Original Research

Muscle Activity in Single- vs. Double-Leg Squats

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ABSTRACT

International Journal of Exercise Science 7(4) : 302-310, 2014. Muscular activity, vertical displacement and ground reaction forces of back squats (BS), rear-leg elevated split squats (RLESS) and split squats (SS) were examined. Nine resistance-trained men reported for two sessions. The first session consisted of the consent process, practice, and BS 1-repetition maximum testing. In the second session, participants performed the three exercises while EMG, displacment and ground reaction force data (one leg on plate) were collected. EMG data were collected from the gluteus maximus (GMX), biceps femoris (BF), semitendinosus (ST), rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), tibialis anterior (TA), and medial gastrocnemius (MGas) of the left leg (non-dominant, front leg for unilateral squats). Load for BS was 85% one repetition maximum, and RLESS and SS were performed at 50% of BS load. Repeated measures ANOVA was used to compare all variables for the three exercises, with Bonferroni adjustments for post hoc multiple comparisons, in addition to calculation of standardized mean differences (ES). Muscle activity was similar between exercises except for biceps femoris, which was significantly higher during RLESS than SS during both concentric and eccentric phases (ES = 2.11; p=0.012 and ES= 2.19; p=0.008), and significantly higher during BS than the SS during the concentric phase (ES = 1.78; p=0.029). Vertical displacement was similar between all exercises. Peak vertical force was similar between BS and RLESS and significantly greater during RLESS than SS (ES = 3.03; p=0.001). These findings may be helpful in designing resistance training programs by using RLESS if greater biceps femoris activity is desired.

KEY WORDS: Back squat, split squat, RLESS, EMG, Force

INTRODUCTION

The back squat (BS) is a fundamental exercise prescribed for both athletes and non-athletes for developing lower-body strength. The resulting leg, hip, and back strength from the prescription of systematic squat resistance training reportedly improves athletic performance when included in a training program (20, 23). Recently, it has been suggested in the lay media that the rear leg elevated split squat (RLESS) places less compressive force on the back, while placing higher stress on the legs, hips and stabilizer muscles (6).

Since BS may be contraindicated in persons with lower back pain, it may be beneficial to examine different variations of squat exercises to determine the benefits of each, as it may have implications for athletic populations. Many studies have examined different types of squats with a variety of measures. For instance, there appears to be differences between variations of the squat for lifting heavy loads (3), and how trunk position affects the joints and muscles involved (18). Additionally, gender differences in mechanics have been demonstrated when performing squats (2, 8, 25).

Electromyographic (EMG) analyses are commonly conducted to quantify electrical activity of muscles during weight training. While the majority of research examining EMG activity and unilateral squats has focused on rehabilitation (i.e. no external load) and general populations (1, 4, 5, 17, 26), one study (21) compared EMG activity levels of the biceps femoris, rectus femoris, and gluteus medius in elite female athletes while performing both loaded back squats and loaded RLESS. They concluded that the RLESS produced greater biceps femoris and gluteus medius EMG activity when compared to the traditional bilateral squat. In addition, RLESS produced a greater knee valgus angle, which may produce greater hamstring activity in an attempt to better stabilize the knee (21). However, a direct comparison with other types of unilateral squat was not conducted in that study.

In addition to kinematics and EMG, the ground reaction forces of bilateral squatting movements have been examined (7, 9, 10, 16, 19), in both loaded (10, 16, 19), and unloaded conditions (7, 9). Similar variables have also been examined during unilateral squatting motions (9, 11, 18, 22, 27), however, these studies focused on unloaded single-leg squats for rehabilitation purposes. Additionally, only two studies used a unilateral squat with a knee range of motion similar to a bilateral squat (9, 11). To our knowledge, this was also the only study that compared the kinetics of a unilateral and bilateral squat, but it focused on patellofemoral force differences and did not report any comparisons of ground reaction forces (9). In one investigation that compared different squat techniques, peak force and peak power appeared to be similar (19), however, this study compared the box squat and traditional BS, not unilateral and bilateral squats.

In an effort to further understand the biomechanical aspects of bilateral and unilateral squat exercises, specifically BS, RLESS, and split squat (SS), this investigation was designed to examine the vertical displacement, muscular activity and unilateral ground reaction forces of these three exercises. We hypothesized that the vertical displacement would be similar in the three types of squat. Additionally, it was expected that most of the thigh and hip musculature would be similarly active in all three exercises with exception being biceps femoris, which was expected to be more active during the unilateral exercises as suggested previously (21). Further, the ankle and knee stabilizer muscles were expected to be more active in the RLESS and SS than the BS, and that the vertical GRF will be similar between the exercises, suggesting similar demands are placed upon the prime mover musculature.

METHODS

Participants

Nine healthy men (ages 24 to 36; 26.1 ± 3.8 years) were recruited to participate. All participants had been participating in a heavy-resistance training program that included squatting exercises for at least the previous six months. Additionally, participants were all familiar with the three exercises. All participants completed a health history questionnaire to screen for any pre-existing health conditions and injuries that would prevent participation. The study's purpose, procedures, and possible risks and benefits were explained to participants both orally and in written form, followed by the signing of informed consent documents. The study procedures were approved by the local University Institutional Review Board prior to beginning research.

Protocol
This study used a repeated measures design to compare the biomechanical differences between a BS, SS, and RLESS. All three exercises were performed with one leg on the force platform and video recorded while muscle activity was monitored via EMG. The independent and dependent variables were selected based on the existing literature, and we have attempted to increase the internal validity by carefully assigning loads based on BS 1-RM.

All participants reported for two sessions: one informed consent and practice session, and one data collection session. After paperwork was completed during the first session, the participants completed a five-minute, self-paced general warm-up on a cycle ergometer, followed by the instruction and the practice of all three squat exercises. In addition, at the end of this session, BS one-repetition maximum (1-RM) testing was completed following protocol described by Harman et al. (12).

For the data collection session, participants completed the same cycle ergometer warm-up followed by seven warm-up sets of bilateral squats. The warm-up sets were performed as follows: six repetitions at 10%, 20%, and 30% 1-RM, three repetitions at 40% and 50% 1-RM, and one repetition at 60% and 70% 1-RM, with a rest period of exactly two minutes between sets. Subsequent to warm-up, single-repetition BS, SS and RLESS were completed in stratified random order. For all lifts, the participant removed the weighted barbell from a rack with a high bar position on the upper back. BS were performed at 85% of the participants' 1-RM with their feet shoulder-width apart and only the left foot on the force plate. This load was used because it represents a normal training load for the participants in our study. Participants were instructed to squat to the lowest level possible and then complete the lift by returning to the starting position. Unilateral squats were performed using half of the load used for the BS. This load was chosen for internal validity reasons, and for the fact that the participants were less trained in using RLESS and SS and thus 1-RM testing for those exercises was not feasible. For the RLESS, the participant was positioned with their left foot on the force platform under their hips, with their right foot elevated behind them with the anterior portion of the ankle on a 40-cm high stand designed for single-leg squats. The participants descended to a position where the knee of the right leg (elevated) touched the ground, and then returned to the starting position. The distance between the center of the stand and the tip of the 1st phalange of left foot was determined for each participant by calculating 85% of leg length (from ASIS to floor). For the SS, each participant was positioned with their left foot in the center of the force platform and right foot behind with a stance at the same length as RLESS (1st phalange to 1st phalange). Participants then descended until the right knee touched the ground, and then returned to the starting position. A rest period of two minutes between the different squat exercises was provided.

A single video camera (Panasonic digital video camcorder, PV-DV203) captured the two dimensional (2-D) motion for analysis. The camera was interfaced with a PC and analyzed with DataPac 5 software (RUN Technologies; Mission Viejo, CA). The shutter speed was set to 1/125 sec and the iris was set to +18 dB. Data were sampled at 60 Hz and filtered with a 4th order, low-pass Butterworth filter at 20 Hz. Analog and kinematic data was synchronized with an analog spike (light-emitting diode (LED) placed in camera's view) to serve as a signal for acquisition. A frame (1.8m) with active LED markers on each corner was used to calibrate the space for the motion analysis. Black curtains were placed in the background to allow for more contrast.

Markers (active LED) were placed on the left end of the barbell and on the left midaxial line at the level of the anterior superior iliac spine (ASIS). Vertical displacement was determined from the barbell marker, and eccentric and concentric phases of the lifts were determined using the vertical displacement of the ASIS marker.

Muscle activity was measured for the gluteus maximus (GMX), biceps femoris (BF), semitendinosus (ST), rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), tibialis anterior (TA), and medial gastrocnemius (MGas) of the left leg. This leg was the non-dominant leg for all participants, and was the front leg for the unilateral squat variations in this study. The non-dominant leg as chosen because generally, balance is better in the non-dominant leg. This was thought to improve the likelihood that the participants would not lose their balance during unilateral squats. Electrode placement was conducted according to the recommendations of Hermens et al. (14). Prior to electrode application, the area was shaved to remove any hair; the skin was then gently abraded with fine sandpaper to remove any other debris and the area was cleansed with alcohol. The electrodes were placed parallel to the estimated resting pennation angle so that the same muscle fibers intersected both electrodes. Electrodes (Ambu Inc.; Glen Burnie, MD) were 2-cm round Ag/AgCl with an inter-electrode distance of two cm, and the ground electrode was placed on the anterior aspect of the patella for signal noise reduction. Signals were recorded and processed using Myopac, Jr. (RUN Technologies; Mission Viejo, CA) with eight dual-lead channels. The electrodes used were passive, therefore pre-amplification was not necessary. The system has a common mode rejection of 90dB, a band pass filter (10-450Hz), and input impedance of 10MΩ. Gain was set at 1000. Synchronized data were collected at 2kHz (Datapac 5; RUN Technologies; Mission Viejo, CA) and channeled through a 12-bit analog-to-digital converter (DAS1200Jr;

Measurement Computing, Middleboro, MA). Data were quantified by computing a root mean square (RMS), 125ms time constant running average of the raw signal over the eccentric and concentric ROM.

Vertical ground reaction force data (N) were acquired with an AMTI BP600900 (Watertown, MA) force platform amplified with an AMTI MSA-6 mini amp (Watertown, MA) at a sampling rate of 2400Hz using a DAS1200JR 12-bit analog to digital converter board (Measurement Computing; Norton, MA) and analyzed using DataPac 5 (RUN Technologies; Mission Viejo, CA). Data was filtered with a 4th order low pass Butterworth digital filter at 20Hz.

Statistical Analyses

Means and standard deviations were calculated for all variables of interest. Each dependent variable was compared with a 1 x 3 repeated measures ANOVA ($p < 0.05$) to determine if any significant differences existed between squatting modalities. Bonferroni post-hoc adjustments to dependent t-tests were used to determine where pairwise differences existed and Cohen's d effect sizes (ES) were calculated to quantify the magnitude of those differences (15), with corrections for

Table 1. Vertical force, displacement, muscle activity.

		Bilateral Squat	RLESS	Split Squat
	Vertical Force (N)	1414.8 ± 251.0	1412.3 ± 258.6	1198.6 ± 187.9*
	Vertical Displacement (m)	0.76 ± 0.04	0.65 ± 0.36	0.83 ± 0.57
CONCENTRIC (RMS mV)	Gluteus Maximus	361.1 ± 228.6	287.8 ± 166.4	258.9 ± 144.7
	Biceps Femoris	392.2 ± 220.4	396.7 ± 186.6	235.6 ± 155.6†*
	Semitendinosis	272.2 ± 176.3	313.3 ± 177.1	247.8 ± 216.4
	Rectus Femoris	1526.7 ± 410.0	1374.4 ± 432.9	1230.0 ± 605.7
	Vastus Lateralis	660.0 ± 363.3	637.8 ± 422.9	512.2 ± 206.6
	Vastus Medialis	718.9 ± 424.6	668.9 ± 332.0	602.2 ± 259.1
	Tibialis Anterior	500.0 ± 340.0	562.2 ± 415.0	390.0 ± 125.1
	Medial Gastrocnemius	277.8 ± 156.4	380.0 ± 305.0	281.1 ± 283.1
ECCENTRIC (RMS mV)	Gluteus Maximus	134.4 ± 66.2	158.9 ± 52.1	166.7 ± 92.3
	Biceps Femoris	161.1 ± 106.6	228.9 ± 134.7	143.3 ± 101.9*
	Semitendinosis	223.3 ± 197.4	204.4 ± 198.8	230.0 ± 228.1
	Rectus Femoris	1182.2 ± 364.9	1228.9 ± 1007.0	886.7 ± 476.7
	Vastus Lateralis	566.7 ± 313.6	582.2 ± 442.4	465.6 ± 235.8
	Vastus Medialis	547.8 ± 291.6	563.3 ± 274.0	553.3 ±287.8
	Tibialis Anterior	567.8 ± 313.0	618.9 ± 300.9	463.3 ± 125.7
	Medial Gastrocnemius	251.1 ± 153.3	240.0 ± 200.9	236.7 ± 301.6

† different than bilateral squat ($p<0.05$); * different than RLESS ($p<0.05$).

repeated measures. ANOVA and Bonferroni adjustments were calculated with SPSS v. 20 (IBM; Armonk, NY).

RESULTS

All nine participants completed the study and their descriptive statistics are presented as mean ± SD (Table 1). Muscle activity was only significantly greater for the BF during RLESS and BS than SS during the concentric phase (RLESS/SS - ES= 2.11, p=0.008; BS/SS - ES=1.78, p=0.029), and significantly greater during RLESS than SS during the eccentric phase (ES= 2.13, p=0.012; Figures 1 and 2). Vertical displacement was similar between the three types of squats. Maximum vertical force (N) was also significantly greater during RLESS than SS (ES= 3.03, p=0.001; Figure 3) and tended to be greater during BS than SS but the trend did not reach significance (ES = 1.42; p=0.058).

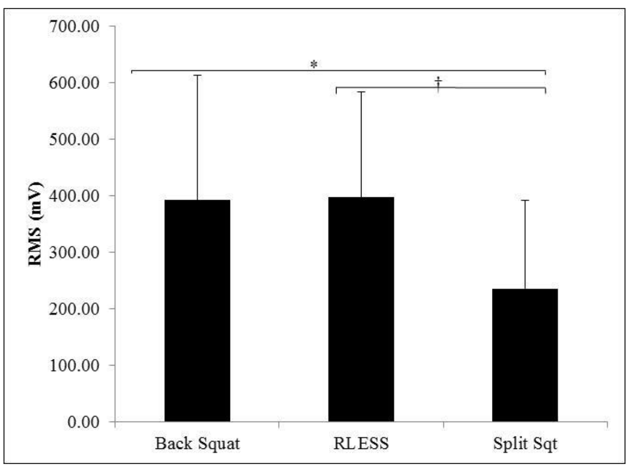

Figure 1. Biceps femoris concentric activity. *p=0.029, ES=1.78; †p=0.008, ES=2.11.

DISCUSSION

This study was designed to compare two different single leg squat techniques and bilateral back squats with respect to vertical range of motion, muscle activity, and vertical ground reaction force. Our data show significantly greater biceps femoris activity during RLESS and BS than SS, similarities in vertical displacement between the three lifts, and some differences in GRF between the different variations of the squat. Our data support contentions that similar lower body muscle activity can be achieved using the RLESS with half the load of BS. This likely would result in less compressive force on the back, however compressive force on the back is beyond the scope of the present study.

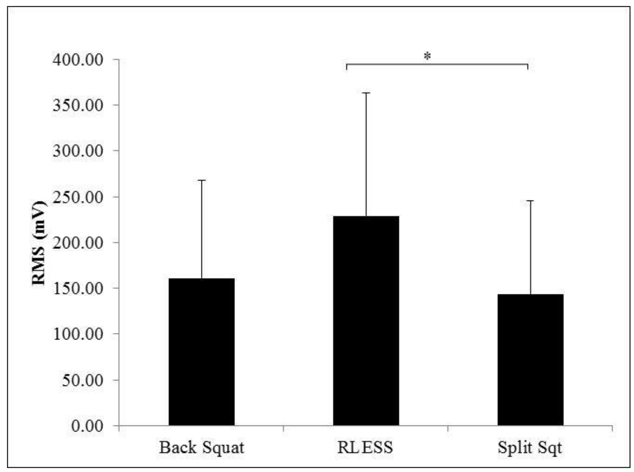

Figure 2. Biceps femoris eccentric activity. *p<0.012, ES=2.19.

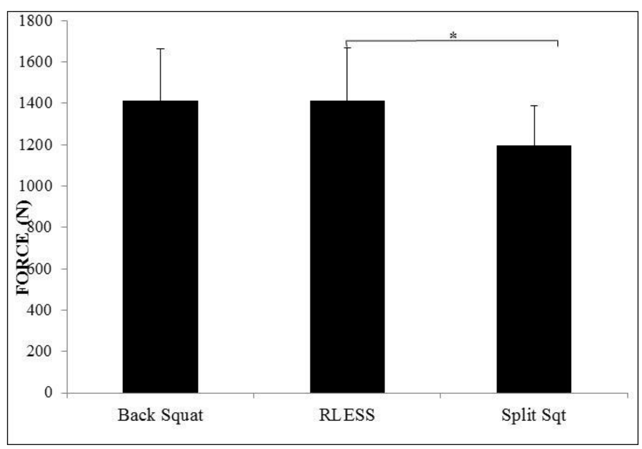

Figure 3. Vertical GRF. *p=0.001, ES=3.03.

Our EMG data support the contention that similar stimulus can be achieved with single leg squats of several types and BS. The only exception was BF activity, where RLESS and BS had a significantly higher activity than the split squat (ES = 2.11 and 1.78 respectively) during the concentric phase of the lifts. RLESS also had significantly higher BF activity during the eccentric phase than split squats (ES = 2.19). Contrary to previous findings (21, 24), neither the RLESS nor the split squat had greater BF or RF activity than the bilateral squat. This may in part be due to differences in load calculation or sample population. One previous study (21) used 85% of the participants' three-repetition maximum (3RM) for each lift, where we used 85% of BS 1-RM for the BS and half that load for the single-leg lifts. They also used a sample of female athletes and we used a sample of resistance-trained men. The other study (24) used a 50lb barbell for both bilateral and single leg squats, and a sample of healthy men. It would be expected that muscle activity would be higher during a single leg squat if the same load were used. However, there are always limitations to calculating relative loads between different weight training exercises.

Peak vertical GRF were similar between the BS and RLESS, suggesting that we adjusted the load sufficiently for loading the leg unilaterally. The RLESS had significantly larger peak ground reaction force than the SS (ES=3.03) at the same load. Peak vertical forces during the BS (1414.81 $\pm$ 250.98N) were larger than the SS (1198.56 $\pm$ 187.88N), however failed to reach significance (ES = 1.42; p=0.058). Previous researchers reported that the rear leg supported between 25% and 45% of the load during a split squat (13) suggesting that the smaller peak forces during the split squat are likely due to a larger portion of the load being supported by the rear leg. However, this is beyond the scope of the present study, as we were only able to collect data from the lead leg within the limitations of our experimental setup.

As was expected, vertical bar displacement was similar between squats, suggesting similar depth of squat. This variable has not been compared between these lifts previously, therefore comparisons with other studies is impossible. We acknowledge that similar bar displacement does not equate to similar joint ranges of motion. One study (21) reported larger trunk inclination during bilateral squats than during RLESS, which likely would translate to greater hip flexion and ROM. Since joint ROM was not examined herein, it is unclear if this was true in the current study; however, for trunk inclination to be different, lower extremity joint ROM would likely be different between squats to maintain the overall vertical displacement. The findings of the current study combined with those previously reported (21) suggest further examination of joint ROM in these three squat types.

Due to the inherent limitations in using 2D video analysis for joint motion, joint kinematics were not examined herein. In addition, we acknowledge the limitation that both legs were not monitored for EMG activity and GRF. While adding 3D analysis and additional EMG channels may be feasible, instrumenting multiple force platforms so that force information can be collected from both legs may be challenging, especially instrumenting a stand for the rear leg in the RLESS. In spite of these limitations, our data are an important contribution to the relative scarcity of data on these types of squat. Our data provides important findings that can be built on with more sensitive measures. Additionally, future studies may consider basing the prescribed loads off of the 1-RM for each individual squat type. Performing multiple repetition sets, including those designed to induce considerable fatigue, may also be of interest to the practitioner.

Rear leg elevated split squats (RLESS) activate the lower body musculature similar to bilateral back squats while using half the load, but increased BF activity was seen for RLESS. Therefore, if additional BF activity is desired, RLESS may be more appropriate than SS or BS. Future research should consider additional measures of force and time such as impulse to clarify the potential differences in bilateral and unilateral squatting. Additionally, comparisons of the dominant and non-dominant leg in unilateral squats may be of interest.

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