



The Effect of Stance Width and Anthropometrics on Joint Range of Motion in the Lower Extremities during a Back Squat

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ABSTRACT

International Journal of Exercise Science 11(1): 764-775, 2018. The purpose of this study was to assess whether changing the stance width has an effect on the range of motion of hip flexion, knee flexion, and ankle dorsiflexion during an unloaded back squat, and whether these joint movements are affected by anthropometric differences. Thirty-two healthy, young adults performed unloaded back squats at three different stance widths, normalized to pelvic width. Joint angles were assessed using electromagnetic motion capture sensors on the sacrum, and thigh, shank and foot of the dominant leg. ANOVA comparison of joint angles for the three stance widths, at 10° intervals of thigh orientation during the squat, indicated that joint angles tended to be larger when stance width was narrower, with the most significant effects on ankle dorsiflexion. A greater trunk/thigh length ratio (relatively long trunk) also tended to be associated with lower ankle and knee angles, while a greater thigh/shank length ratio (relatively long thigh) tended to be associated with higher ankle and knee angles, for the two narrower stance widths. The most practical implication of our findings is that individuals with limited ankle dorsiflexion, or with particularly long legs / thighs, may benefit from a wider stance width when squatting.

KEY WORDS: Segment length, joint mobility, exercise prescription

INTRODUCTION

Substantial emphasis has been placed on assessing and correcting technique during the back squat (10, 14), which is a key element of many resistance training programs. Range of motion (ROM) deficits in the joints of the lower limbs, however, may affect the ability of an individual to squat with proper technique (4, 8, 9). Furthermore, anthropometrics (e.g. relative length of the torso and lower limbs) may affect the joint motion required during a squat (14). It is of interest, therefore, to provide a more objective assessment of how factors related to squat

technique and anthropometrics may affect the ROM requirements in the lower limbs during a squat.

An easily modifiable factor related to squat technique is stance width (lateral distance between the feet), although there has been minimal prior work evaluating its impact on joint angles. Escamilla et al. (5) found that lower limb joint angles tended to increase with increased stance width (normalized to shoulder width), with the strongest correlations at the hip. These data were collected during a power lifting competition, however, with each competitor self-selecting their preferred stance. As such, these data cannot be used to evaluate the effect of changing an individual's stance width. Peng et al. (16) reported larger hip flexion and ankle dorsiflexion angles, but lower knee flexion angles, when baseball catchers increased the width of their catching stance. The catching stance, however, may differ from the recommended squat technique during resistance training. These previous studies do not provide a detailed analysis of how stance width affects the ROM requirements of the lower limbs during the back squat. Furthermore, while the literature provides subjective descriptions of how anthropometrics may affect squat technique (14), to our knowledge this has not been objectively assessed.

The primary objective of this study was to assess whether changing the stance width has an effect on the ROM of hip and knee flexion, and ankle dorsiflexion, during an unloaded back squat, in young, healthy adults. A secondary objective was to determine whether anthropometrics affect these ROM values: specifically the ratio of trunk to thigh length, and of thigh to shank length. Three-dimensional kinematic data were acquired during a full, unloaded back squat, with joint angles calculated based on the relative orientation of the upper and lower segments. Based on previous findings, we hypothesized that increasing the stance width would increase the joint ROM during the back squat. Moreover, we hypothesized that a lower trunk/thigh ratio (relatively shorter trunk) would increase the hip angle, while a higher thigh/shank ratio (relatively longer thigh) would increase the ankle dorsiflexion angle during the squat.

METHODS

Participants

A convenience sample of thirty-two (32) young, healthy adults participated in the study (Table 1). Subjects were eligible to participate if they were between 18 and 35 years old and were capable of performing an unloaded back squat so that the backs of their thighs were parallel to the ground or lower (based on visual assessment), with their feet positioned at 100% of their pelvic width. Subjects were excluded if they had a difference in leg length (thigh + shank) ≥ 0.025 m, or a known condition (self-reported) that would affect the movement, strength or balance of the lower limbs, or would otherwise limit their ability to fully and safely participate in the study.

Table 1. Subject demographics and anthropometrics.

Sex	Male = 20, Female = 12
Leg Dominance	Left = 4, Right = 28
Age (years)	24±2
Trunk Length (m)	0.54±0.03
Thigh Length* (m)	0.40±0.03
Shank Length* (m)	0.40±0.03
Trunk/Thigh Ratio*	1.37±0.10
Thigh/Shank Ratio*	0.98±0.04

* Dominant leg; Values are Mean (SD)

A sample size calculation was based on published data (7), which reported a mean of 38.5° (SD 5.9°) of ankle dorsiflexion while squatting, with the feet flat on the floor. A minimum sample size of 30 was determined for three pairwise comparisons (three stance widths), aiming to identify at least a 5° difference between conditions, with an alpha value of 5% and a 1-beta value of 80%.

Leg dominance was determined by asking the subjects which leg they would preferentially use to kick a ball. Anthropometric measurements were taken with a tape measure, as follows: trunk length - vertical distance from the acromion to the greater trochanter, on the side of the dominant leg; thigh length - distance from the greater trochanter to the lateral epicondyle of the femur; shank length - distance from the lateral epicondyle of the femur to the lateral malleolus of fibula.

All subjects provided written, informed consent prior to participation. Ethics approval for this study was received from the local institutional review board.

Protocol

Subjects were asked to perform a full, unloaded back squat, barefoot, as described by Myer et al. (14), holding a light, cylindrical, wooden dowel (0.02 m diameter) across the back of their shoulders. Three different stance widths were tested – 100%, 150% and 200% of pelvic width – with pelvic width measured as the distance between the greater trochanters. The three widths were marked on the floor, and the subjects were instructed to align the lateral borders of their heels with the appropriate marks. Toe-in/out angle was self-selected by each subject.

Subjects performed three repetitions of the back squat for each stance width (nine repetitions total), with the order of the stance widths randomized for each subject. The subjects were asked to repeat any repetition where the squat technique was deemed flawed by the tester, based on visual observation, and verbal feedback was given to allow the subject to correct themselves for future trials.

Kinematic data was acquired, in three dimensions (3D), using a TrakSTAR electromagnetic motion capture system with model 800 sensors (Ascension Technology Corporation, Milton, VT, USA). Sensors were affixed to the skin, using custom molded urethane clips and double-sided, hypoallergenic wig tape, on the sacrum and the dominant leg (Table 2). The orientation of each sensor, within the transmitter-embedded reference frame, was used to define a 3×3 Euler

rotation matrix for that sensor. These matrices were then used to determine the hip flexion, knee flexion, and ankle dorsiflexion angles, by multiplying the rotation matrix of the lower sensor by the transpose of the rotation matrix of the upper sensor (e.g. hip angles: rotation of the thigh sensor relative to the rotation of the sacrum sensor). The joint angles of interest were the calculated angles in the sagittal plane of the sensor-embedded reference frame for the upper sensor.

Table 2. Sensor placement and joint angle calculation.

Sensor	Sensor Placement and Alignment
Sacrum	Midline of sacrum, with top of sensor aligned with top of first sacral vertebra
Thigh	Long axis of sensor on a line between greater trochanter and lateral epicondyle of femur
Shank	Long axis of sensor on a line between head of fibula and lateral malleolus
Foot	Lateral calcaneus; long axis perpendicular to the 5th metatarsal

Prior to the squat trials, subjects were asked to hold an upright, quiet standing position for five seconds, in order to record reference measurements for the lower limb joint angles, based on sensor placement. The primary outcome measures - hip flexion, knee flexion and ankle dorsiflexion - were measured as the difference between the reference position (upright standing) and the angle achieved during the back squat. Joint angles were recorded during the descent phase of the squat, at ten-degree intervals for the orientation of the thigh sensor (Table 2) relative to vertical.

For each subject, the joint angle data were averaged over the three repetitions for each stance width, at each ten-degree interval for thigh orientation. Data were only analyzed if the subject reached the specified thigh orientation for all three repetitions, for all stance widths. Joint angle calculations were done using custom software in Matlab (The MathWorks, Natick, MA).

Statistical Analysis

Repeated-measures, one-way ANOVA, with pairwise comparisons, were used to assess the effect of stance width on the joint angles achieved (hip flexion, knee flexion, ankle dorsiflexion) at each ten-degree interval for thigh orientation. Mauchly's Test was used to assess sphericity, and, if violated, a Greenhouse-Geiser correction was applied to the results of the ANOVA.

Pearson correlation analyses were also run, at each ten-degree interval for thigh orientation, to test for a relationship between each joint angle and two anthropometric ratios: trunk/thigh length and thigh/shank length (Table 1).

All statistical analyses were performed using IBM SPSS software (Version 23, Armonk, NY).

RESULTS

Not all of the subjects in the study reached the same squat depth, based on the orientation of the thigh sensor relative to vertical. All 32 subjects reached a 50° thigh angle for all repetitions. One subject failed to reach 60° for one repetition, and was excluded from the analysis at this thigh angle (N=31). Only 18 and 8 subjects reached thigh angles of 70° and 80°, respectively, for all

repetitions. Results of the ANOVA at these angles (but not the correlations) are reported, but should be interpreted with caution. Only two subjects consistently reached a thigh angle of 90°, and, as such, these data are not reported.

Mauchly's Test of Sphericity was significant for nearly all ANOVA. As such, Greenhouse-Geiser corrections were applied to all ANOVA findings.

Joint angles for hip flexion, knee flexion and ankle dorsiflexion all tended to be larger at narrower stance widths (Figure 1).

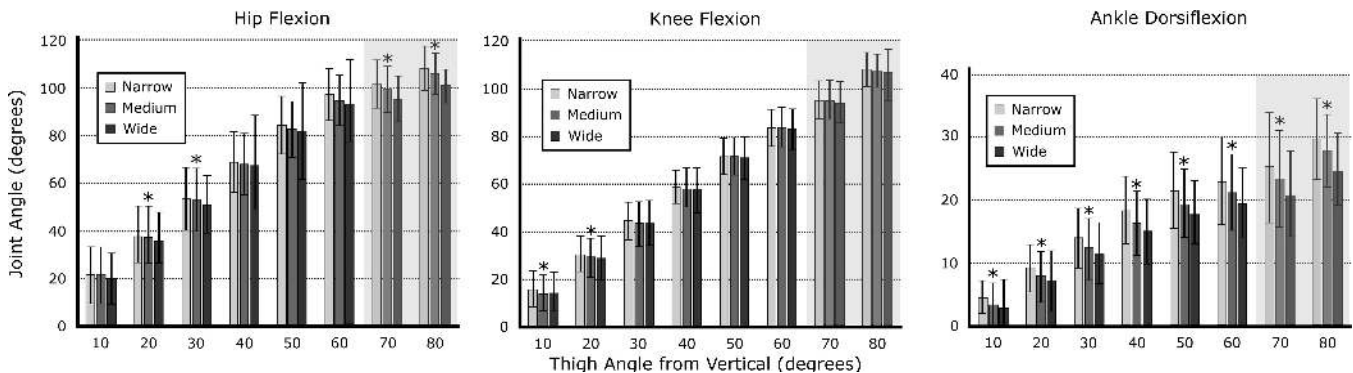


Figure 1. Joint angles for the three stance widths, at ten-degree intervals of thigh orientation relative to vertical during the descent phase of the unloaded back squat. Results at 70° and 80° (greyed areas) should be viewed with caution due to reduced sample size ($N = 18$ and 8 , respectively).

* indicates a significant main effect of stance width.

Hip flexion was only significantly affected by stance width at certain points early in the squat, with low effect sizes (Figure 1). A significant main effect of stance width was found at a thigh angle of 20° ($F = 4.569$, $p = 0.018$, $\eta_p^2 = 0.128$) and 30° ($F = 6.998$, $p = 0.003$, $\eta_p^2 = 0.184$). In both cases, pairwise comparisons found differences between the narrow and wide stance ($p = 0.014$ & 0.006), and the medium and wide stance ($p = 0.05$ & 0.004). No significant differences were found at 10° or from 40° to 60° ($F = 0.326$ to 2.809 , $p = 0.072$ to 0.594 , $\eta_p^2 = 0.010$ to 0.083). Significant differences, with larger effect sizes, however, were found for those subjects who reached 70° ($F = 19.405$, $p < 0.001$, $\eta_p^2 = 0.533$) and 80° ($F = 11.464$, $p = 0.012$, $\eta_p^2 = 0.656$), with pairwise differences between all stance widths ($p < 0.001$ to 0.034).

Knee flexion was only significantly affected by stance width early in the squat as well, also with low effect sizes (Figure 1). A significant main effect was found at a thigh angle of 10° ($F = 6.129$, $p = 0.009$, $\eta_p^2 = 0.165$) and 20° ($F = 3.764$, $p = 0.047$, $\eta_p^2 = 0.108$). Pairwise differences were found, at both points, between the narrow and medium stance ($p < 0.001$ & $p = 0.001$), and, at 10°, between narrow and wide stance ($p = 0.014$). No significant differences were found from 30° to 80° ($F = 0.203$ to 3.081 , $p = 0.069$ to 0.681 , $\eta_p^2 = 0.021$ to 0.09).

Ankle dorsiflexion, unlike the other joints movements, was significantly affected by stance width at all thigh angles, with increasing effect sizes as the thigh angle increased ($F = 5.372$ to 19.497 , $p < 0.001$ to 0.016 , $\eta_p^2 = 0.148$ to 0.697) (Figure 1). At 10° and 20°, pairwise differences were

found between the narrow and medium stance ($p = 0.006$ & 0.001), and the narrow and wide stance ($p = 0.019$ & 0.004). From 30° to 70° , pairwise differences were found between all stance widths ($p < 0.001$ to 0.041). At 80° , pairwise differences were found between the narrow and wide stance ($p = 0.007$), and the medium and wide stance ($p = 0.005$).

No significant correlations were found between hip flexion angle and trunk/thigh length ratio, for any stance width ($r = -0.073$ to -0.271).

For the knee flexion angle, significant negative correlations with the trunk/thigh ratio were found for the narrow (from 30° to 60° ; $r = -0.374$ to -0.402 ; $p = 0.023$ to 0.035), medium (at 50° ; $r = -0.350$; $p = 0.050$) and wide stance width (at 40° and 50° ; $r = -0.352$ and -0.360 ; $p = 0.047$ and 0.043). All but two of the other correlations (narrow and medium stance widths at 10°), however, showed a trend toward significance ($p < 0.100$).

For ankle dorsiflexion, significant negative correlations with the trunk/thigh ratio were only present for the medium stance width, from 10° to 50° ($r = -0.354$ to -0.453 ; $p = 0.009$ to 0.047), with the highest correlation at 30° . At 60° , the correlation approached significance ($r = -0.305$; $p = 0.095$). Correlations for the narrow ($r = -0.123$ to -0.299) and wide ($r = -0.192$ to -0.285) stance widths were not significant.

No significant correlations were found between hip flexion angle and thigh/shank length ratio, for any stance width ($r = -0.081$ to 0.159).

For the knee flexion angle, significant positive correlations with the thigh/shank ratio were present at all thigh angles for the narrow stance width ($r = 0.369$ to 0.454 ; $p = 0.009$ to 0.038). The same was true for the medium stance width ($r = 0.368$ to 0.480 ; $p = 0.016$ to 0.038), at all but 10° ($r = 0.344$; $p = 0.054$). For both stance widths, correlations generally increased as thigh orientation increased (i.e. deeper into the squat). The correlations at the wide stance width, however, were not significant ($r = 0.243$ to 0.336).

For ankle dorsiflexion, correlations with the thigh/shank ratio were significant for both the narrow ($r = 0.352$ to 0.451 ; $p = 0.010$ to 0.048) and medium ($r = 0.354$ to 0.432 ; $p = 0.016$ to 0.047) stance widths, with the exception of the narrow width at 60° ($r = 0.318$; $p = 0.081$). None of the correlations was significant, however, for the wide stance width ($r = 0.133$ to 0.218).

Figure 2 illustrates the significant correlations for the knee and ankle angles with the thigh/shank ratio at a thigh angle of 50° , for the medium stance width.

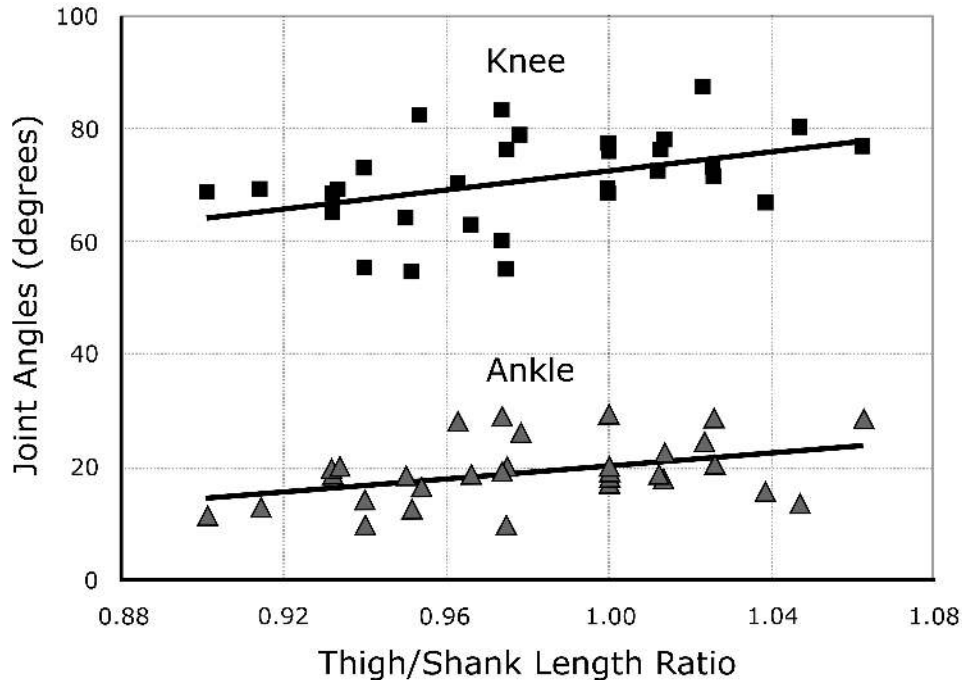


Figure 2. Knee and ankle angle, in the medium stance width, at a thigh orientation of 50° from vertical, relative to the thigh/shank length ratio. Both correlations were statistically significant.

DISCUSSION

The primary objective of this study was to determine whether changing the stance width during an unloaded back squat would have an effect on sagittal plane joint angles in the lower limbs. Our results indicate that widening the stance width tends to reduce the joint angles throughout the squat, but that ankle dorsiflexion is most affected (at least relative to the available ROM) by the change (Figure 1). A secondary objective was to determine whether anthropometrics, specifically the trunk/thigh ratio and the thigh/shank ratio affect joint ROM during the squat. The trunk/thigh ratio, which if increased would tend to bring the center of mass forward during the squat, had some negative correlations with knee flexion and ankle dorsiflexion, but no correlation with hip flexion as initially hypothesized. The thigh/shank ratio, which if increased would tend to bring the center of mass backwards during the squat, had positive correlations with knee flexion and ankle dorsiflexion, as hypothesized, but no correlation with hip flexion. The potential implications of these findings are discussed below.

The main finding of our study is that stance width during a back squat will affect the ankle dorsiflexion ROM, but has much less effect on knee and hip flexion ROM (except possibly for very deep squats, where hip flexion is more strongly affected by stance width) (Figure 1). The need for more ankle dorsiflexion when squatting with a narrower stance may have important implications. A lack of ankle dorsiflexion may predispose the individual toward knee valgus during the squat (2). It has been suggested that individuals with a dynamic knee valgus should perform squats with a wider stance width (10). Our finding support this recommendation for those individuals who are compensating for a lack of ankle dorsiflexion. Reduced ankle

dorsiflexion will also limit the forward inclination of the shank, described as anterior tibial translation by Myer et al. (14). These authors suggest that the inclination of the shank should match that of the trunk, and that limited tibial translation will affect normal hip and knee mechanics. Limiting anterior tibial translation has been shown to increase torque at the hips and reduce torque at the knees during the squat (6). It may also lead to increased knee valgus (12) and increased spine flexion (11). Thus, adequate ankle dorsiflexion ROM is necessary to maintain proper squat technique (14), as well as achieving squat depth (8). Individuals with limited ankle dorsiflexion may benefit, therefore, from a wider stance width when squatting (as well as exercises to increase ankle dorsiflexion ROM, if indicated).

Our results regarding reduced joint ROM when squatting with a wider stance width appear to be contrary those of previous studies. In a sample of baseball catchers, a wider catching stance was associated with increased hip flexion and ankle dorsiflexion (7). There may be differences in technique, however, between a back squat and a catching stance in baseball. As such, these results may not be directly comparable. Escamilla et al. (5), however, studied a sample of power lifters, and reported those with a wider stance when squatting tended towards increased lower limb joint angles, most notably at the hip. Once again, these findings may not be directly comparable with ours, as this previous study assessed joint angles in the athletes' preferred squatting stance, rather than directly assessing the effect of changing the stance width. As such, the athletes' preferred stance width may have been related to other factors, such as segment lengths, that could also have influenced joint angles.

Our findings indicate that a higher trunk/thigh length ratio (relatively longer trunk) tended to be associated with a decrease in knee flexion and, for the medium stance width, a decrease in ankle dorsiflexion during the squat (negative correlations). The latter corresponds to the assertion by Myer et al. (14) that anterior tibial translation would be affected by the torso and leg length ratio. This finding is likely explained by the distribution of the segmental masses of the body. A longer trunk, when leaned forward during the squat, will tend to bring the mass of the head, arms and trunk forward, which will allow for less knee flexion and ankle dorsiflexion at the same thigh angle (Figure 3B). This, as opposed to a reduction in hip flexion (as we had initially hypothesized), which would also bring the mass of the upper body backwards. The fact that the correlations with joint angles were not significant at all thigh inclinations, however, and had no correlation with hip flexion, suggests that different individuals may choose different compensations for the different segmental mass distribution.

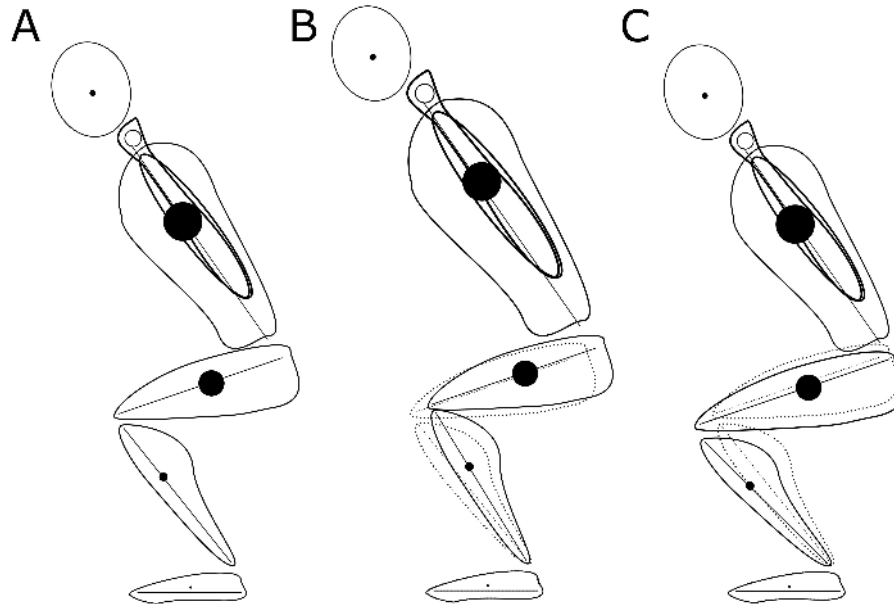


Figure 3. Approximate representations of the squat position, with the thigh at a 70° angle from vertical. A. Mean segment lengths for the study population. B. Increase in the trunk/thigh length ratio (increased trunk length) leading to decreased ankle dorsiflexion and knee flexion (hip flexion and thigh angles unchanged). C. Increase in the thigh/shank ratio (increased thigh length) leading to increased ankle dorsiflexion and knee flexion (hip and thigh angles unchanged). The dotted lines in (B) and (C) represent the lower limb position in (A), while the solid circles represent the approximate positions and relative magnitudes of the centers of mass for each segment (foot, shank, thigh, trunk + arms, head).

Our findings also suggest that an increase in the thigh/shank length ratio (relatively longer thigh) is consistently associated with more knee flexion and ankle dorsiflexion in the narrow and medium stance widths. This can also be explained by the distribution of segmental mass, as a longer thigh would bring the mass of the thigh (and the upper body) backwards. An increase in the anterior tibial translation, through increase dorsiflexion with an associated increase in knee flexion, would compensate for this (Figure 3C). An increase in hip flexion could also be used to compensate, but we found no correlations with hip flexion at any stance width.

The observation that hip flexion did not correlate significantly with either of the anthropometric ratios, at any stance width, suggests that changing the hip flexion angle may not be a preferred compensatory strategy during the back squat. This may be explained, potentially, by the fact that we recorded joint angles during the descent phase of the squat. Myer et al. (14) suggest that the squat should be initiated by “breaking the hips back” (pg. 17), and that tibial translation (associated with ankle dorsiflexion and knee flexion) should follow. More in-depth analysis of compensatory patterns during squatting would be required to make any conclusive statement in this regard.

Additionally, there were no significant correlations between the anthropometric ratios and joint angles at the wide stance width. This may be explained, potentially, by the hip abduction (and toe-out) angle required at this stance, which effectively shortens the thigh in the sagittal plane, and thus alters both of the ratios assessed in this study. This effective reduction in the

thigh/shank ratio, which had stronger correlations with ankle dorsiflexion angle than the trunk/thigh ratio, might also explain why less ankle dorsiflexion was required in the wide stance width. This further outlines the potential utility of the wide stance width for individuals with relatively long thighs, who might otherwise lack the ankle mobility to achieve a full back squat.

Before advocating the use of a wider stance width to reduce the required ankle dorsiflexion ROM, it is important to examine other potential consequences of this change in technique. Almosnino et al (1) reported that a wider stance width slightly increases the external flexion and adduction moment at the knee during an unloaded squat (if toe-out angle is also increased, the internal rotation moment is slightly reduced). These authors, however, state that the differences are likely not clinically significant. The higher adduction moment does mean, however, that particular attention should be paid to avoid knee valgus when squatting with a wider stance (even if ankle dorsiflexion does not limit the movement). Stance width does not appear to have a significant effect on quadriceps muscle activation (13, 15), nor does the toe-in/out angle (3, 17). A wider stance width, however, may increase the activation of the adductor longus and gluteus maximus muscles (13, 15), therefore slightly changing the training effect of the exercise (as would be expected).

Our study had several limitations, which must be considered when interpreting our findings. Our subjects were all young and healthy, and capable of performing a full, unloaded back squat. As such, it may not be possible to generalize our study findings. Further study of older individuals, or those who are not able to complete a full squat, may provide more insight into the factors that affect joint ROM when squatting. The addition of weight to the back squat may also have an effect on joint angles, as it will affect the position of the overall center of mass. Our study also included both male and female subjects. Although we normalized stance width to pelvic width, which may compensate for some anthropometric differences between the sexes, there remains some indication in the literature that different factors may affect squat depth for women and men (8). The stance-widths used in our study were also constrained by aligning the lateral edges of the heels with marks placed on the floor, but the toe-in/out angle was self-selected by each individual. This may have contributed some variability to our data. Variability in sensor placement may have also affected our data, although we normalized the joint angles to the quiet standing position. While sensor placement will not affect the ANOVA comparison (as sensor placement did not change for the three stance widths), it may have affected the absolute joint angles that were measured, and thus the correlation analyses.

Our study findings demonstrate that stance width will affect the lower limb joint angles during the unloaded back squat, with the most significant effects being on ankle dorsiflexion. Our results also demonstrated that, while hip flexion was not correlated with our anthropometric measures, these did affect ankle dorsiflexion and, to a somewhat lesser degree, knee flexion. This is particularly important for ankle dorsiflexion, as while most individuals do not approach the end-range of knee flexion during a squat, the full ankle dorsiflexion range is often required, to the point where ankle dorsiflexion can be a limiting factor for squat depth (8). A large thigh/shank length ratio, or a small trunk/thigh length ratio, may make a deep squat more

difficult, due to the increased ankle dorsiflexion required. These effects may be offset, to some degree, by adopting a wider stance width during the squat.

Our findings support previous indications that ankle dorsiflexion may be a limiting factor when performing a full back squat (8). Furthermore, long thighs relative to the trunk and/or shank may increase the dorsiflexion range required to squat. Squatting with a wider stance width, however, requires less ankle dorsiflexion than squatting with a narrower stance. Individuals with limited ankle dorsiflexion, or with particularly long legs / thighs, may benefit from a wider stance width when squatting (as well as exercises to increase ankle dorsiflexion ROM, if indicated).

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REFERENCES

1. Almosnino S, Kingston D, Graham RB. Three-dimensional knee joint moments during performance of the bodyweight squat: effects of stance width and foot rotation. *J Appl Biomech* 29(1): 33-43, 2013.
2. Bell DR, Padua DA, Clark MA. Muscle strength and flexibility characteristics of people displaying excessive medial knee displacement. *Arch Phys Med Rehabil* 89(7): 1323-8, 2008.
3. Boyden G, Kingman J, Dyson R. A comparison of quadriceps electromyographic activity with the position of the foot during the parallel squat. *J Strength Cond Res* 14(4): 379-82, 2000.
4. Cook G, Burton L, Hoogenboom B. Pre-participation screening: the use of fundamental movements as an assessment of function - part 1. *N Am J Sports Phys Ther* 1(2): 62-72, 2006.
5. Escamilla RF, Fleisig GS, Lowry TM, Barrentine SW, Andrews JR. A three-dimensional biomechanical analysis of the squat during varying stance widths. *Med Sci Sports Exerc* 33(6): 984-98, 2001.
6. Fry A, Smith J, Schilling B. Effect of knee position on hip and knee torques during the barbell squat. *J Strength Cond Res* 17(4): 629-33, 2003.
7. Hemmerich A, Brown H, Smith S, Marthandam SS, Wyss UP. Hip, knee, and ankle kinematics of high range of motion activities of daily living. *J Orthop Res* 24(4): 770-81, 2006.
8. Kim SH, Kwon OY, Park KN, Jeon IC, Weon JH. Lower extremity strength and the range of motion in relation to squat depth. *J Hum Kinet* 45: 59-69, 2015.
9. Kritz M, Cronin J, Hume P. The bodyweight squat: a movement screen for the squat pattern. *Strength Cond J* 31(1): 10, 2009.
10. Kushner AM, Brent JL, Schoenfeld BJ, Hugentobler J, Lloyd RS, Vermeil A, Chu DA, Harbin J, McGill SM, Myer GD. The back squat part 2: targeted training techniques to correct functional deficits and technical factors that limit performance. *Strength Cond J* 37(2): 13-60, 2015.

11. List R, Gulay T, Stoop M, Lorenzetti S. Kinematics of the trunk and the lower extremities during restricted and unrestricted squats. *J Strength Cond Res* DOI: 10.1519/JSC.0b013e31827360342012.
12. Macrum E, Bell DR, Boling M, Lewek M, Padua D. Effect of limiting ankle-dorsiflexion range of motion on lower extremity kinematics and muscle-activation patterns during a squat. *J Sport Rehabil* 21(2): 144-50, 2012.
13. McCaw ST, Melrose DR. Stance width and bar load effects on leg muscle activity during the parallel squat. *Med Sci Sports Exerc* 31(3): 428-36, 1999.
14. Myer GD, Kushner AM, Brent JL, Schoenfeld BJ, Hugentobler J, Lloyd RS, Vermeil A, Chu DA, Harbin J, McGill SM. The back squat: A proposed assessment of functional deficits and technical factors that limit performance. *Strength Cond J* 36(6): 4-27, 2014.
15. Paoli A, Marcolin G, Petrone N. The effect of stance width on the electromyographical activity of eight superficial thigh muscles during back squat with different bar loads. *J Strength Cond Res* 23(1): 246-50, 2009.
16. Peng YC, Lo KC, Wang LH. Lower extremity muscle activation and kinematics of catchers when throwing using various squatting and throwing postures. *J Sports Sci Med* 14(3): 484-93, 2015.
17. Signorile J, Kwiatkowski K, Caruso J, Robertson B. Effect of foot position on the electromyographical activity of the superficial quadriceps muscles during the parallel squat and knee extension. *J Strength Cond Res* 9(3): 182-7, 1995.