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Biomechanical Differences Between the Bulgarian Split-Squat and Back Squat

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ABSTRACT

International Journal of Exercise Science 14(1): 533-543, 2021. The Bulgarian split squat (BSS) is a unilateral lower extremity strength exercise; however, the mechanical demands have not been fully elucidated. The purpose of this study was to compare ankle, knee, and hip joint net joint moment impulse (NJMI), work (NJW), peak net joint moment (NJM) and peak displacement between the BSS and traditional bilateral back squat (BS). Following a practice and 1-repetition maximum (1-RM) session, 2x3 BS (70% 1-RM) and BSS (35% 1-RM) were completed by twenty resistance trained males (24.20 ± 2.50 yrs, 1.76 ± 0.06m, 85.3 ± 13.90 kg). Significant squat type x joint interactions were revealed for NJMI ($p < 0.001$), NJW ($p < 0.001$), peak NJM ($p < 0.001$), and peak displacement ($p = 0.011$). For both squats, hip NJMI, NJW, and peak NJM was significantly greater than both ankle ($d = 5.50$-9.40) and knee ($d = 7.50$-8.50). While knee NJMI ($d = 2.80$) and peak NJM ($d = 2.10$) during the BSS was statistically less compared to ankle, during BS knee NJMI was statistically greater than ankle ($d = 3.00$). Ankle and knee NJW were statistically similar during BSS ($d = 0.30$), whereas knee NJW was statistically greater than ankle during BS ($d = 3.20$). Comparing between squat types within each joint demonstrated statistically equal peak displacement for the ankle ($d = 0.14$) and hip ($d = 0.11$), whereas knee joint peak displacement was significantly less for the BSS compared to BS ($d = 0.82$). Both the BSS and BS are hip dominant exercises. The BSS may best be used in circumstances to focus on hip extension while minimizing the knee joint demands, such as the early phases of knee rehabilitation or when addressing isolated hip extension deficiencies.

KEY WORDS: Unilateral, bilateral, kinetics, kinematics, impulse, work

INTRODUCTION

Specificity of movement patterns with regards to the biomechanical demands of athletic movement patterns (14) are often heavily considered in designing strength and conditioning and rehabilitation exercise programs. Many athletic skills rely on fundamental lower-body movements that are performed in a unilateral fashion or contain transient periods of unilateral stance (e.g. sprinting, jumping and change of direction) (21). In comparison to bilateral exercises like the back squat (BS), unilateral weight-bearing exercises may be considered more specific to these types of athletic movements (13). Additionally, performing unilateral squatting exercise may help prevent between-leg strength discrepancies (9, 13).

Improvements in strength through the use of traditional bilateral BS have been well established (5, 13, 16). For this reason, it is often used as standard reference in interventional and biomechanical comparison studies (1, 9, 18). The Bulgarian split-squat (BSS) is a unilateral lower extremity strength exercise similar to a split-squat, but performed by supporting the foot of the non-stance limb on an elevated, stable structure placed behind the body that is utilized for both performance enhancement and rehabilitation from injury (16). While electromyographic (EMG) analyses have been conducted on the BSS, there is yet to be a study that elucidates the kinetics and kinematics at the joint level (5). Research has demonstrated that the BSS promotes greater recruitment of the gluteus maximus than the BS, suggesting the BSS is potentially a more hip dominant exercise (17). Additionally, the BSS has been shown to have higher EMG activity for the hamstrings relative to the quadriceps muscles compared to the BS, indicating a high hamstrings to quadriceps ratio (5, 13).

While it is important to know the muscles being activated during an exercise, it is also important to assess differences in the joint kinetics and kinematics to better understand the results of the underlying muscle activations at the joint level. Knowing the underlying kinetic and kinematics characteristics that occur at lower body joints, would provide practitioners with the necessary information to assist with matching client needs with the demands imposed by an exercise. For example, the kinetic variables impulse and work provide insight regarding net torque production over time and torque production through the range of motion, respectively. From a kinematic perspective, peak displacement reflects the range of motion used at each joint during the exercise. Given the high incidence of knee related pathologies, quantifying the knee joint biomechanical demands of the BSS would help clinicians select the BSS at the appropriate times in a rehabilitation program. Therefore, the purpose of this study was to compare ankle, knee, and hip joint kinetics and kinematics between the BSS and the BS. Specifically, this study compared net joint moment impulse (NJMI), net joint work (NJW), peak net joint moment (NJM) and peak displacement during BSS and BS at the ankle, knee, and hip joints. Based on the findings in previous EMG research (5, 13, 16), it was hypothesized that the NJMI, NJW, peak NJM, and peak displacement would be lower during the BSS than the BS, particularly at the knee joint.

METHODS

Participants

Twenty males (Table 1) with > 6 months lower extremity resistance training completed two days of study participation (minimum 48-h separation). Subjects with a lower body musculoskeletal injury within the last six months prior to the study were ineligible. All subjects that volunteered to participate were screened to determine their training experience using a comprehensive health and medical history questionnaire. Although the subjects were required to have previous lower extremity resistance training experience, they were not required to have experience with the BSS. Volunteers were given a verbal and written description of the study procedures, the opportunity to ask questions and the option to decline to participate. The study has been approved by the local Institutional Review Board (IRB), with all the subjects signing IRB approved written informed consent forms to ensure the subjects were knowledgeable of the risk and procedures associated with the study.

Table 1. Subject characteristics (n = 20).

Descriptive	Mean ± SD
Age (yrs)	24.2 ± 2.5
Height (m)	1.76 ± .06
Body mass (kg)	85.3 ± 13.9
1-Rep max (kg)*	149 ± 37.8
Resistance training experience (y)	5.9 ± 2.8

Note: Participants back squat one-repetition maximum established on visit 1.

Protocol

A counterbalanced, within-subject design was used to test the main hypothesis that the NJMI, NJW and peak displacement would be lower at the knee joint during the BSS than the BS. Each subject established their one-repetition maximum (1-RM) back squat on their first visit. After 48 hours of recovery, during a second visit, ankle, knee, and hip kinetics and kinematics were recorded during completion of the BS and BSS (between subjects randomized order) using 70% and 35%, respectively, of their 1-RM weight that was established on their first visit.

Testing sessions were separated by a minimum of 48 hours. On the first visit, two measurements of the subjects were taken to standardize the height of the box for the elevated (rear) leg and distance of the lead toe from the box during the BSS. The standardized height for the box for the rear leg was measured as the height of the base of the patella to the ground (14-16). The rear foot was placed in a fixed position on the box that was prevented from moving posteriorly by a piece of wood fastened to the box. The standardized distance of the lead toe from the box was established by measuring the distance of the front foot from the box when the subject squatted to parallel and their patella was directly over the lead toe, which was visually assessed. (14-16). BSS technique involved the dominant leg placed anterior and in-line with hip joint while the rear leg was elevated patella height. The dominant leg was operationally defined as the preferred limb for kicking a ball (20). During the back squat, participants were told to maintain the bar on the spines of their scapulae.

On the first visit, after the measurements and prior to 1-RM testing, all subjects warmed up on a cycle ergometer for 5 minutes at a self-selected pace and completed a standardized dynamic warm-up. After the warm-up, subjects were familiarized with the BSS technique using a standard Olympic barbell. The BSS was practiced initially with just the subject bodyweight, before progressing to a barbell. During the BSS and BS, all subjects practiced technique with the barbell until they could comfortably squat to a depth of 90 degrees knee flexion at a self-selected pace for 5 repetitions while maintaining proper technique. All technique was verified by a certified strength and conditioning specialist. After the practice for the BSS, a 1-RM for the BS was conducted to determine the weights used for the data collection session. The 1-RM protocol was done in accordance to the procedures set by the National Strength and Conditioning Association (11). For 1-RM testing, power rack safety rails were utilized, and a spotter was present.

The second visit began with a replication of the warm-up and dynamic stretching that had been completed during the first visit. Subjects then completed 6 sets of warm-ups of the bilateral BS. The warm-up sets included six repetitions at 30% and 40% of the 1-RM, three reps at 50%, 60% and 70% of the 1-RM with exactly a two minute rest period in between each set (5). Subsequent to the BS warm-up, subjects warmed up for the BSS on both legs initially with just the subjects' bodyweight, before progressing to an unloaded barbell, then to a barbell with the 35% of the subjects 1-RM for three repetitions. For all warm-up lifts, the participant removed the weighted barbell from a rack in the high bar position on the upper back. After the warm-up BS and BSS sets, subjects were then outfitted with electromagnetic sensors on their sacrum, thigh, shank, and foot on their self-reported dominant leg.

The order of the lifts for data collection was randomized. Subjects completed two sets of three repetitions for the first randomized exercise before moving onto the subsequent exercise. The BS was completed using 70% of the 1-RM, while 35% of the 1-RM was used for the BSS. The BSS was performed with half the load of the BS because subjects had less experience with the BSS and a 1-RM test for the BSS was unfeasible. Subjects were reminded to descend to a depth of approximately 90-degree knee flexion. The depth of the squats was qualitatively monitored by visual observation and when perceived deviations occurred feedback was provided to the participants. A five-minute recovery time was given between each set of exercises.

An extended-range, 9-sensor electromagnetic tracking system (MotionStar, Ascension Technology Corporation, Inc, Burlington, VT) with all the hardware settings in the default mode collected 3-dimensional kinematic data (100 Hz) using the MotionMonitor software acquisition software package (Innovative Sports Training, Inc, Chicago, IL). After the familiarization sets, sensors were attached to the sacrum, thigh, shank, and foot of the subjects' self-reported dominant limb using pre-wrap and double-sided tape. During the setup, the ankle- and knee-joint centers were calculated by locating midpoints between contralateral points at each respective joint with an electromagnetic sensor attached to a customized calibrated stylus. The hip-joint center was established using a series of 8 points along a circumduction cycle for each hip to approximate the apex of femoral motion (12). The participants' height and mass were also recorded for anthropometric calculations required for locating each segment's center of mass (23).

The 3-dimensional ankle, knee, and hip joint angles and net joint moments and the segment center-of-mass 3-dimensional position data (feet, shanks, thighs, pelvis) were calculated using the MotionMonitor software and exported as text files. Further data reduction procedures were conducted using Matlab-based scripts (The Mathworks, Inc, Natick, MA).

The instantaneous total body center of mass (TBCM) position was determined for each trial using the segment center of mass and anthropometric data. The beginning and end of a trial were operationally defined as occurring when the vertical TBCM velocity exceeded $-0.02\ m \cdot s^{-1}$ and $0.02\ m \cdot s^{-1}$, respectively. For both the ankle and hip kinetics, the polarity was reversed so that angular extension and net joint extensor moments would be positive, thereby matching the knee joint. Four dependent variables at each joint (ankle, knee, hip) from the kinetic and kinematics data were determined: NJMI, NJW, peak NJM, and peak displacement. Net joint flexor-extensor moments were normalized to body mass, with impulses calculated as the integrated magnitude of the net-joint moment curve. To calculate eccentric and concentric work, net joint power was first calculated as the product of angular velocity (radians) and the net joint moment (normalized to body mass). Eccentric and concentric work was then calculated as the integrated magnitude of the absolute net joint power curve. Peak displacement angles were expressed relative to each participants' standing calibration position. Based upon their potentially confounding effects on NJMI and NJW, two performance summary descriptors, repetition time and squat depth were computed. Repetition time was computed as the length of time between the beginning and end of a repetition and squat depth was computed as the difference in vertical position of the TBCM at the beginning of a trial to the peak inferior displacement occurring during a trial.

Statistical Analysis

The average of three trials for the BSS and BS for each dependent variable, NJMI, NJW, peak NJM, peak displacement, repetition time, and squat depth was calculated and used for statistical analyses. The α level for all statistical analyses was set at 0.05. Separate two-factor repeated-measures analysis of variance (condition squat type by joint) were used for statistical comparison of the NJMI, NJW, peak NJM and peak displacement. Simple main effect post hoc comparisons with Bonferroni adjustments were used when significant interactions were identified. Additionally, standardized *d*-family effect sizes were computed for all post hoc comparisons. Paired sample t tests were conducted on repetition time, and squat depth.

RESULTS

Significant squat type by joint interactions were revealed for both NJMI ($p < 0.001$, $\eta^2_p = 0.78$), NJW ($p < 0.001$, $\eta^2_p = 0.61$), and peak NJM ($p < 0.001$, $\eta^2_p = 0.80$). For both squats, hip NJMI (Figure 1), NJM (Figure 2) and peak NJM (Figure 3) was significantly greater than both ankle (d = 5.50-9.40) and knee (d = 2.30-8.50). While knee NJMI ($p < 0.001$, $d = 2.80$) and peak NJM ($p < 0.001$, $d = 2.10$) during the BSS was statistically less compared to ankle, during BS knee NJMI was statistically greater than ankle ($p < 0.001$, $d = 3.00$). Ankle and knee NJW were statistically similar during BSS ($d = 0.30$), whereas knee work was statistically greater than ankle during BS ($d = 3.20$).

Comparing between squat types within each joint demonstrated similar results for NJMI, NJW and peak NJM. The ankle joint had significantly greater NJMI ($p < 0.001$, $d = 2.50$), NJW ($p < 0.001$, $d = 2.10$), and peak NJM ($p < 0.001$, $d = 1.80$) during the BSS, whereas the knee ($p < 0.001$, 2.80-3.50) and hip ($p < 0.001$, d = 1.70-2.00) joints had significantly greater NJMI, NJW and peak NJM during the BS.

During the BSS, ankle displacement was significantly less than knee ($p < 0.001$, $d = 5.60$), which in turn was significantly less than hip ($p = 0.004$, $d = 0.62$). In contrast, during BS, hip and knee displacement was statistically identical ($p = 1.0$, $d = 0.01$), with the ankle being significantly less than both ($p < 0.001$, d = 7.30-7.50) (Figure 4).

Comparing between squat types within each joint demonstrated statistically equal peak displacement for the ankle ($p = 0.151$, $d = 0.14$) and hip ($p = 0.640$, $d = 0.11$), whereas knee joint peak displacement was significantly less for the BSS compared to BS ($p < 0.001$, $d = 0.82$). While repetition time was statistically similar ($p = 0.545$, $d = 0.17$) between the BSS (2.39 ± 0.32) and BS (2.44 ± 0.24s), the squat depth for the BS (0.264 ± .042m) was significantly greater ($p = 0.007$, $d = 0.91$) than the BSS (0.299 ± .035).

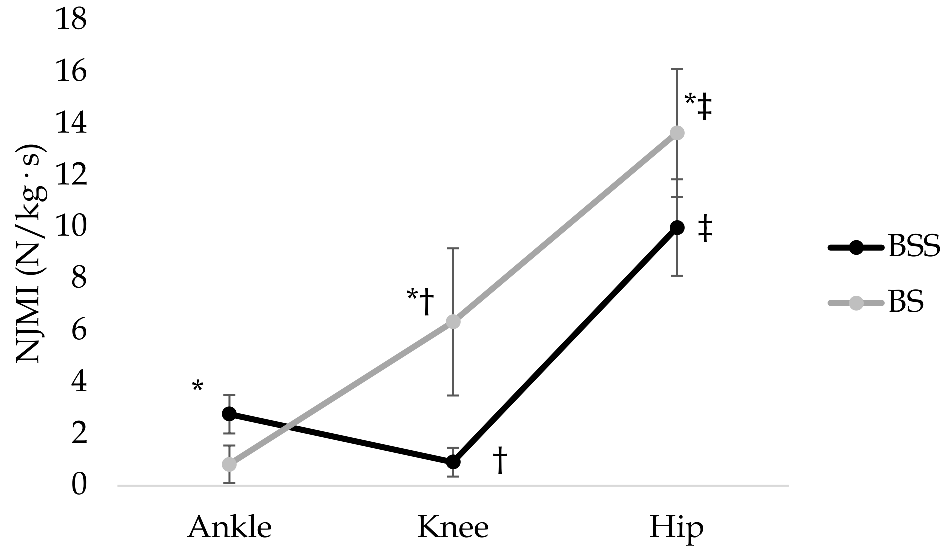

Figure 1. Net joint moment impulse during the back squat (gray line) and Bulgarian split squat (black line). Error bars represent one standard deviation. * significant difference between squats within joint; † significant difference between ankle and knee within squat; ‡ significant difference between hip and ankle/knee within squat type.

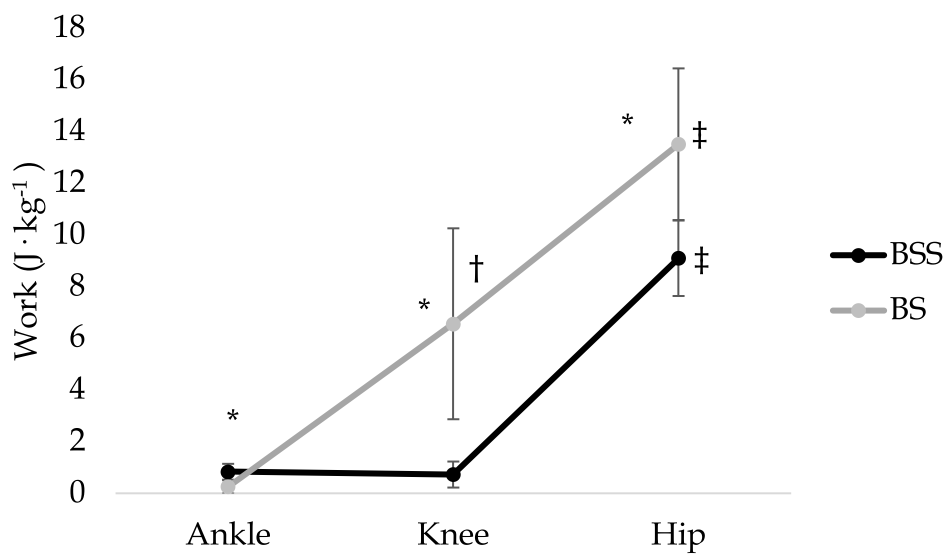

Figure 2. Net joint work during the back squat (gray line) and Bulgarian split squat (black line). Error bars represent one standard deviation. * significant difference between squats within joint; † significant difference between ankle and knee within squat; ‡ significant difference between hip and ankle/knee within squat type

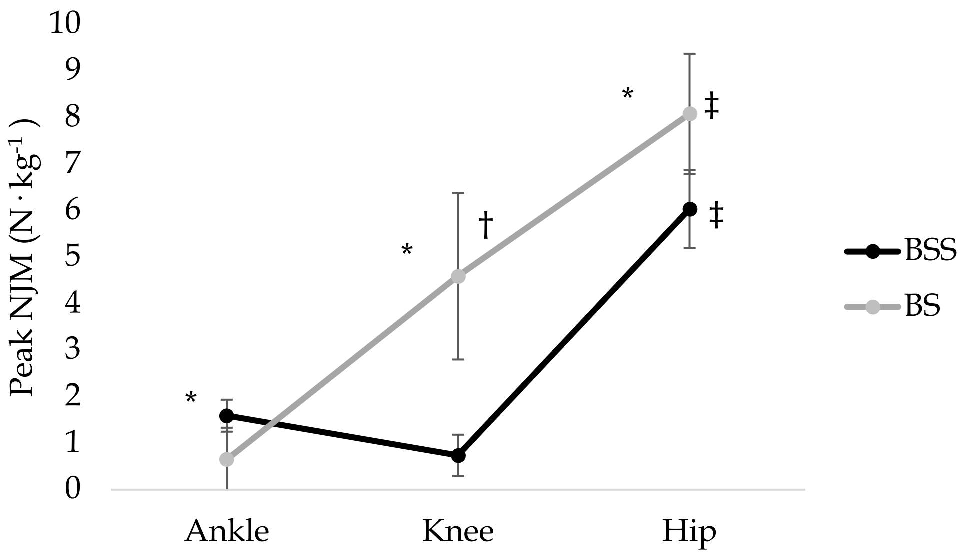

Figure 3. Peak net joint moments during the back squat (gray line) and Bulgarian split squat (black line). Error bars represent one standard deviation. * significant difference between squats within joint; † significant difference between ankle and knee within squat; ‡ significant difference between hip and ankle/knee within squat type

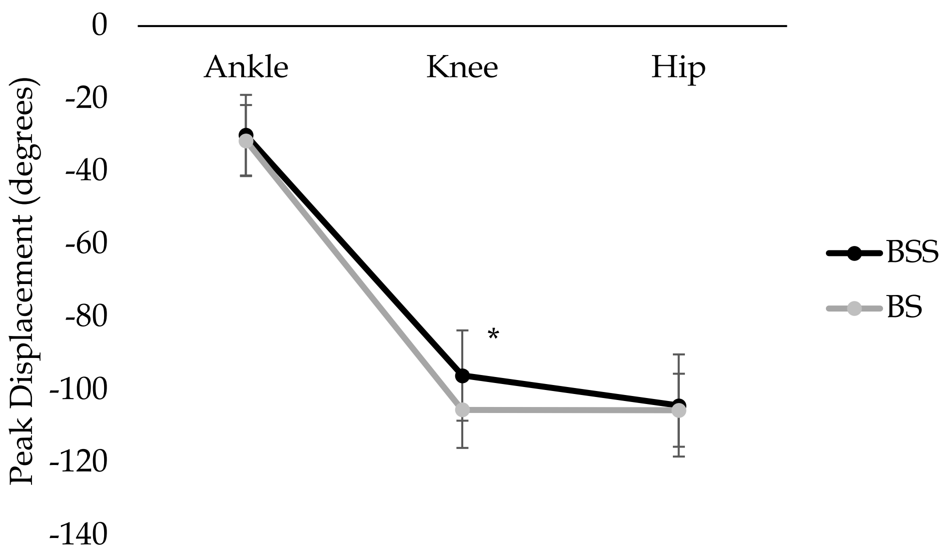

Figure 4. Peak displacement during the back squat (gray line) and Bulgarian split squat (black line). Error bars represent one standard deviation. * significant difference between squats within joint

DISCUSSION

The primary purpose of this study was to determine the ankle, knee, and hip kinetic and kinematic differences between the BSS and BS. While the results demonstrate that similar to the BS, the BSS is a hip dominant exercise, the knee kinetics and a peak displacement were different between the two exercises. Whereas the knee was secondarily involved with the BS, during the BSS the knee was much less involved, to the extent that both NJMI and peak NJM were significantly greater for the ankle compared to the knee. While ankle and hip joint range of motion were near identical for the two exercises, the peak displacement for the knee was less during the BSS. Collectively, these results suggest that the BSS may be a better exercise selection in circumstances when the goal is to focus on hip extension, particularly unilaterally, while minimizing the knee joint demands, such as the early phases of knee rehabilitation or when addressing isolated hip extension deficiencies.

NJMI represents the sustained NJM across time, while NJW indicates the sustained NJM through a range of motion. Based on the confounding influence repetition time and squat depth could exert on the NJMI and NJW outcome measures, a secondary purpose was to compare these two summary performance measures. In contrast to precisely controlling the pace and depth of each repetition through utilization of a metronome or real-time feedback from the electromagnetic system, we sought to have participants perform each exercise as they would under typical strength and conditioning environments, which often incorporates visual qualitative monitoring by a strength and conditioning coach. While participants self-selected to perform both squat exercises at the same pace, they demonstrated slightly, but statistically significant, greater squat depth during the BS (average difference was ~0.035m). Based on the joint peak displacement results, the difference in squat depth can be attributed solely to significantly less knee flexion during the BSS (average differences was ~9.2°).

Thus, while the NJMI results are not confounded by differences in repetition time, potentially explaining the knee joint NJW difference between the squat exercises could be the knee joint peak displacement differences identified. Despite the potential to explain the knee NJW differences, we do not think the difference in knee joint peak displacement can completely account for the differences identified for several reasons. First, the effect size comparing knee joint NJW between the squat exercises was more than three times as large as the effect size comparing peak knee joint displacement. Secondly, the pattern of significant differences yielded for the peak NJM exactly paralleled NJW with comparable effect sizes. Previous investigations considering the effects of squat depth on peak knee NJM demonstrated that squat depth had a significant effect on peak knee NJM; however, in one investigation (24) significant effects were not realized until maximum depth (deep squats) was attained, while in a subsequent investigation (2), there were no significant changes knee extensor relative muscle effort (computed from NJM) until knee flexion angles reached a depth range between 105° to 119°. Given that our average knee flexion angles were 96° and 105° for the BSS and BS, respectively, coupled with the magnitude of the knee joint kinetics effect sizes between squats, the differences in peak knee flexion cannot completely account for the knee peak NJM and NJW results. Finally, studies examining muscle activation during BS of varying depths have failed to demonstrate significant differences in either the hamstring or quadriceps muscle groups between BS varying from parallel to full squat depths (3, 4).

Consistent with previous joint kinetic research (10, 24), our NJMI, NJW and peak NJM results confirm the BS to be a hip dominant exercise, followed by the knee, and then the ankle. Our NJMI, NJW and peak NJM results support the notion that BSS is also a hip dominant exercise; however, in contrast to the BS, for the BSS the ankle contributed secondarily followed by the knee. These results parallel previous research examining joint kinetic during lunges and split squats. Riemann et al investigated the NJMI and NJW occurring at ankle, knee and hip joints while performing the traditional lunge under different loads (20) and step lengths (19) and reported a similar order for the NJMI and NJW as the BSS. Schütz et al also reported higher hip moments than knee moments during split squats, with the peak knee and hip NJM becoming greater with more ankle flexion and a longer step length.

Our joint kinetic results support the conclusions of the previous EMG research examining the BSS. EMG studies comparing the BSS and BS also discovered that muscles acting on the hip contributed greater than muscles acting at the knee during the BSS. However, studies did not investigate EMG activity occurring at the ankle joint (5, 13, 16). Mausehund et al. 2018 reported that EMG activity during the BSS was greater in the hamstrings than the quadriceps compared to the split squat and single leg step up. Based on high hamstring coactivation, they concluded that it would be wise to implement the BSS during the early phases of anterior cruciate ligament (ACL) reconstruction, opposed to the other single leg exercises. Other studies examining the EMG of the unilateral and bilateral lower body exercises concluded that the higher hamstring to quadriceps activity of the unilateral exercises represented an increase in hip joint contributions with a concurrent decrease in knee joint involvement (5, 16). Based on these findings, they concluded that the knee joint demands were less for single leg exercises compared to their bilateral counterparts (5, 16).

For the purposes of this study, we asked that subjects had 6 months of current lower body strength training experience. This was defined as a minimum of 1 time per week lower body strength training throughout the previous 6 months. Although subjects had experience with lower-body strength training, including experience with the BS, they did not necessarily have experience with the BSS, thus necessitating the familiarization session following establishment of the BS 1-RM. It is plausible that being less experienced with the BSS compared to the BS could have influenced the kinematic and kinetic measures; however, it is worthwhile to note that repetition time was similar between the two squats suggesting participants completed the BSS at the same pace as the BS. Additionally, based on the previous reports of gender differences in squatting mechanics (6, 22), we only included male participants. Because of the effects of the iron contained in the barbell on electromagnetic fields, we were unable to track trunk position. Trunk position has been demonstrated to influence lower extremity joint kinetic during forward lunges (8). Although we encouraged the trunk to remain upright during both exercises, it is likely that trunk position could have been subtly difference between the two squats, thereby influencing the lower extremity joint kinetics. While we encouraged subjects to perform a "high bar" back squat we ultimately did not standardize the position of the barbell on the participants back which could have influenced trunk position.

Future research examining the BSS should directly measure trunk position. Additionally, the load that was used for during data collection for both squats was based off the participants' BS 1-RM. We chose 70% of the 1-RM for three repetitions based on these studies and relative estimates of training load (11). During data collection, we used half the weight for the BSS as used for the BS based on previous research (5, 11). Because it was likely that the participants were less trained on the BSS, and unilateral lower-body strength training in general, conducting 1-RM testing for the BSS would have increased the risk of injury for the participants, as well as challenge the validity of the BSS 1-RM attained. Furthermore, our study involved a comparison between the traditional bilateral BS and single leg BSS. Future research should consider a direct joint kinetic comparison between the BSS and other single leg style squats, such as single leg squats and split squats. Finally, it is important to note that we only assessed joint kinematics and kinetics for the dominant limb. Previous research has demonstrated significant limb asymmetry with regards to force production (21) and in joint kinetics (9) during exercises such as the BS. By extension, it is likely that limb asymmetry exists during the BSS, suggesting that future research compare joint kinematic and kinetics between the dominant and nondominant limbs serving as the lead limb.

In conclusion, both the BSS and BS are hip dominant exercises. While the knee is secondarily involved with BS, the knee is less involved with the BSS. Practitioners can use these results as rationale for utilizing the BSS in circumstances in which there is a need to focus on restoring or enhancing hip joint extension unilaterally, particularly if there is a need to concurrently avoid increasing knee joint contributions secondary to knee dysfunction or pathology.

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