Comparison of Back Squat Kinematics Between Barefoot and Shoe Conditions

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ABSTRACT
The purpose of the study was to compare the kinematics of the barbell back squat between two footwear conditions and to evaluate the results with respect to recommendations put forth in the National Strength and Conditioning Association position statement for proper squat technique. Twenty-five subjects with 5 - 7 years of resistance training experience participated. Selected kinematics were measured during a 60% of 1RM barbell back squat in both barefoot and athletic shoe conditions. Paired-samples T tests were performed to compare the two footwear conditions. Significant differences were found in trunk (50.72±8.27 vs. 46.97±9.87), thigh (20.94±10.19 vs. 24.42±11.11), and shank segment angles (59.47±5.54 vs. 62.75±6.17), and knee joint angles (81.33±13.70 vs. 88.32±15.45) at the peak descent position. Based on the kinematic analysis of the barefoot squat, two kinematic advantages are countered by two disadvantages. Coaches and instructors should acknowledge these results with respect to a performer's capability, and be aware the advantages and disadvantages of barefoot squat from a kinematic perspective.

Key words: Athletic Shoes, Barbell Back Squat, Barefoot Exercise, Kinematic Analysis

INTRODUCTION

The barbell back squat is a universally accepted exercise used by athletes of all skill levels to develop muscular strength in the trunk and lower extremities. It is used in both strength and conditioning and rehabilitation settings [1, 2]. The barbell back squat is so popular that the National Strength and Conditioning Association (NSCA) developed a position statement

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to be used as guidelines for proper technique back in the early 1990s [3]. Several specific suggestions were offered for proper barbell back squat technique: 1) descend in a controlled manner until the thigh segments reach a position at least parallel to the floor; 2) keep the shank segments as close to vertical as possible in order to reduce shear force in the knee joint; and 3) keep the feet stationary and flat on the floor [3]. The NSCA position statement also suggested keeping a normal lordotic posture with the torso being as close to vertical as possible during the entire lift. This last suggestion is consistent with findings of previous studies supporting the contention that maintaining normal lordotic posture reduces lumbar disc shear stress [4-6].

Trunk orientation can have a significant effect on squat kinetics. The barbell back squat generates high compressive force in the vertebral column because of the added weight on the upper back [7]. Forward trunk lean would then lead to greater torques, especially at lower joints in the vertebral column and at the hip joint [8]. Increased loads in the low back with increasing forward trunk lean and backward hip displacement have also been reported [9, 10]. Research has shown that highly skilled lifters perform the lift with a more erect trunk position as compared to less skilled lifters [11]. Therefore, the normal lordotic posture is highly recommended when performing the back squat.

With the preceding discussion of barbell back squat technique in mind, the present study addressed the influence of footwear on squat kinematics. Specifically, the recent, popular trend of active individuals exercising with no footwear or minimal footwear is the motivating factor behind the present experiment. Most notably, barefoot running has increased its popularity among the running community. Running without shoes also has been shown to reduce impact forces by approaching the ground with mid- / fore-foot at the initial contact, and thus researchers speculate that impact-related injuries may be reduced [12, 13].

Along with the barefoot running trend, there are some fitness enthusiasts who engage in barefoot resistance training. Being barefoot when performing powerlifting exercises such as the squat and deadlift has become noticeable in recent years. Furthermore, it has been suggested that barefoot training improves overall balance and stability, however this speculation was based on non-peer reviewed articles [14-16]. Barefoot training enthusiasts believe that the use of footwear should be minimal and only used for protection [14]. Some footwear manufacturers have developed “barefoot-like” shoes to emphasize the sensation of being barefoot while offering some protection. Authors of popular literature have proposed that barefoot training may be advantageous with respect to improvements in foot muscle strength and overall stability [15, 16]. These suggestions are now being applied to strength training activities, including the squat exercise [16].

As a recent study suggested, barefoot running changed kinematic data [12, 13], but there is a need for empirical evidence to see whether a lack of footwear also influences kinematics of the barbell back squat. Therefore, based on the fact that suggested benefits of training without footwear have not been objectively tested, the primary purpose of this investigation was to compare the kinematics of the barbell back squat between shod and unshod conditions. The secondary purpose was to evaluate the results with respect to the recommendations put forth by the NSCA position statement for proper squat technique. Hypotheses of this study include a prediction that greater trunk forward lean and more vertical shank with the barefoot squat will be observed due to the intention of maintaining overall stability to achieve a desired depth of squat height. Thigh segment would be similar since the instruction was to perform a full squat. It was also hypothesized that peak flexion angles of hip, knee and ankle will be smaller in the barefoot condition since the trunk forward lean could be a factor in reaching the desired squat height. Lastly, it was hypothesized that kinematic data from the barefoot condition would be unsupported by the recommendations of the NSCA's position statement, especially regarding the three segment angles measured in the present study.

METHODS

SUBJECTS

Volunteers (*n* = 25: male = 20, female = 5) from American football, rugby, soccer, and volleyball were used for this study, and all reported five to seven years of experience in resistance training which included the barbell back (age: 21 ± 4 years old, height: 178 ± 10 cm, mass: 83 ± 13 kg). Subjects were members of intercollegiate athletic teams and clubs at the time of the study, and data collection was scheduled during their off-season. It is important to note that those volunteers were recruited based on the teams' willingness to work with laboratory faculty and availability at the time of the study and there was no specific reason how they were selected including the gender variability. A one-repetition maximum (1RM) test was completed when their off-season training started, which corresponded to approximately one month prior to data collection. All tested subjects were able to lift at least equal to their body mass of external weights, up to 1.5 times of body mass. As all of them belonged to intercollegiate athletic and club teams, they reported the 1RM test results to calculate their 60% of 1RM for this study. All subjects were free from injury for at least three months prior to the time of testing. The University's Institutional Review Board approved all procedures for this study, and subjects offered verbal and written consent prior to data collection.

INSTRUMENTATION

One 60 Hz digital camera (PV-GS55, Panasonic, Japan) was placed approximately 1.3 m high and 5 m away from the wooden platform to capture movements of the lifter in the sagittal plane. Reflective markers were placed on the left side of the body at each subject's 5th metatarsal joint, lateral malleolus, lateral femoral epicondyle, and greater trochanter to form rigid body segments [8, 11, 17]. An additional marker was placed on the end of the barbell. These five points created segments for the trunk, thigh, shank, and foot in order to calculate relative angles (see Figure 1) [8, 11, 17]. A segment from the hip to the end of the barbell was used to approximate the trunk segment since the end of the barbell is in a fixed position at the shoulder joint [8, 11, 17]. The video data were then imported into motion analysis software (Vicon Motus version 9.2, Centennial, CO).

TESTING PROCEDURES

The data were collected at the University's Human Performance Laboratory. Barbell back squat in both running shoe and barefoot conditions were performed on the same day during the same testing session. Time of data collection was mid-morning for all participants to avoid effects of the participants' regularly scheduled afternoon workouts. Subjects wore their own running shoes that they regularly use in the weight room. All shoes were categorized as a cushioning-type, with the rear foot area constructed of ethylene-vinyl-acetate. The primary function of this type of shoe is to absorb vertical force during impact. Subjects were asked to warm-up as they normally would prior to lifting with both static and dynamic stretching followed by barbell back squatting with lighter weights than the calculated 60% of 1RM. Since all subjects were familiar with the barbell back squat, only a brief instruction was given to ensure that squat speed was similar during the descent and ascent (within subjects) and across all subjects. A metronome was set at one second audio

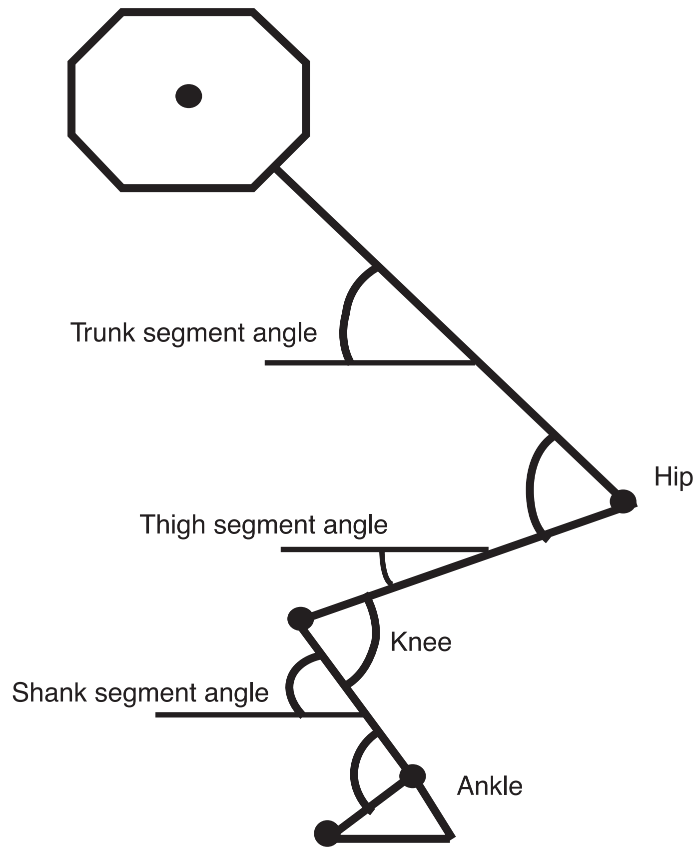

Figure 1. Reflective Marker Placement for Toe, Ankle, Knee, and Hip Joints and at the End of the Barbell to Create Segments
Kinematic measurements of ankle, knee, hip joint angles and trunk, thigh, and shank segmental angles.

signal and used to ensure the rhythm of the squat speed being consistent among the subjects with 2-1-2-2 count (2 counts down, 1 count at bottom, 2 counts up, and 2 counts rest, and repeat repetitions). By regulating the squat speed, unwanted accelerations of center of mass were controlled. A previous study showed that varied squat speed lead to altered body alignment [4], which might influence squat kinematics. With the metronome, squat speed was regulated between subjects. Additionally, in order to assure a relatively accurate sagittal plane view of the squat motion, subjects were instructed to place their feet straight, approximately at shoulder width, and position themselves directly perpendicular to the camera position.

Since the barefoot squat was an unfamiliar condition for all subjects, practice sets were provided to ensure an adequate comfort level before the actual trials were performed. In order to achieve a comparable effort from all subjects, all lifts were performed with a relatively light load [18, p. 399], which was 60% of the subject's 1RM. This relatively light intensity was necessary because squatting in bare feet was unfamiliar for all subjects. During the pilot study (n = 10), use of 80% of 1RM created varied squat speeds depending on how subjects initially learned to squat. Varied squat speed is known to alter squat kinematics significantly [4]. Therefore, 60% of 1RM was chosen to help match all subjects' squat speed. The order of the footwear conditions was chosen randomly. For each squat repetition, subjects began standing erect with the barbell on the upper back (high-bar position) and descended until the thigh segments were approximately parallel to the floor, and then ascended back to the starting position. All subjects performed two sets (one set for each footwear condition) of five repetitions. A rest period of two to five minutes was given between each of the sets.

DATA AND STATISTICAL ANALYSIS

The kinematic data analyzed in this study were computed directly with the motion analysis software. Only data from the third and fourth repetitions were considered, and these data were averaged and subsequently used for analysis. Angular displacement data were generated for the trunk segment, the thigh segment, the shank segment, and hip, knee, and ankle joints (see Figure 1). The peak joint flexion angles of the lower extremity generally occur at the peak descent position of the back squat so the kinematics at the peak descent position were used for statistical analysis [8, 19].

Angles of the trunk, thigh, and shank segments and peak flexion angles of the hip, knee and ankle joints for each subject in each footwear condition were used for analysis. To compare the differences between footwear conditions, Paired-samples T tests were used for each dependent variable. The Predictive Analytics SoftWare was used for the analyses (SPSS: An IBM company, New York, NY). In order to reduce type-I error, the standard alpha-level of 0.05 was divided by the number of variables (six dependent variables) to yield an alpha level of 0.008. Effect size for each variable was also calculated as η^2.

RESULTS

Mean data of six kinematic variables for each experimental condition are shown in Table 1. There were four variables showing statistically significant differences. Peak trunk angle was significantly reduced (i.e., greater trunk flexion) ($T(1,24) = 3.396$, $p < .001$) in the barefoot condition. Peak thigh angle was greater ($T(1,24) = 4.341$, $p < .001$) also in the barefoot condition indicating it was farther from the parallel line, and peak shank angle was also greater ($T(1,24) = 5.008$, $p < .001$) indicating it was closer to a vertical line. Finally, peak knee flexion angle ($T(1,24) = 5.934$, $p < .0001$) was significantly greater (i.e., less knee flexion) in the barefoot condition as well. Hip and ankle peak flexion angles between the footwear conditions were nearly identical and showed no statistically significant differences.

Table 1. Means and Standard Deviations Kinematic Data for Both Lifting Conditions

Peak Angles (deg)	**Running Shoes**	**Barefoot**	**Effect size**
Trunk *	50.72 ± 8.27	46.97 ± 9.87	.41
Thigh *	20.94 ± 10.19	24.42 ± 11.11	.33
Shank *	59.47 ± 5.54	62.75 ± 6.17	.51
Hip	72.37 ± 13.85	71.87 ± 13.90	.04
Knee *	81.33 ± 13.70	88.32 ± 15.45	.48
Ankle	99.40 ± 9.15	98.10 ± 9.02	.14

Note: * indicates the p value is less than 0.008.

It should be noted that the foot segment, when considered in the sagittal plane with respect to the floor was slightly different between two footwear conditions. The foot, defined as the segment between the lateral malleolus and the 5th metatarsal markers, was closer to horizontal in the barefoot condition (barefoot: 31.95 ± 5.20°, running shoes: 35.27 ± 5.57°). This was expected because running shoes have a slightly raised heel.

DISCUSSION

The purpose of the present study was to determine the effects of footwear (or more appropriately, the lack of footwear) on selected kinematics during a barbell back squat. When comparing the kinematic differences identified in the present study with suggestions offered by the NSCA position statement [3], the barefoot condition results in two unfavorable results and two favorable results. First, the barefoot squat created a greater degree of trunk flexion. It is speculated that the subjects leaned forward in order to gain greater overall stability, or simply could not maintain an upright posture. As previously mentioned, forward flexion of the trunk stresses the low back by increasing the amount of shear force, especially when there is an external load involved [5, 6, 9, 10]. It is important to note that the current study data cannot fully support such a statement since the objective of the study was to determine the kinematic differences between the two footwear conditions, and did not measure kinetic data. However, it is suggested that barefoot squatting may not be ideal for individuals with a history of low back pain due to increased trunk flexion, and future research is warranted to help support or refute this speculation.

Second, the NSCA position statement recommends that the thigh segments should reach parallel to the floor when fully descended to get the exercise's full benefit [3]. Prior to the trials, instructions were given to the subjects to squat as they normally do, but peak thigh angle showed that the lifters were unable to squat to the desired position during both conditions. Furthermore, subjects' peak thigh angle was greater during barefoot squatting when compared to the shoe condition (24 ± 11° and 21 ± 10°, respectively) suggesting that it was more difficult for subjects to attain the thigh segment parallel to the ground position. Potentially, the technique restriction that was utilized in the present study (foot placement was perpendicular to the camera position) may compromise the overall squat technique including the thigh segment not to reaching parallel positions. Even though the barefoot squat may compromise proper squat mechanics, it is questionable whether three degrees makes a practical difference.

Third, it is recommended that the shank segment should stay near vertical as much as possible when performing back squat [3]. The present data showed that the barefoot condition actually supported this suggestion by keeping the shank closer to a vertical line (the difference was approximately 3°). As mentioned in the results section, the foot segment angle was different by 3°, which likely explains the shank segment difference. It is interesting to observe that ankle peak dorsiflexion angle was different by only 1°, but the knee peak flexion angle was significantly different by 7°. During the back squat with shoes, the greater degree of anterior tilt of the shank may result in a greater knee flexion angle.

Lastly, the favorable result for the barefoot squat is that it created 7° less knee flexion. Several studies reported that greater knee joint force as well as greater joint torque is associated with the greater knee flexion angle [18, 19, 20]. Therefore, the barefoot condition, which elicited less knee flexion, may be beneficial with regard to forces and torques at the joint.

The kinematic data from the running shoe squat condition was very similar to previously reported data [8]. Therefore, we are confident in the measurement procedure. There are, however, some limitations to the present study. First, even though a comparison of the high-bar and low-bar squats was not mentioned, there is a possible kinematic difference between the two. The high-bar position was chosen for the present study because the high-bar squat is commonly used by non-competitive powerlifters and is typically a form used in the protocols of previous studies [1,18, 19]. For that reason, the authors believed that it was more appropriate to analyze the high-bar squat.

The present study included relatively experienced individuals in resistance training. It is important to mention that 1RM used in the present study was taken one month prior to data collection. There is a potential gain in 1RM due to the training between the 1RM test and data collection period. The 1RM was tested for off-season training purposes and it was not agreeable with coaches to re-measure the 1RM just for the study purpose. Although the kinematic differences between the two footwear conditions were found in the present study, it is not evident that the barefoot squat kinematics remains the same if lifters continue to perform the squat in this condition over time. With that being said, future studies should focus on evaluating barefoot squatting after a suitable training duration.

Even though 2D analysis has been a common approach for biomechanical studies of the squat [8, 11, 17], in order to better minimize the measurement error, 3D analysis should be utilized for future study. For example, trunk, thigh, and shank segment angles showed statistically significant difference by approximately 3°. This angle difference may come from not only the effect of the footwear, but also could be due to the measurement error from the software. Additionally, relatively low effect sizes (under 0.6) were observed for each variable. Thus, this should be considered carefully since the squat mechanism is not purely in the sagittal plane. In future studies with the 3D approach, the foot placement restriction that was utilized in the present study would be changed to a more natural foot placement which may lead to different results. Future analysis needs to address this issue. As mentioned in the methods section, 60% of 1RM seems relatively light and the present data may seem impractical. However, based on the pilot study, it was noticed that the barefoot squat was more difficult for all subjects to perform at higher intensities, and therefore, the light intensity was chosen for the present study. Future studies can investigate the difference of 1RM and identify an equivalency of the intensity between the two footwear conditions.

CONCLUSION

The current study found some disadvantages of the barefoot squat from a biomechanical perspective, but this does not mean that the authors are opposed to barefoot training overall. Rather, barefoot training should be recognized and utilized in both fitness and rehabilitative fields for its potential benefits, especially considering the potential gains in balance and stability. Since some websites and non peer-reviewed articles mainly focus on positive outcomes of barefoot training, the negative traits that were identified in the present study should be noted for careful supervision of training. The findings from this study should be acknowledged by the individuals who train barefoot or provide information to fitness professionals to better educate their clients and patients on barefoot training.

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