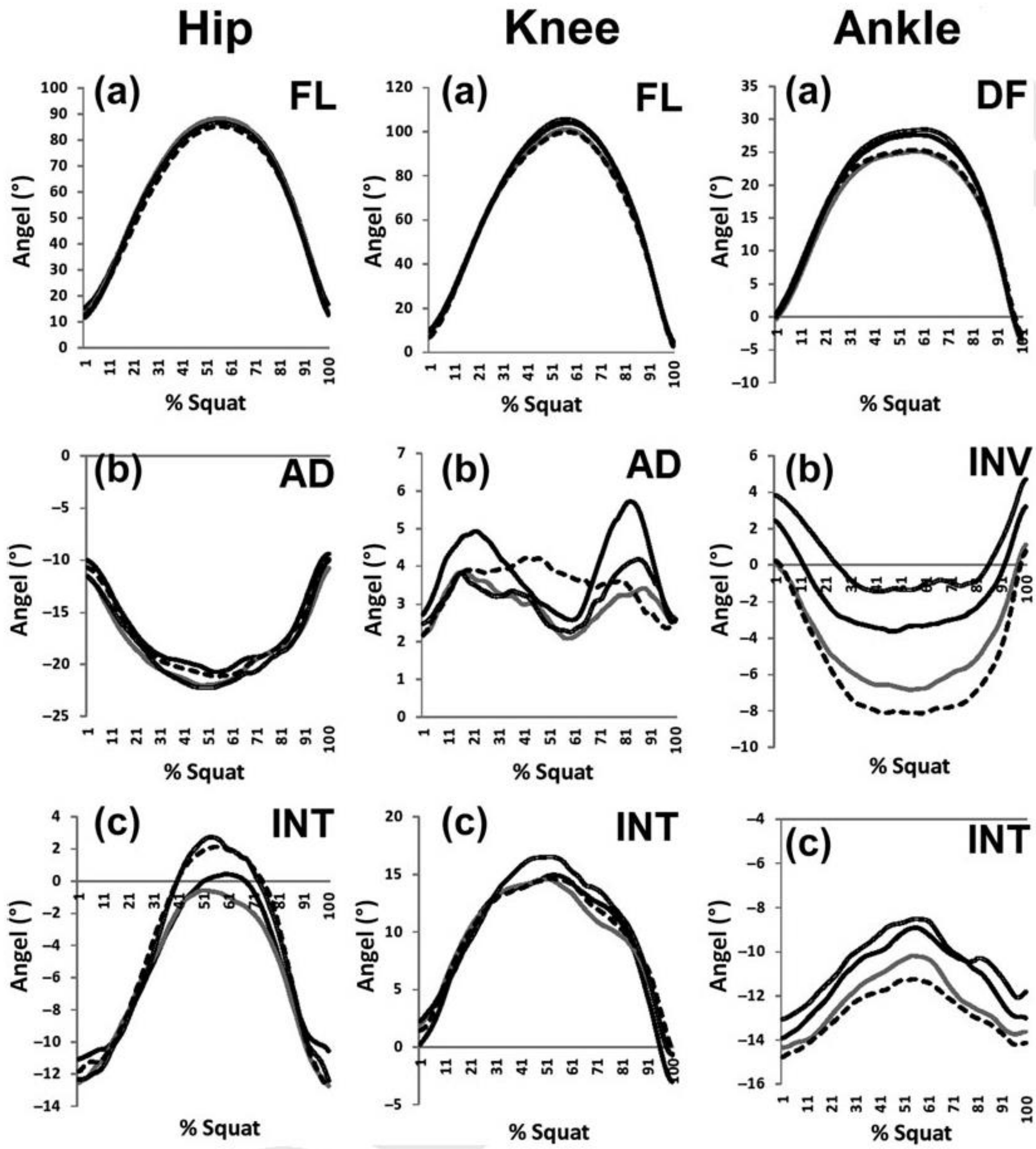

Figure 1. Torso kinematics in the (a) sagittal, (b) coronal and (c) transverse planes as a function of footwear (black = running shoe, grey = barefoot-inspired and dash = barefoot, black outline = weight lifting; EXT = extension, RT = right tilt, RR = right rotation).

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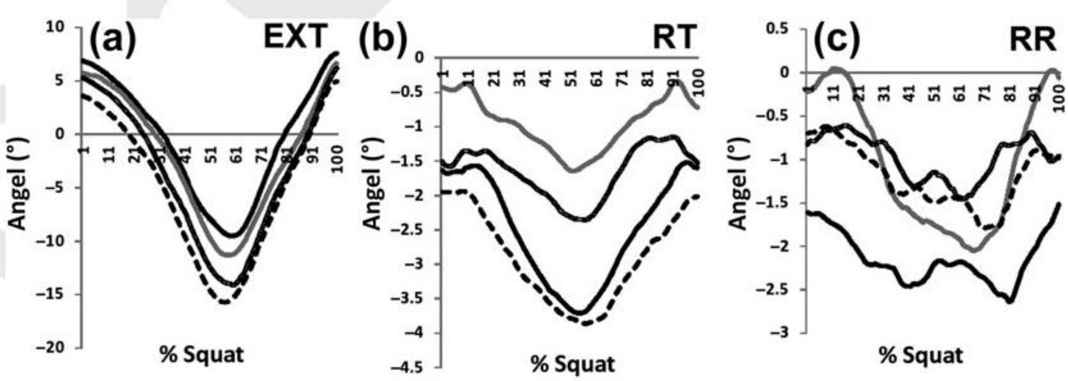

Figure 2. Mean hip, knee and ankle joint kinematics in the (a) sagittal, (b) coronal and (c) transverse planes as a function of footwear (black = running shoe, grey = barefoot-inspired and dash = barefoot, black outline = weight lifting; FL= flexion, DF = dorsiflexion, AD = adduction, IN = inversion, INT = internal).

Table II. Muscle activation magnitudes (% MVC) as a function of footwear

	Barefoot	Barefoot inspired	Weightlifting shoes	Running shoes
Mean muscle activation				
Gastrocnemius	21 ± 0.13	24 ± 16	27 ± 22	25 ± 19
Tibialis anterior	43 ± 0.18	44 ± 25	46 ± 15	43 ± 15
Rectus femoris	77 ± 0.56	86 ± 56	81 ± 52	94 ± 67A*
Bicep femoris	38 ± 0.24	57 ± 49	41 ± 24	40 ± 24
Rector spinae	47 ± 0.19	46 ± 20	46 ± 20	46 ± 19
Peak muscle activation				
Gastrocnemius	50 ± 35	0.63 ± 0.40	96 ± 130	64 ± 50
Tibialis anterior	112 ± 41	1.36 ± 1.26	125 ± 033	114 ± 40
Rectus femoris	207 ± 177	2.32 ± 1.81	215 ± 162	261 ± 208A*
Bicep femoris	114 ± 88	1.69 ± 1.54	119 ± 091	117 ± 83Erector
spinae	102 ± 39	1.00 ± 0.44	98 ± 037	99 ± 43

A, significantly different from barefoot.
*Significant main effect.

coronal plane for the ankle, ($p < 0.05$, $g^2 = 0.29$). p Post hoc pairwise comparisons showed that both peak eversion were significantly greater in the barefoot condition compared to the running shoe and weightlifting footwear (Table I).

EMG amplitude

Significant main effects were found for mean and peak

muscle activation for the RF ($p < 0.05$, $g^2 = 0.26$) and p ($p < 0.05$, $g^2 = 0.33$). Post hoc pairwise comparisons p showed that both peak and mean muscle activation were significantly greater in the running shoe com- pared to squatting barefoot (Table II).

Discussion

The aim of the current investigation was to assess the influence different footwear had on the 3-D kin- ematics and muscle activation potentials during the barbell back squat. This represents the first study to examine the 3-D kinematic and EMG differences between barefoot, barefoot-inspired, weightlifting and running shoes in the barbell back squat.

In support of the main hypothesis, it was con- firmed that 3-D kinematic differences were observed between footwear. The primary observation was that squat depth was significantly greater in the running shoe condition compared to barefoot. This is sup- plemented by the increase in knee flexion in the running shoe condition that was observed in the current investigation, which facilitated the increase in squat depth. Increases in knee flexion concur with the observations of Sato et al. (2013) who showed seven degrees less knee flexion in comparison to a conventional running shoe, and that it was also more challenging for lifters to attain the desired parallel squat position.

Sato et al. (2013) hypothesised that this reduction in knee flexion in the barefoot condition may be clinically beneficial in reducing the knee torque experienced during squat lifts. The musculoskeletal structures of greatest risk from injury during deep squatting are the menisci and articular cartilage (Escamilla, 2001). Compressive knee loading has been shown to be greatest at around 130° of knee flexion, whereby the meniscus and articular cartilage bear significant amounts of strain (Nisell & Ekholm,

1986). Increased squat depth may also augment patellofemoral deterioration due to femoral contact with the base of the patella during flexion move- ments (Escamilla, 2001). There is little evidence, however, which implicates an increased squat depth with injury to these sites (Meyers, 1971; Panariello et al., 1994; Steiner, Grana, Chillag, & Schelberg- Karnes, 1986). This may be AQ11 because the extent of knee flexion during the barbell back squat does not reach a level where maximal compressive loading is experienced (Nisell & Ekholm, 1986), as evidenced by the sagittal plane knee characteristics observed in the current study. Additional prospective work is therefore required before the clinical benefits of barefoot squatting can be advocated.

In further support of the original hypothesis, it was observed that significant differences were observed in terms of the EMG magnitude between the foot- wear conditions. Specifically it was demonstrated that EMG amplitude in the RF was significantly greater whilst wearing running shoes compared to the barefoot condition. It is likely that this relates to the increase in squat depth observed in the current investigation. This concurs with the observations of Gorsuch et al. (2013) who showed that increases in squat depth were also associated with increased muscular activation in the RF muscle. This increase in muscular activation indicates that the running shoe condition may mediate an increased training stimulus from the squat activity, in which one of the primary functions is to target the quadriceps muscle group.

That ankle motion in the sagittal plane was found to be significantly greater in the weightlifting shoes and running shoes compared to barefoot, oppose the anecdotal observations of Hadim (2009). They hypothesised that ankle joint freedom of movement would be enhanced during the barefoot squat. This observation may be due to the more forward inclination of the tibia in the weightlifting and running shoes, mediated by increases in knee flex- ion. The coronal plane motion of the ankle, how- ever, was shown to be significantly greater in the barefoot condition when compared to the running shoes and weightlifting footwear. It is likely that this observation relates to the medially posted midsoles and varus wedges that are typically present in weightlifting shoe and running shoe, designed to control excessive ankle eversion (Sinclair et al., 2013). This finding may have clinical significance as increases in eversion magnitude have been linked with the aetiology of chronic injuries (Duffey, Martin, Cannon, Craven, & Messier, 2002; Lee, Hertel, & Lee, 2010; Taunton, Clement, & McNicol, 1982; Willems et al., 2006). However, these findings have yet to AQ12 be evidenced in weightlifting studies.

The observations from the current study may relate to the barefoot squatting experience. Whilst the participants examined in the current investiga- tion were all experienced in back squat lifting, they do not habitually perform their squat exercises barefoot. Therefore, the findings obtained in the current examination may relate to the experience of the participants in barefoot training. Future research is clearly warranted to replicate the current invest- igation using participants who habitually train with- out shoes. Furthermore, despite the apparent inability to provide biomechanical advantages, the majority of participants still indicated that they preferred not to wear shoes for squatting. It is proposed that this subjective preference towards barefoot squatting relates to the degree of shoe midsole material in the weightlifting and running footwear, which serves to reduce the proprioceptive sensation of the floor underneath the foot.

A potential limitation of the current investigation is the all-male sample, which may limit its generalisa- bility. The mechanics of female squat lifting have received scant attention in strength and con- ditioning literature. However, females have additional intrinsic and extrinsic factors that may influence their lower extremity mechanics and susceptibility to injury during the squat, such as joint laxity, joint flexibility, various structural mal-alignments and hormonal influences (Ferber, Davis, & Williams, 2003; Horton & Hall, 1989). Based on this information it is unlikely that that the findings from the current investigation can be generalised to females. It is therefore recom- mended that the current investigation can be repeated using a female cohort. In addition, that the current investigation examined only one barbell squat load may also serve as a potential limitation. Kellis, Arambatzi, and Papadopoulos (2005) showed that the mechanics of the squat differed significantly as a function of different squat weights. Therefore the observations from the present study may not be applicable to different squat loads and it may be pru- dent for future analyses to examine the influence of different footwear on the mechanics of the barbell squat using different loads.

In conclusion, whilst previous investigations have examined the biomechanical differences between shod and un-shod squat lifting, the current know- ledge with respect to the degree to which these modalities differ is limited. The present study adds to the current knowledge of barefoot squatting by providing a comprehensive 3-D kinematic and EMG evaluation. The results from the current investiga- tion confirm that footwear can significantly influence the kinematics and EMG potentials of the barbell squat. This further emphasises that athletes who perform squat movements should carefully consider their choice of training footwear. Furthermore, whilst this study supports anecdotal evidence of athletes who prefer to train barefoot or in barefoot- inspired footwear due to increased foot propriocep- tion, no biomechanical evidence was found to support this notion. Future, work should nonethe- less consider the relationship between subjectively appropriate and biomechanically appropriate foot- wear during the barbell back squat.

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