Manuscript title: Kinematic variations in the barbell back squat under different footwear conditions in female college athletes

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BACKGROUND: The barbell back squat is one of the most performed exercises, being important for the strengthening of lower limbs and trunk. Recently, it has become popular to train under different conditions of footwear or without it, and some investigations have analyzed the changes that this brings, with some contradictions in this regard. The purpose of this study was to analyze the kinematic variations under different shoe conditions (running shoes, barefoot and barefoot with heel raised) in the back squat in female university athletes.

METHODS: Fifteen (15) athletes in the 3 conditions with a load equal to 70% of their one-maximum repetition (1RM), were recorded and analyzed to determine the angles of the ankle, knee, hip and trunk by 5 movements in each condition.

RESULTS: The use of enhancement significantly increased ($p < 0.05$) the dorsal flexion angle of the ankle, against the footwear condition and barefoot without enhancement (109.6°+/-11.1° vs. 99.1°+/-9.0° vs 101.3° +/-11.5°). No significant differences were observed in any of the other variables.

CONCLUSIONS: An optimal squat technique is important for preventing injuries, optimal rehabilitation and for improving sports performance. Increased dorsal ankle flexion angle may protect distal tibiofibular joint.

Key words: barefoot, high heels, biomechanics, foot condition.

Introduction

The barbell back squat is one of the basic exercises of any training routine and is used, both in rehabilitation and in conditioning, in order to increase the strength of the lower extremities and trunk[1,2]. According to the position statement of the National Strength and Conditioning Association (NSCA) the exercise begins with an upright position of the trunk, the hip and knee joints extended and the ankles in a neutral position, then descend in a controlled way until the thighs reach a position at least parallel to the ground, keeping leg segments as close as possible to the vertical to reduce the cutting force on the knee joint and feet fixed and flat on the ground[3]. The bar squat recruits many of the muscles of the lower limbs, predominantly quadriceps, hamstrings, anterior tibial, gastrocnemius and soleus[4].

Beyond the health benefits and the low risk of strength training injuries compared to other sports, squats have been identified as one of the strength exercises with a higher risk of injuries to the lower extremities and trunk compared to other strength exercises[5,6,7]. To reduce the chances of this happening it is necessary to evaluate the kinematics of the different body segments during the performance of the workout, and to know the variations that occur under different conditions, for example, with different types of footwear or support widths.

Different studies have evaluated the kinematic changes that occurred when the area of the support base and the angles of support of the feet are changed. In this regard, Lorenzetti et al.[2] state that in order to avoid great moments of force in the knee and hip joints, extreme positions must be prevented, which coincides with Escamilla et al.[8].

Variations in kinematics also have been studied under different conditions of footwear: with running shoes (RS), weightlifting shoes (WS), barefoot (BF) and heel raised (HR). It has been suggested that heel elevation leads to a more erect torso with a lumbar curvature and a more neutral pelvic position[9,10,11]. Sato et al.[12] claimed that the inclination of the trunk is reduced when WS are used compared with BF condition. However, Whitting et al.[13] compared the use of RS with the use of specific footwear for weightlifting, finding lower ankle dorsiflexion angles in the latter, not being able to verify that this reduces the inclination of the trunk. In this respect, it is claimed that the use of RS leads to a greater depth of the squat, without significant differences in torso and hip kinematics[14, 15, 16]. It is important to explore this aspect, since an increase in the inclination of the trunk can be considered a risk factor, due to the raise in the pressure of the lumbar discs[17,18].

Also, it is important to study the angles of the knee and ankle, because a decrease in the first and an increase in the second produce a greater activation of the knee extenders[15]. As with the trunk, contradictory results have been reported. Some studies identify less knee flexion when using RS[14], while others find no differences[12]. Respecting the ankle, increased dorsiflexion angle (greater opening) has been reported when the heel was lifted, either using a platform or with heels lifted by a weightlifting shoe[12,14].

Respecting the barefoot condition, during recent years, the tendency to train in this way has grown under the arguments that this improves proprioception and provides greater stability and generation of strength in lower limbs[19], but not much is known about biomechanical changes.

For the above reasons, and according to the most recent review[20], there is a need to expand research in female populations, as many of the studies have focused exclusively on male populations[13,16] or with a small female sample[21]. In fact, according to our search, this is the first study of this type that focuses on a completely female sample, which is important because of the biomechanical differences and laxity between both sexes.

The purpose of the present study was to analyze kinematic variations of the joints of the ankle, knee and hip, in addition to the inclination of the trunk, in female university athletes under 3 different footwear conditions: RS, BF and HR. We aimed to know if the use of a heel lift platform and the barefoot condition affects the trunk inclination and the knee flexion, respectively. We hypothesized that lifting the heels could decrease the trunk inclination and the barefoot condition could increase knee flexion. Additionally, we wanted to get a complete picture of the squat kinematics under different shoe conditions.

Methods

Subjects

Fifteen female college athletes (age 21.9 ± 1.7 years, height 1.63 ± 0.06 m, weight 62.1 ± 8.7 kg, squat experience 4.0 ± 1.7 years) with, at least, 3 months free to injury were recruited at different university teams. Participants with osteosynthesis elements, cardiovascular/neurological disease or pregnant were excluded. Subjects were informed of the purpose, risks, benefits, and experimental procedures involved before entry into the study and it has been conducted in accordance with the principles set forth in the Helsinki Declaration. Ethical approval was granted from the bioethics committee of the National University of Entre Ríos on April 13th, 2022 with protocol number 021324/22. Written informed consent, with the benefits and risks of the investigation, was obtained from participants prior to data collection.

Experimental Approach to the Problem

This study compared kinematics variations under different shoe conditions in female college athletes when performing a barbell back squat. The exercise was performed with RS, BF and HR. To minimize potential biases, the shoe condition was randomized for each participant. Only subjects with at least 2 years of resistance training experience (including squats) were eligible to participate. We considered 4 angles for our study: inclination of the trunk with respect to the vertical, hip flexion, knee flexion and dorsal ankle flexion. All subjects were instructed not to train legs at least 48 hours before the initial test.

Procedures

First, the one-repetition maximum (1RM) was determined for each participant in the barbell back squat. My Lift app (Version 10.0.6) was used[22,23] to determine 1RM. My Lift uses scientifically validated algorithms that enable highly accurate 1RMs by simply recording an exercise. To do this, My Lift uses the high-speed camera available on most iPhones and iPads to measure the speed at which the exercise is being performed, which is highly correlated with maximum strength capabilities. This novel methodology is used mainly as a replacement for encoders. On the second day, with at least 48 hours of difference the participants returned to complete 3 sets of 5 repetitions of the back squat with 70% of 1RM in every foot condition: RS, BF and HR. The rest between sets was three minutes.

The same instructions were explained for all. They must perform a barbell back squat like they usually did, aiming to get their thighs horizontal to the floor. Participants were left to choose their preferred leg width, but it was measured on each participant to be repeated for each shoe condition. They were instructed to rest the bar on their trapezius muscles, above the scapulae, with their hands grasping the bar at shoulder width, and keeping their head and eyes facing forward. Participants did not perform any leg training in the time between the first and second data collection. The series were recorded with one smartphone, iPhone 12 (Pro Max, iOS 12, Apple Inc.) at 120 FPS and the kinematics measured with Kinovea (Version 0.9.5). This software has been previously validated for 2D movement analysis[24]. The smartphone was placed perpendicular to the frontal plane at a height of 1.3 m and positioned 5 meters of distance to the right of the subject. It was calibrated before with a reference vertical line. The order of the footwear conditions was randomized. A 2.5 cm solid wedge was used to lift the heels. Both for the 1RM test and the recording of the squat, a standardized heat input was previously carried out.

A calibrated anatomical system technique was used to quantify joints kinematic[25]. Reflective markers were placed on both sides of each participant: greater trochanter of hip, lateral femoral epicondyle of knee, lateral malleolus of ankle and fifth metatarsal joint of toe. Regarding this last marker, when the participants wore RS, the marker was placed on the shoe, in the same position for all the participants. This was possible since they all used the same shoe model, only varying the size. An additional marker at the end of the barbell was placed. These points created four angles: trunk with vertical (trunk inclination), trunk with thigh (hip flexion), thigh with shankbone (knee flexion) and shankbone with foot (ankle dorsiflexion) (Figure 1). These angles were collected at the time of the maximum descent of the squat for the table´s averages. Also, the squats were normalized from 0 to 100% to unify the curves independently of the time.

Figure 1 - Markers placements and kinematics measurements

Statistical Analyses

Sample size estimation was calculated *a priori* based on an expected difference of means of +/- 5^0, a power of 0.8, an α level of 0.05 and the effect size reported in previous studies[12-14]. Similar sample sizes have been used in other studies with comparable objectives[13-16,26,28]. Analyses were performed using JMP software (Version 16). Means and standard deviations were calculated for each foot condition. ANOVA test was applied with a level of significance of 0.05 for analysis of variance. All significant interactions were followed up with Bonferroni corrections for multiple comparisons (post hoc tests). If the sphericity assumption was violated, the degrees of freedom were adjusted using the Greenhouse–Geisser correction.

To graph the curves ad-hoc software has been developed in MATLAB R2019a to automatically detect the beginning and end of each repetition from a signal with several repetitions. All the points where the first derivative approaches zero are selected. Due to the characteristics of the squat, the initial and final positions are with high values of ankle flexion. So, those points that don't overcome the mean plus a standard deviation of the signal are rejected. The beginning and end of repetition are selected from those points where the distance in time is greater than 10 times the mean of the differences. In the signals where the automated detection didn't work, manual selection was done. The same point in time was used to determine the beginning and end of each repetition in every evaluated joint. Each signal (five per athlete in each condition) was resampled in 100 points. The mean for each athlete in each condition was made, and the mean for the condition considering all athletes.

Data availability

The data associated with the paper are not publicly available but are available from the corresponding author on reasonable request

Results

Table I shows the average values of the angles under each footwear condition at the time of maximum squat descent.

Table I - Angular kinematic parameters (^{0}) of each footwear condition. Means and standard deviation.

	Running Shoes (RS)	Barefoot (BF)	Heel Raised (HR)	*p-value*
Trunk inclination	34.5 ± 7.8	33.0 ± 8.8	32.1 ± 7.9	*0.73*
Hip flexion	73.6 ± 15.5	79.0 ± 15.6	78.6 ± 16.1	*0.67*
Knee flexion	80.0 ± 13.8	85.0 ± 13.1	83.4 ± 12.1	*0.58*

Ankle flexion	99.1 ± 9.0	101.3 ± 11.5	109.6 ± 11.1*^	*<0.05*

* 3rd vs 2nd, ^3rd vs 1st

Trunk inclination:

No significant differences ($p = 0.73$) in trunk inclination were found in the maximum descent. Normalized curves for trunk inclination between the footwear conditions are shown below (Figure 2).

Figure 2

Hip flexion:

No significant differences ($p = 0.67$) in hip flexion were found in the maximum descent. Normalized curves for hip flexion between the footwear conditions are shown below (Figure III).

Figure 3

Knee flexion:

No significant differences ($p = 0.58$) in knee flexion were found in the maximum descent. Normalized curves for knee flexion between the footwear conditions are shown below (Figure 4).

Figure 4

Ankle flexion:

A significant difference was found with the HR condition ($p < 0.05$). The use of a solid platform increased the angle of ankle flexion (a more open angle). Post hoc pairwise comparisons showed that peak angle was significantly greater in the HR compared to the RS and BF. Normalized curves for ankle flexion between the footwear conditions are shown below (Figure 5).

Figure 5

Discussion

There is a current debate about the use of different footwear (or not using it) during weight training, arguing a possible effect on injury prevention and/or proprioceptive improvement. Our research aimed to assess the biomechanical modifications that occur in female athletes who performed a barbell back squat under three different conditions: with running shoes, barefoot and barefoot with heel raises. Our hypothesis was that heel lift by wedges could lead to a more upright posture (less trunk inclination) and the barefoot condition would provide more security, increasing knee flexion (decreasing the angle). The use of a HR reduced the trunk inclination and produced a greater angle of ankle flexion, but the first difference was too small and not significant. Contrary to our idea, the performance of the barefoot squat produced the smallest knee flexion (but not significant), with the impact in relation to the activation of the rectum femoralis of the quadriceps.

We acknowledge that there are limitations and strengths in this study. Kinematic differences exist between sexes, and these distinctions should be considered for any biomechanical investigation. To our knowledge, this is the first study exploring footwear kinematics during a back squat with an entirely female sample. As a limitation, it is worth mentioning that the 2D analysis shows only a part for all biomechanics information. The load on the lumbar spine must include other data for a complete assessment. Finally, the use of a marker at the end of a bar to determinate the trunk inclination could provide inaccurate results. This study evaluated the barbell back squat with a high position but some subjects may be in favor of a low position of the bar. Also, the configuration of the laboratory may not have been familiar and may have affected the technique. On the other hand, some athletes reported never training in a barefoot condition.

The biomechanics of the squat in women has received lower attention in the literature on strength training compared to men[14], although these have laxity, hormonal and biomechanical factors that can have an important influence[21], and produce differences in squatting techniques[27]. As far as we know, this is the first study with a sample exclusively constituted by females with experience in resistance training.

Our results observed at the trunk level support what was found by previous investigations[14,16,26] finding no changes in these segments with different footwear. Paraspinal muscle activation has also been evaluated, which did not differ when the heel was raised[16]. However, some authors[28] recommend raising heels in novices as it decreases the moment in L4/L5, likening them more to experienced lifters, although without finding differences between the different conditions of footwear in the more experienced athletes (similar to our study). This research considers women, but only evaluates 5 with weight lifting experience and does not make a subgroup analysis by gender. At the same time, it measures the effects on lumbar curvature with heel lift, finding no differences and emphasizing that an increase in load at L4/L5 is not necessarily associated with differences in lumbar curvature, but it suggests this may be more related to the inclination of the trunk. Other studies[21,29] disagree, claiming that the use of footwear with a wedge in the heel can decrease the inclination of the trunk. One possible explanation is that none of these studies analyzes an exclusive female sample or does the analysis by sex. On the other hand, some of the studies analyze the use of lifting shoes, others an inclined platform and ours the use of a wedge in the heel, more similar to a low-cost strategy used in gyms and rehabilitation centers with few resources.

At the level of the knee joint, it is important to analyze the possible modifications since it has been described that a greater degree of flexion (decrease in angle) induces a greater activation of the rectus femoris[15] which could mean for performance and rehabilitation. It has been reported[14] a greater depth of squats with sneakers. We did not find significant differences in our study. One possible explanation is that the unfamiliarity of the exercise in barefoot condition leads to less depth. In this case it would not be the sports shoes that would determine a greater depth but that the exposure to a new condition (barefoot) would cause insecurity in the athlete. In other studies[12] the angle of the knee is not evaluated, but the one that forms the thigh with the horizontal not reporting changes.

Respect to the ankle, our findings support what was stated in other works[12,14] in terms of the increase of the dorsiflexion angle (greater opening) when using an enhancement or heels raised by a weightlifting shoe. Although some researchers[14] evaluated the relative movement, that is from position 0 to the maximum position, and in our case we considered the maximum opening angle, the comparison is valid. The increase in ankle angle has been postulated as a strategy to increase the activation of knee extenders, although this was ruled out by a study[16].

Barefoot workouts have not gotten the same attention as wearing wedges on heels or specialist weightlifting shoes. In our study, this condition produced less knee flexion, without increasing ankle mobility, although both differences were not significant. Most of our sample was used to training with sports shoes, so this may be due to familiarity with one type of footwear or another, rather than the modification that produces the footwear itself.

The recommendation to lift the heels during the squat to achieve a lower inclination of the trunk can be a simple story, or to influence a population inexperienced in this type of exercise and be used as an initiation strategy. To prevent back injuries during the squat, it may be more important to place more emphasis on proper technique and a safe progression of resistance[3]. The use of wedges to increase the degree of ankle dorsiflexion may prove a valid method and may protect distal tibiofibular syndesmosis.

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Conflicts of interest

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Authors' contribution

Maximiliano E. ARLETTAZ[1 *]: Methodology. Formal analysis. Data Curation. Writing - Original Draft. Writing – review & editing. Visualization.

Lucas N. DORSCH[1]: Conceptualization. Methodology. Formal análisis. Writing - Original Draft. Writing – review & editing. Visualization.

Magalí SGANGA[2]: Methodology. Formal análisis. Writing - Original Draft. Writing – review & editing. Visualization.

Nicole D. BOOTH[3]: Methodology. Formal análisis. Writing - Original Draft. Writing – review & editing. Visualization. Language corrections.

Jorge S. FARABELLO[1]: Methodology. Formal análisis. Writing - Original Draft. Writing – review & editing. Visualization.

All authors read and approved the final version of the manuscript.

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