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WILEY

Effects of barbell back squat stance width on sagittal and frontal hip and knee kinetics

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Different stance widths are commonly utilized when completing the barbell back squat during athletic general preparedness training. Width manipulation is thought to influence sagittal plane stimuli to the hip and knee extensors, the primary extensor musculature in the squat. However, how width manipulation affects frontal plane stimuli is less understood. Knowledge of hip and knee net joint moments (NJM) could improve exercise selection when aiming to improve sport-specific performance and prevent injuries. Fourteen adult amateur rugby athletes were recruited for this study. After a familiarization period, participants performed wide- (WIDE, 1.5× greater trochanter width) and narrow-stance (NARROW, 1× greater trochanter width) barbell back squats to femur parallel depth, using relative loads of 70% and 85% of one-repetition maximum. Sagittal and frontal plane hip and knee kinetics and kinematics were compared between widths. A Bonferroni-corrected alpha of 0.01 was employed as the threshold for statistical significance. Knee flexion angle was statistically greater in NARROW than WIDE ($P < 0.0001$, $d = 2.56$-2.86); no statistical differences were observed for hip flexion angle between conditions ($P = 0.049$-0.109, $d = 0.33$-0.38). Hip-to-knee extension NJM ratios and knee adduction NJMs were statistically greater in WIDE than NARROW ($P < 0.007$, $d = 0.51$-1.41). At femur parallel, stance width manipulation in the barbell back squat may provide substantial differences in biomechanical stimulus in both the sagittal plane and the frontal plane. In certain contexts, these differences may have clinically relevant longitudinal implications, from both a performance and a injury prevention standpoint, which are discussed.

KEYWORDS
acceleration, change in direction, kinematics, kinetics, Strength training

1 | INTRODUCTION

The barbell back squat is a widely popular and utilized strength training exercise to support general preparedness for the demands in multiple sports.[1,2] Due to its applicability in such a vast array of athletic populations, multiple variations have been developed and utilized in practice. Variations that have been objected to biomechanical research include, but are not limited to, stance width, unilateral vs bilateral, depth, and degree of knee restriction.[2] Although not extensively studied, some variations have been compared in long-term studies, which have demonstrated differential performance adaptations.[3,4] Therefore, further acute biomechanical research on different squatting variations should help improve our understanding of potential long-term decisions and study design.

The net moment of force requirements of the hip and knee joints has been the subject of investigation in

numerous squat studies.[5-7] In terms of transfer to sport performance, kinetic variables such as net joint moment (NJM) ratios between the hip and knee have been proposed as an aiding method in establishing coherence between athletic maneuvers and strength exercises.[8] In the sagittal plane, this can be quantified by dividing the peak hip extension NJM by the peak knee extension NJM during an athletic task, thereby creating a hip-to-knee extension NJM ratio. Values above 1.0 would be considered more "hip-dominant," and values below 1.0 would be considered more "knee-dominant," thus suggesting the possibility of differential agonist musculature utilization between the involved joints. The hip-to-knee extension NJM ratio has shown to rise above 1.0 with increasing effort in athletic tasks, such as jumping and sprinting,[9,10] suggesting the importance of developing the hip musculature for maximal, dynamic efforts.[8] Different athletic lower-body maneuvers also involve varying degrees of demand from biomechanical planes outside the sagittal plane. Although squatting is generally considered a sagittal-plane exercise, lower barbell back squat strength levels have shown to be associated with decreased frontal plane knee control in both bilateral and unilateral landing tasks in athletic populations, a common risk factor for knee injury.[11] Therefore, a greater understanding of the frontal plane requirements could be of value for injury prevention and general preparedness training.

Although not considered a sport-specific exercise, there may be value in understanding how kinematic manipulations in the barbell back squat—such as stance width when performed to a similar and commonly used depth—affect the prime extensor joint demands from a three-dimensional (3D) perspective. Therefore, the goal of this study was to investigate the biomechanical differences between the wide barbell back squat (WIDE) and the narrow barbell back squat (NARROW) to femur parallel depth on hip and knee joint mechanics in a population of intermediate male and female rugby athletes. Our main hypothesis was that stance width manipulation in the squat will substantially alter the sagittal and frontal plane NJMs.

2 | MATERIALS AND METHODS

2.1 | Participants

All participants were recruited from the Jyväskylä Rugby Club. In total, a convenience sample of 14 amateur rugby players (6 men, 8 women; mean ± SD: age = 27 ± 4 years; height = 174 ± 10 cm, body mass = 81 ± 22 kg; squatting experience: 4 ± 2 years) volunteered for this study. Only athletes with a minimum of 1 year of active barbell back squatting experience, a WIDE or NARROW one-repetition maximum (1-RM) to body mass ratio of at least 1.0, who had no health issues that may affect or be worsened by the

performance of the barbell back squat, and who completed all of the required familiarization sessions could participate in the experiment. Written informed consent was obtained from all participants on the first day of familiarization, and approval for this study was granted by the University of Jyväskylä Ethical Committee and was performed in the accordance with the Declaration of Helsinki.

2.2 | Study design

A cross-sectional, repeated-measures design was used to compare kinematic and kinetic measures of two different width variations of the barbell back squat. All participants were familiar with barbell back squat to femur parallel depth and completed 3 weeks of familiarization with both stance widths. The fourth week was devoted to 1-RM testing for both the WIDE squat and the NARROW squat on two separate days in a randomized order. Data were collected during week 5, during one testing session 5-7 days after the final 1-RM test (Figure 1).

2.3 | Familiarization

All familiarization sessions were conducted at the University of Jyväskylä Neuromuscular Research Center's gym. Familiarization was carried out over 3 weeks, which consisted of six sessions (two per week) in total; these sessions were considered a prerequisite for testing. The sets and repetitions were maintained throughout the familiarization phase, with a primary focus on technique and a secondary focus on overload. Participants performed 3-4 sets of 4-6 repetitions per stance width, depending on the weight used. The WIDE and the NARROW had the following biomechanical similarities: depth, tempo, bar positioning, and footwear. In terms of depth, the goal was to standardize a realistic depth to obtain with technical proficiency for most athletes. Thus, femur parallel depth was proposed as an appropriate depth for both high stimuli while avoiding visually apparent lumbopelvic movement. This lumbopelvic stability was promoted by means of coaching in the familiarization sessions. Cueing was standardized, and the participants were presented with both internal cueing and external cueing, with a priority on the external.

Because squatting mechanics would be measured without shoes to avoid their effects on kinematics,[12] familiarization
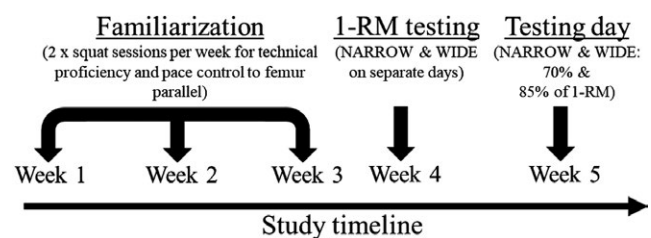

FIGURE 1 Five-week study time line

was also completed without shoes, with an exception made for shoes with no heel-toe drop. The barbell was placed on top of the posterior deltoids for both NARROW and WIDE.

A standardized warm-up protocol was used for all sessions, which included 5 minutes on a cycle ergometer (Teambike, PRECOR, USA), followed by 5 minutes of the dynamic full body warm-up routinely used in their team practice. In the first session, participants' current squat mechanics were screened with the help of a video camera. Following screening, both the WIDE and the NARROW were first practiced with no external load. Wide squat positions were practiced with a wall drill. The wall was used as a coaching tool so that participants could practice posterior displacement of the hips while maintaining an upright trunk position.[13] Our goal was that the trunk angle would be similar to the narrow position; therefore, the wall functioned as a practical external cue to avoid excessive forward lean. Width was increased until participants could comfortably shift their weight toward their heels and achieve close-to-vertical shin positioning. At this point, stance width was 1.52 ± 0.07 greater trochanter distance. The narrow squat position was practiced based on the recommendations of the National Strength and Conditioning Association.[14] The main exception was that a

slightly narrower stance was employed, by standing in greater trochanter width (0.99 ± 0.04) instead of shoulder width (Figure 2). In the NARROW, anterior knee translation was encouraged, but restricted to the extent that the heel did not come off the ground. In general, the angle of the feet relative to the antero-posterior axis in the NARROW was ~10 to 20° and ~30 to 40° in the WIDE (controlled visually by the practitioner), depending on each individual's movement.

At the end of the first session, squat widths for both WIDE and NARROW were measured using the distance between left and right legs' medial calcaneal border. These distances were used in proceeding familiarization sessions and in the testing session.

After the first week, a tempo was played to the participants via a metronome application (Pro Metronome, EUMLab, Xanin Technology, Germany) so that a descent pace of 3 seconds could be maintained. For the ascent phase, the instruction was to rise as quickly as possible without a "bounce" at the bottom. Depth to femur parallel was controlled visually, and verbal feedback was provided by an experienced practitioner. In the WIDE, anterior knee translation past midfoot was avoided with the help of a dowel placed in front of the knees.
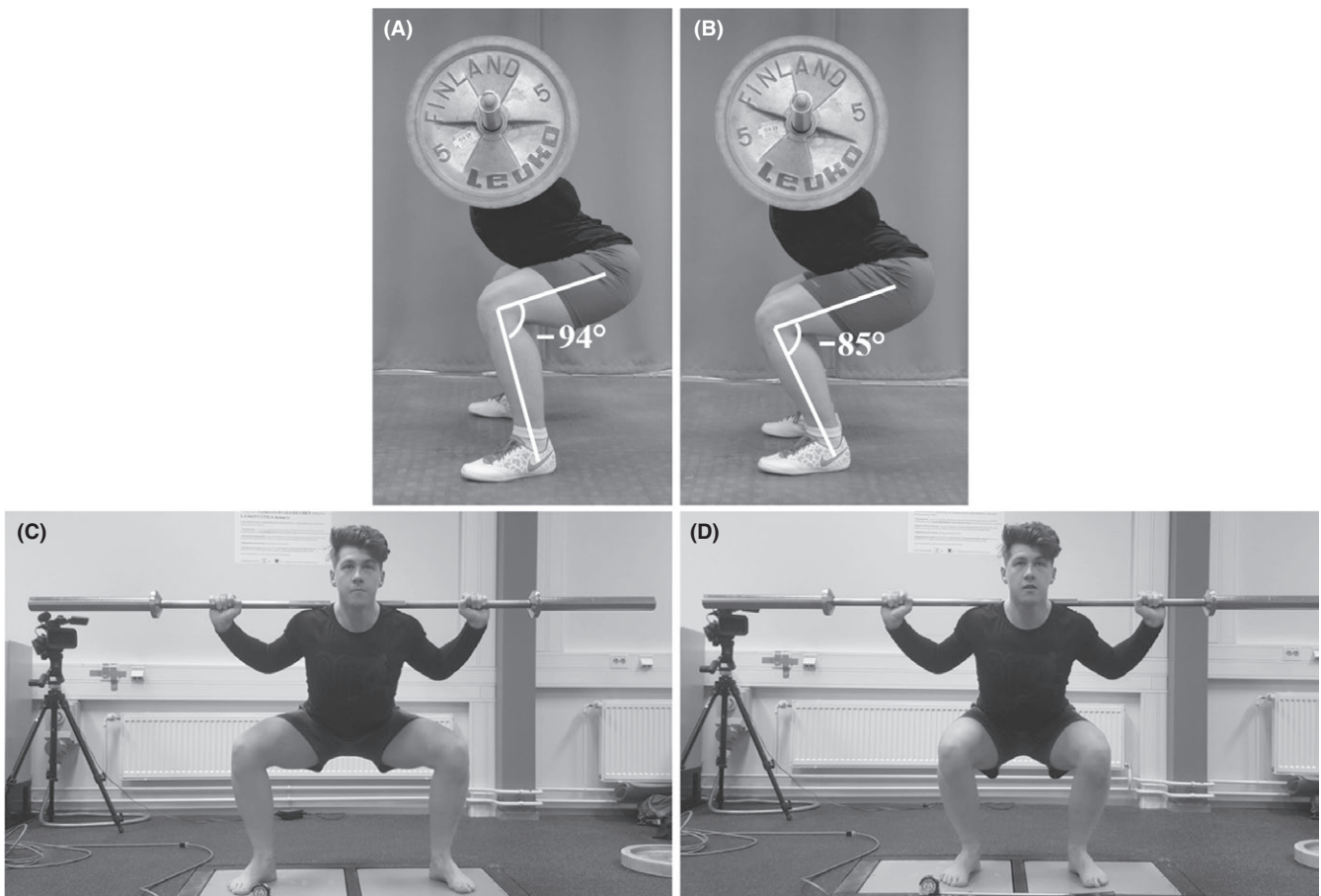

FIGURE 2 Side view and front view of a typical position taken in this study. Stance width was measured from the medial border of the heel and compared to greater trochanter width. WIDE width (A, B) and NARROW (C, D)

2.4 | 1-RM testing

After 3 weeks of familiarization, two extra sessions were de-voted to test 1-RM in both the WIDE and the NARROW. The 1-RM test order was randomized for all participants. The 1-RM protocol is largely consistent with the procedure de-scribed by Kreamer & Fry[15]. Consecutive 1-RM trials were completed until any unwanted technical alterations became visually apparent, such as a change in the synchronization of hip and knee movement in the ascent phase (such as the hip coming up first), clear valgus collapse, any clear devia-tions in the spine, and center of pressure (COP) shifts (ie, heel coming off ground during the NARROW). Because all participants could probably lift significantly more weight without these restrictions, the 1-RM testing employed can be better described as "technical 1-RM testing.".

2.5 | Preparation—kinematics and kinetics

Before performing the warm-up for the squats, 14-mm-diam-eter reflective markers were secured following the full body Plug-in Gait Model in the Nexus Software (Vicon Motion Systems Inc, Oxford, UK), excluding the arms. The C7 marker was placed 4 cm above the C7 vertebrae due to bar-bell placement. To determine 3D ground reaction forces, L5/S1, hip, and knee NJM, and kinematics, 3D marker displace-ments were recorded with 7-camera Vicon motion analysis system at 250 Hz sampling frequency (Vicon Motion Systems Inc, Oxford, UK) and two force plates (AMTI, Watertown, MA, USA) at a 1000 Hz sampling frequency using Nexus software. The origin of the global axes was set to the corner of the force plates. The x, y, and z axes were set to anterior-posterior, mediolateral, and vertical directions, respectively.

2.6 | Squat protocol

Before the measured squats were initiated, a general warm-up was completed, as were squat warm-up sets with 30% and 50% of 1-RM for both NARROW and WIDE. A total of four conditions were measured as follows: WIDE and NARROW with 70% and 85% of 1-RM. Condition order was evenly balanced between participants; thus, half of the participants started with WIDE or NARROW using 70% of their 1-RM, which was randomized. After completion of the 70% condi-tions, the 85% of 1-RM condition was independently carried out following the same process. This format was chosen to avoid any potentiation effects from lower to higher weights. Given the experienced population, fatigue was assumed to not play an appreciable role with the tested volume. Each condition had to include two technically acceptable repeti-tions for analysis. Repetitions in a set were completed one at a time with an inter-repetition rest time of 30 seconds. Inter-set rests were constrained to 2-3 minutes. Tempo and depth were controlled according to the familiarization protocol via oral feedback from the practitioner.

2.7 | Data analysis

Net joint moments were calculated by inverse dynamic calcu-lations in the Nexus software based on the full body Plug-in Gait model, using participants' anthropometric data (found in Table S1), ground reaction force (GRF) data, and kinematic data. The NJMs calculated in this study are expressed as the internal (muscles) net moments with respect to distal segment local coordinate system. Specifically, L5/S1, hip, knee, and ankle NJM in all 3 planes, external forces in the vertical and mediolateral directions, and anterior-posterior COP data were analyzed further from the ascent phase of the squat after export-ing all kinetic and kinematic data from the Nexus software after first smoothing force plate data with an 8 Hz low-pass, fourth-order Butterworth filter. All kinematic and kinetic data from the force plates were exported to, and analyzed in, Microsoft Excel. Reported joint kinematics, NJM, and external force data were summed between legs and averaged between repetitions. NJM from all biomechanical planes was normalized to partici-pants' body mass and expressed as N.m/kg. Normalization dra-matically improved normality due to the testing of both female and male participants. Following this, peak NJM was found for each plane for L5/S1, hip, knee, and ankle joints. L5/S1 and ankle frontal plane NJM; L5/S1, knee, and ankle transverse plane NJM; and antero-posterior forces are not reported due to low (ie, negligible) values. Vertical and mediolateral forces were reported, and COP was presented in the anterior-poste-rior direction as a function of movement time (displacement vs time). All charts were interpolated to a 0%-100% format (ie, a percent of movement duration). Due to similar kinetic and kin-ematic behavior between loads, only charts for 70% of 1-RM are represented in the paper while charts for 85% of 1-RM can be found in Figures S1 and S2.

2.8 | Statistical analysis

Test-retest reliability for each variable analyzed was as-sessed by intraclass correlation coefficient (ICC) and coefficient of variation (CV) using Hopkins[16] spread-sheet. ICCs were defined as poor (ICC < 0.40), fair ($0.40 \leq$ ICC < 0.60), good ($0.60 \leq$ ICC < 0.75), and ex-cellent ($0.75 \leq$ ICC ≤ 1.00). Normality was ensured using Shapiro-Wilk's test of normality. Potential differences in measured kinematic and kinetic variables between WIDE and NARROW and between loads were analyzed using a paired-sample t test. Because a convenience sample was used and an a priori power analysis was not performed, post-hoc power ($1-\beta$ given moderate or large effect sizes) and sensitivity (effect size needed for 80% power given our final sample size) were calculated using G*Power.[17] Effect sizes

$$([ES = \overline{WIDE} - \overline{NARROW} / \sqrt{SD^2_{WIDE} + SD^2_{NARROW}/2}])$$

were calculated for all variables,[18] allowing interpretation of our data against Hopkins' benchmarks to assign small ($\geq$0.2), moderate ($\geq$0.6), large ($\geq$1.2), very large ($\geq$2.0), and nearly perfect ($\geq$4.0) effects.[19] Alpha was set at $P < 0.05$, and Bonferroni adjustments were made for hip and knee sagittal and frontal plane variables to correct for multiple comparisons.[20] Bonferroni adjustments were made in the following categories to minimize probability for type I error, such that a priori alphas became the following: (a) NJM values ($0.05/5 = 0.01$) and (b) kinematic values ($0.05/5 = 0.01$). A denominator of five was chosen for Bonferroni adjustments because this was the number of tests within a family of tests that could provide support in favor of our hypotheses. Descriptive statistics for L5/SI sagittal NJM, hip transverse NJM, ankle sagittal NJM, hip transverse angle, and ankle dorsiflexion angle are presented in additional information (Table 2). Descriptive data are presented as mean $\pm$ standard deviation (SD).

3 | RESULTS

Out of the 14 participants recruited for this study, 10 participants' data could be used for kinetic and kinematic analyses. Data were disregarded for specific subjects due to varying equipment malfunctions that led to pivotal disruptions in all measured squatting conditions. With the inclusion of 10 participants, an ES of 1.3 would have been needed for 80% power at the Bonferroni-adjusted alpha ($\alpha = 0.01$). Moderate (ES = 0.6) and large (ES = 1.2) ESs would result in statistical powers of 16% and 70%, respectively. Among all repeated measures variables, no statistical differences were found between the female and male participants. Participant data is found in Table 1.

3.1 | Reliability

Descriptive statistics for all mechanical variables are presented in Tables 2 and 3. All variables were normally distributed, as per Shapiro-Wilk tests. For the 2 repetitions averaged for each squat condition, ICC's ranged from fair to excellent for all variables. Specifically, all kinematics and external kinetics ranged

from 0.60 to 0.99 (Fair—Excellent). All reported NJM variables range from 0.90 to 0.99.

3.2 | Kinematics

All kinematic data is found in Table 2 and visualized in Figure 3. In width comparisons, both loading conditions of WIDE reached statistically greater hip abduction ($P < 0.003$, $t(9) <-4.97$, $d > 1.48$), with a difference of $5.8 \pm 2.7°$ at 70% of 1-RM and $5.1 \pm 3.1°$ at 85% of 1-RM, and hip internal rotation angles ($P < 0.001$, $t(9) <-5.50$, $d > 0.92$), with a difference of $4.5 \pm 1.7°$ at 70% of 1-RM and $3.5 \pm 1.1°$ at 85% of 1-RM. Both loading conditions of NARROW reached statistically greater knee flexion ($P < 0.001$, $t(9)>6.56$, $d < -2.56$), with a difference of $9.7 \pm 3.1°$ at 70% of 1-RM and $8.9 \pm 4.1°$ at 85% of 1-RM. Within the same load, only ascent time was statistically different for both widths ($P < 0.007$, $t(9) <-3.62$, $d > 0.20$), with a difference of 0.2 ± 0.1 seconds between NARROW loads and 0.3 ± 0.3 seconds between WIDE loads.

3.3 | Kinetics

All kinetic data is found in Table 3 and visualized in Figure 4. Statistical effects were observed for width comparisons, in that increased hip-to-knee extension NJM ratios were present in both WIDE loading conditions ($P < 0.002$, $t(9) <-4.4$, $d > 1.31$), with a ratio difference of 0.3 ± 0.2 at both 70% and 85% of 1-RM. Knee extension NJMs reached a small ES ($d < -0.44$) in both NARROW loading conditions but only statistically greater in the NARROW 70% of 1-RM condition ($P = 0.003$, $t(9) = 3.96$, $d = -0.47$), with a difference of 0.3 ± 0.2 N.m/kg. Knee adduction NJMs reached small ES ($d > 0.50$) in both WIDE loading conditions but only statistically greater in the WIDE 70% of 1-RM condition ($P = 0.006$, $t(9) = -3.53$, $d = 0.56$), with a difference of 0.3 ± 0.3 N.m/kg. Within the same width, effects of load were present for both WIDE and NARROW for hip extension ($P < 0.002$, $t(9) <-5.11$, $d > 0.40$), with a difference of 0.4 ± 0.2 N.m/kg in NARROW and 0.3 ± 0.2 N.m/kg in WIDE.

4 | DISCUSSION

The main findings were that an increase in stance width by ~50% from greater trochanter width had statistically small to large effects on kinematics and kinetics in the barbell back

TABLE 1 Participant characteristics after BBS width and 1 RM testing

	Body mass (kg)	Width of stance in wide/GT width	Width of stance in narrow/GT width	Wide 1-RM (kg)	Narrow 1-RM (kg)	Relative wide 1 RM (AU)	Relative narrow 1 RM (AU)
Mean	81 ± 22	1.52 ± 0.1	0.99 ± 0.1	108 ± 35	108 ± 32	1.33 ± 0.2	1.33 ± 0.2

1 RMs are normalized to body mass.

GT, greater trochanter; AU, arbitrary units; RM, repetition maximum.

TABLE 2 Kinematics of the wide and narrow barbell back squat at 70% and 85% of 1-RM

	Narrow 70%	Wide 70%	95% CI of the difference		Statistics		Narrow 85%	Wide 85%	95% CI of the difference		Statistics	
			Lower	Upper	P-value	ES			Lower	Upper	P-value	ES
Hip flexion (°)	107.1 ± 5.6	109.1 ± 4.9	−4.70	0.56	0.109	0.38	105.7 ± 6.1	107.7 ± 6.2	−3.98	−0.01	0.049	0.33
Knee flexion (°)	105.8 ± 2.8[a]	96.1 ± 3.9[a]	7.41	12.06	<0.0001	−2.86	104.4 ± 3.1[a]	95.5 ± 3.8	5.82	11.99	<0.0001	−2.57
Hip abduction (°)	18.5 ± 4.1	24.3 ± 3.4[a]	−7.84	−3.70	<0.0001	1.54	18.0 ± 4.3	23.1 ± 2.2[a]	−7.34	−2.72	0.001	1.49
Descent phase (s)	3.22 ± 0.29	3.27 ± 0.44	−0.32	0.21	0.673	0.13	3.36 ± 0.50	3.1 ± 0.48	−0.12	0.22	0.521	−0.53
Ascent phase (s)	1.16 ± 0.20	1.10 ± 0.20	−0.02	0.15	0.157	−0.30	1.36 ± 0.28	1.43 ± 0.37	−0.14	0.01	0.113	0.21

CI, confidence interval; RM, repetition maximum, ES, effect size.
[a]Post-Bonferroni adjustments statistically different between widths.

TABLE 3 NJM results for the wide and narrow barbell squat at 70% and 85% of 1-RM

NJM (N.m/kg)	Narrow 70%	Wide 70%	95% CI of the difference		Statistics		Narrow 85%	Wide 85%	95% CI of the difference		Statistics	
			Lower	Upper	P-value	ES			Lower	Upper	P-value	ES
Hip-to-knee NJM extension ratio	1.48 ± 0.22	1.82 ± 0.26[a]	−0.52	−0.16	<0.0001	1.41	1.57 ± 0.21	1.86 ± 0.23[a]	−0.42	−0.15	0.001	1.32
Hip sagittal (ext)	3.73 ± 0.68	4.06 ± 0.71	−0.65	−0.01	0.047	0.47	4.08 ± 0.65	4.36 ± 0.74	−0.51	−0.04	0.024	0.40
Hip frontal (abd)	1.51 ± 0.74	1.67 ± 1.0	−0.55	0.23	0.382	0.18	1.59 ± 0.76	1.75 ± 1.04	−0.57	0.25	0.408	0.18
Knee sagittal (ext)	2.57 ± 0.57[a]	2.29 ± 0.61	0.12	0.44	0.003	−0.47	2.66 ± 0.62	2.39 ± 0.59	0.08	0.45	0.01	−0.45
Knee frontal (add)	1.34 ± 0.57	1.65 ± 0.54[a]	−0.49	−0.10	0.006	0.56	1.46 ± 0.60	1.77 ± 0.62	−0.53	−0.09	0.011	0.51

N.m/kg, moments relative to body mass; CI, confidence interval; RM, repetition maximum; ES, effect size.
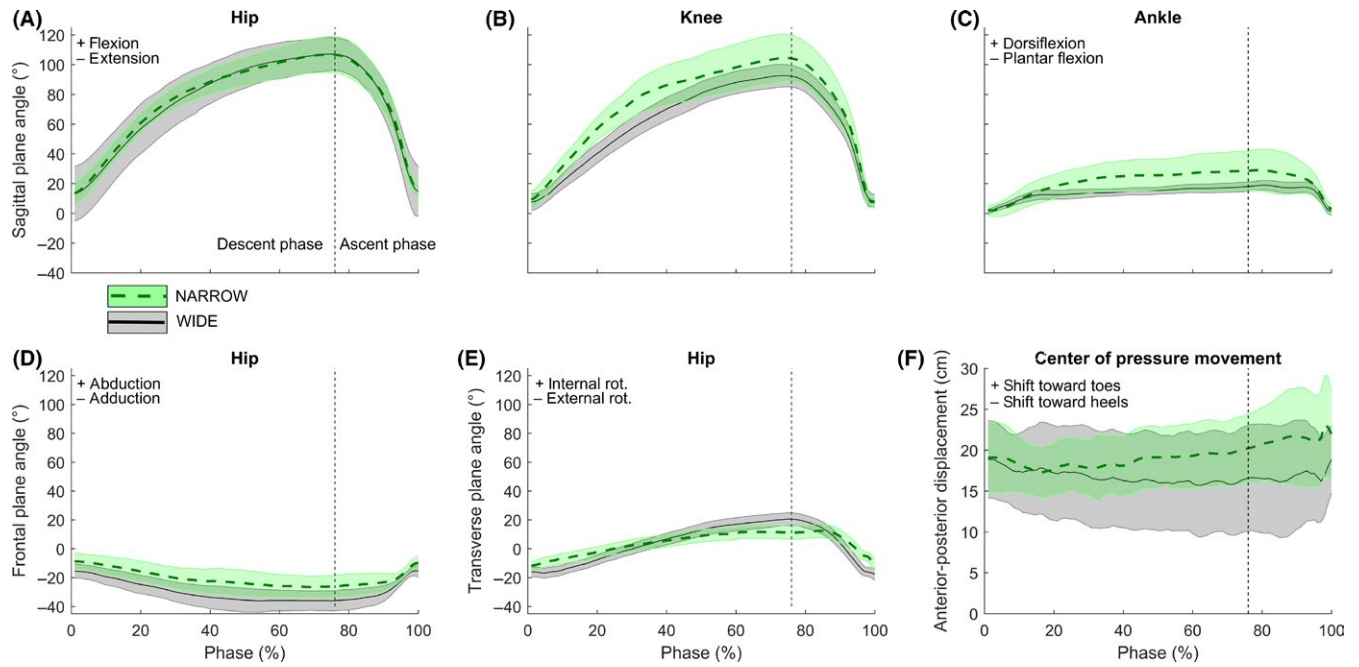[a]Post-Bonferroni adjustments statistically different between widths.

FIGURE 3 Kinematic interactions for the WIDE (black line average, grey ribbon for SD) and the NARROW (dashed green line average, green ribbon for SD) in the descent and ascent phase represented by the A, hip flexion, B, knee flexion, C, ankle dorsiflexion, D, hip add/abduction, E, hip rotation, and F, anterior-posterior displacement on the force plate. All interactions are the group average of the 70% of 1 RM squat. Dotted vertical line indicates start of ascent phase
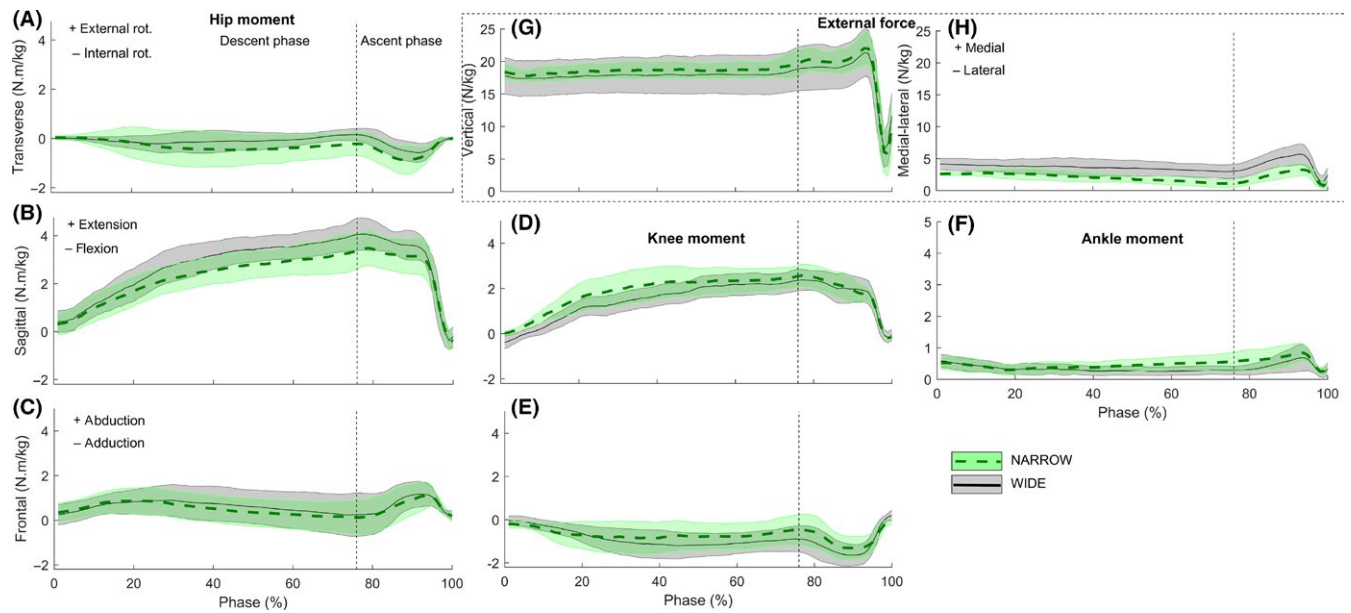

FIGURE 4 NJM and GRF interactions for the WIDE (black line average, grey ribbon for SD) and the NARROW (dashed green line average, green ribbon for SD) in the descent and ascent phase represented by the A, hip transverse plane, B, hip sagittal plane, C, hip frontal plane, D, knee sagittal plane, E, knee frontal plane, F, ankle sagittal plane, G, vertical force, and H, mediolateral force. All interactions are the group average of the 70% of 1 RM squat. Dotted vertical line indicates start of ascent phase

squat at femur parallel depth. Specifically, these effects were present both in the sagittal plane and in the frontal plane, which may have clinically relevant implications for athletic populations that utilize the barbell back squat during their training. These findings are discussed in detail from both a sagittal plane perspective and a frontal plane perspective.

4.1 | Net joint moments

The interpretation of hip-to-knee extension NJM ratio results can be completed more thoroughly with the consideration of other biomechanical planes where NJMs were quantified. In the case of interpreting the hip-to-knee extension NJM ratio in squatting mechanics, premature conclusions can easily be made due to the fact that NJM values do not take into consideration co-contraction at the knee, which can be attributed to the relationships between the hamstrings and quadriceps.[21] The effect of co-contraction between the WIDE and NARROW barbell back squat positions at parallel depth is still slightly unclear. To our knowledge, no modeling studies have been performed on the topic, and all but McGaw & Melrose[22] of the previous studies comparing barbell back squat widths while utilizing electromyography (EMG) has not standardized depth further than informing the participant to go "as deep as possible",[23,24] a variable that can arguably vary significantly within athletic populations.[25] The potential negative effects of co-contraction on movement velocity during the ascent phase do not appear to be significant, based on the similar times of ascent phase performance (Table 2). This notion is in line with Swinton et al,[6] who showed no statistical differences in system kinetics between NARROW and WIDE. However, these are presented as group effects and co-contractions at one joint can possibly be compensated for at other adjacent joints by placing agonists and/or synergistic musculature in a more optimal position in terms of force-length relationships. A similar quadriceps EMG amplitude found in previous studies comparing NARROW and WIDE barbell back squat positions[22-24] can possibly also be associated with a more medially directed resultant force vector, potentially increasing the sagittal plane moment arm at the knee. In addition to the limitations surrounding NJM analysis, differences in quadriceps utilization between squatting widths should not be inferred solely based on EMG results.[26] Based on anecdotal evidence, squatting in substantially wider position (ie, at or above ~1.5× greater trochanter width) can hinder depth and knee flexion. Greater knee flexion angles have been suggested to be a larger determinant of quadriceps utilization than external load when observing angle-specific relative muscular efforts in the squat.[21,27] This implies that a narrower squatting width (ie, between hip and shoulder width) under maximal range of motion conditions should, in general, stimulate the quadriceps more than a substantially wider position.

In addition to the sagittal plane, frontal plane analyses at the hip and knee helped determine possible resultant joint moment contributions. An effect size above 0.50 for greater knee frontal plane NJM (knee adduction NJM or varus moment) was found in WIDE at both loads, peaking in the ascent phase (Figure 4). The increased knee adduction NJM in WIDE should, in theory, impact mostly the abduction moment requisites at the hip joint. This may be associated with the increased gluteus maximus EMG amplitude found in the wide squat in previous studies comparing squatting widths.[22,24] Therefore, in WIDE, the hip-to-knee extension NJM ratio measured in the sagittal plane might provide a realistic idea of the NJM relationship between the hip and knee, since the decreased knee extension NJM is, to some extent, "cancelled out" by in the increased knee adduction NJM. This idea is consistent with Winter's support moment theory as it applies to gait.[28] Thus, such knowledge of differences in hip-to-knee NJM extension ratios between squatting widths at femur parallel depth may provide practitioners with a biomechanical rationale for exercise implementation when looking to stimulate the hip and knee extensors.

In terms of role of load in the hip-to-knee extension NJM, multiple studies have shown that hip dominance increases with load in the squat[27,29,30] (stance was around shoulder width), although contradictory evidence also exists.[31] These contradictory results may be explained by both anecdotal observations and research, in that it is common to observe shifts in kinematics in the ascent phase when loads approach the proximity of 1-RM or are taken to failure. Particularly, increased trunk lean and hip flexion in relation to knee flexion has been shown to take place in different squat fatigue studies.[30,32,33] Such kinematics may decrease the external moment arm at the knee, while increasing it at the hip, leading to changes in NJMs. Our results complement this theory, as we did not observe statistical shifts in kinematics with increased load. This may be due to utilization of strict technical 1-RM, where no clear shifts in kinematics were allowed. Therefore, the observations made in this study carry potentially more validity in specific movement pattern research, rather than those that prioritize external load.

4.2 | Frontal plane stimulus

The statistically greater knee adduction NJM demands in the WIDE are likely related to how the resultant GRF vector behaves in the barbell back squat, particularly in the ascent phase. From Figure 3, it can be observed that the mediolateral GRF (in this case, directed medially) is utilized substantially in both widths, but more-so in the wider position. This is logical, as the resultant GRF aims toward center of mass. To give the reader a better visualization of the resultant GRF vectors medial movement, we decided to use direction cosines to calculate the angle of the GRF vector in the frontal plane, relative to the horizontal axis, during the ascent phase. Calculations showed a mean angle of 75° in the WIDE and 80° in the NARROW, contributing to the statistically greater medially directed GRF in the WIDE position. Although the

vertical GRF component was on average 4-5 times higher compared to the medially directed GRF in both widths (medial/vertical force ratio in WIDE: 0.26:1 [CI_{90} = 0.19-0.33] vs NARROW: 0.16:1 [CI_{90} = 0.12-0.21], with no effect between loads), this suggests that the barbell back squat, under such conditions, should not be considered a strictly vertical GRF/sagittal plane stimulus for the athlete.

Practitioners might connect the increased medially directed GRF demand to be a beneficial stimulus for the hip musculature to increase general preparedness in sports with a combination of high mediolateral and horizontal GRF demands, such as sports involving change in direction.[34] The medially directed resultant GRF vector may in part be responsible for co-contractions around the hip in both barbell back squat conditions, specifically, adductor/abductor co-contraction. In a recent study by Nagahara et al,[35] increased medial impulse in sprint acceleration was associated with improved sprint performance in intermediate level sprinters. Based on these results, the authors of Nagahara et al[35] concluded that the adductors should also play an important role in generating greater propulsive performance. A wider squat position has been found to statistically increase the EMG amplitude of the adductor longus muscle.[22] Although McGaw & Melrose[22] results may imply potential for improved adductor stimulation in a wider squat position, Paoli et al[24] squat width comparison showed no difference in adductor magnus EMG amplitude, arguably the most influential adductor muscle in propulsive performance. Therefore, more comprehensive studies on the role of the adductor muscles at different squatting widths are needed for stronger conclusions.

Most sports that involve ballistic movement require lower-body strength in all planes of motion. However, the barbell back squat only provides substantial stimulus in the vertical direction and, to a limited extent, the mediolateral direction. Thus, it could be argued that the appropriate ratio between the two should be studied for understanding the potential for different practical outcomes. Because the NARROW position also provided a small stimulus in the medial direction, it can be argued that this might be sufficient enough for transfer in certain sports. This notion is to some extent supported by McCurdy et al[11] results, where strength levels in the barbell back squat, measured in this case in a hip-to-shoulder width position, were strongly correlated ($r = 0.88$) with frontal plane landing control in both bilateral and unilateral conditions, albeit only utilizing a population of female athletes. Unfortunately, strength levels in a wider position were not compared. Training studies are needed to explore this hypothesis.

To the authors' knowledge, no studies have compared the relationship between vertical and mediolateral GRF ratios between athletic tasks and commonly utilized multijoint strength training exercises or the potentially different long-term implications of them. There is, however, distinctive evidence that sagittal plane manipulation of the barbell back squat in the form of depth variation presents both significant differences in biomechanical parameters[36] and in long-term performance outcomes.[3,4] Therefore, based on the discussed frontal plane differences, it might be conceivable that the degree of transfer for propulsive performance can be manipulated in certain cases if different widths in the barbell back squat are utilized, but training studies are needed to confirm.

From an injury prevention standpoint, controlling frontal plane movement at the knee can be of high value and seems to be related to strength levels of adjacent joints, one of which being the hip. Specifically, decreased knee adduction NJM in athletic tasks, such as drop jump landings, has been associated with increased peak valgus angles in female athletes.[37] In terms of what excessive valgus might depend on, Tate et al[38] have demonstrated that, in post-anterior cruciate ligament reconstruction athletes, decreased frontal plane stability in single leg landings was moderately correlated with lower hip extensor strength (measured isometrically). The role of the hip musculature is complex in nature due to multiple muscles influencing movement in multiple planes. Some muscles might be more appropriate for stability (ie, resisting perturbations), others may play a greater role in dynamic movement, and some may provide both. In a side-stepping study, increased effort in the task showed an increase in hip extension NJM demands, but not hip abduction demands.[39] This led the authors to conclude that hip abduction strength might be more important for stability in frontal plane movement, while strengthening the extensor group would yield greater performance gains. Therefore, functional and time-efficient strengthening of the lower-body might mean finding exercises that highly stimulate simultaneously both dynamic and stability demands of the hip in different biomechanical planes. Based on our results and previously published observational research,[11] strength gains from barbell back squatting in certain conditions may provide such stimuli, especially in a wider position.

It is important to consider the stimulus of adjacent joints; therefore, we plotted ankle dorsiflexion kinematics and kinetics in Figures 3 and 4, and descriptive statistics are provided as additional information for the ankle, in addition to L5/S1 NJM. In a NARROW squat, plantar flexor relative muscular effort is high and peaks toward the end of the ascent.[27] These kinetic changes correspond with COP movement shifting toward the forefoot, albeit more so in NARROW (Figure 3). Swinton et al[6] results demonstrated that a narrower squat position produced significantly higher ankle NJM than wider position, while our results did not significantly differ but demonstrated small to moderate effects in favor of the NARROW position (additional information, Table 2). Therefore, in terms of ankle NJM, long-term implications may differ.

4.3 | Perspectives

The biomechanical differences between the WIDE and the NARROW barbell back squat conditions to femur parallel depth present new questions for future research. Specifically, based on prior results and our present findings, we suggest further exploration on whether the barbell back squat can provide a clinically relevant stimulus outside of the sagittal plane when widening the stance, while simultaneously increasing the hip-to knee extension NJM ratio. This could be valuable information for lower extremity injury prevention and possibly has certain ergogenic effects, for tasks such as change in direction and linear acceleration. Long-term programs comparing adaptations between NARROW and WIDE with strict technical demands are needed to confirm the existence of differential training outcomes.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.