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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

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, hamstrings, 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 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 footwear, 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 cushioned 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 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 capability 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 efficacy of the barefoot squat.

Shorter et al. (2011) examined power production during the back squat whilst wearing trainers, barefoot-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 addition to angulation profiles of the hip, knee and ankle joints. Their findings were contrasted against the National Strength and Conditioning Association (NSCA) 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 examining 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. Therefore, 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 conditions 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 musculoskeletal 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 accordance 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 representative of loads used for a 12RM work out (Brzycki, 1993). Participants completed five back squat repetitions in each footwear 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 systems technique (CAST) was utilised to quantify joint kinematics (Cappozzo, Catani, Croce, & Leardini, 1995). To define the anatomical frames of the pelvis, right foot, shank, thigh and torso, retroreflective markers were positioned onto the calcaneus, first
and fifth metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, anterior (ASIS) and posterior (PSIS) superior iliac spines, xiphoid process, greater trochanter, acromion process 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 tracking 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 bandage. 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. Bipolar 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 randomised. Upon conclusion of the data collection, participants were asked to subjectively indicate which shoe condition that they preferred for squatting. 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) (Sinclair, Taylor, Edmundson, Brooks, & Hobbs, 2012). All kinematic waveforms were normalised to 100% of the squat movement phase then processed trials were averaged. Discrete 3-D kinematic measures from the hip, knee and ankle 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 Butterworth 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 investigation 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 adjustment to control for type I error. Effect sizes were calculated using partial eta-squared ($\eta_p^2$). If the sphericity assumption was violated then the degrees of freedom were adjusted using the Greenhouse–Geisser correction. The data were screened for normality using a Shapiro–Wilk which confirmed that the normality assumption was met. A chi-square ($\chi^2$) 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 ($\chi^2 = 4.14, p < 0.05$) 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 ($\eta^2 = 0.36$) 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 barefoot (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).

3-D kinematics

The results indicate that whilst the 3-D kinematic curves from the torso, hip, knee and ankle shown as a function of different conditions were quantitatively similar, significant differences were found between footwear.

Torso

No significant ($p > 0.05$) differences in torso kinematics were found between the footwear conditions (Table I; Figure 1).

Hip

No significant ($p > 0.05$) differences in hip joint kinematics were found between the footwear conditions (Table I; Figure 2).

Knee

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

<table>
<thead>
<tr>
<th>Table I. Angular kinematic parameters (°) as a function of footwear</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Footwear</strong></td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td><strong>Torso</strong></td>
</tr>
<tr>
<td>Peak flexion</td>
</tr>
<tr>
<td>Peak left tilt</td>
</tr>
<tr>
<td>Peak left rotation</td>
</tr>
<tr>
<td>Relative ROM X</td>
</tr>
<tr>
<td>Relative ROM Y</td>
</tr>
<tr>
<td>Relative ROM Z</td>
</tr>
<tr>
<td><strong>Hip</strong></td>
</tr>
<tr>
<td>Peak flexion</td>
</tr>
<tr>
<td>Peak adduction</td>
</tr>
<tr>
<td>Peak internal rotation</td>
</tr>
<tr>
<td>Relative ROM X</td>
</tr>
<tr>
<td>Relative ROM Y</td>
</tr>
<tr>
<td>Relative ROM Z</td>
</tr>
<tr>
<td><strong>Knee</strong></td>
</tr>
<tr>
<td>Peak flexion</td>
</tr>
<tr>
<td>Peak adduction</td>
</tr>
<tr>
<td>Peak internal rotation</td>
</tr>
<tr>
<td>Relative ROM X</td>
</tr>
<tr>
<td>Relative ROM Y</td>
</tr>
<tr>
<td>Relative ROM Z</td>
</tr>
<tr>
<td><strong>Ankle</strong></td>
</tr>
<tr>
<td>Peak dorsiflexion</td>
</tr>
<tr>
<td>Peak eversion</td>
</tr>
<tr>
<td>Peak internal rotation</td>
</tr>
<tr>
<td>Relative ROM X</td>
</tr>
<tr>
<td>Relative ROM Y</td>
</tr>
<tr>
<td>Relative ROM Z</td>
</tr>
</tbody>
</table>

A, significantly different from barefoot; X, sagittal plane; Y, coronal plane; Z, transverse plane.

*Significant main effect.
Figure 1. 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).

Figure 2. 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).
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 coronal plane for the ankle, \((p < 0.05, \eta^2_p = 0.29)\). 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; Figure 2).

EMG amplitude

Significant main effects were found for mean and peak muscle activation for the RF \((p < 0.05, \eta^2_p = 0.26)\) and \((p < 0.05, \eta^2_p = 0.33)\). Post hoc pairwise comparisons showed that both peak and mean muscle activation were significantly greater in the running shoe compared to squatting barefoot (Table II).

Discussion

The aim of the current investigation was to assess the influence different footwear had on the 3-D kinematics 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 confirmed 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 supplemented 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 movements (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 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 footwear conditions. Specifically it was demonstrated that EMG amplitude in the RF was significantly greater whilst wearing running shoes compared to

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

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

*Significant main effect.

A, significantly different from barefoot.
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 flexi-
on. The coronal plane motion of the ankle, however,
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; Tauntion, Clement, & McNicol,
1982; Willems et al., 2006). However, these findings
have yet to 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 inves-
tigation 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 condi-
tioning 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 proprioce-
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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his technical assistance.

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