MULTI-PLANAR ANALYSIS OF THE TRADITIONAL BACK SQUAT AND SMITH MACHINE BACK SQUAT

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This study evaluated the kinetic differences between the traditional back squat (T-BS) and Smith machine back squat (SM-BS) performed at a variety of loads. Ten subjects were tested in six conditions including the T-BS and SM-BS each performed at 50%, 80%, and 100% of the subject's five repetition maximum load on a force platform. The analysis of vertical ground reaction forces (GRF) revealed significant main effects for exercise load ($p \leq 0.001$) but not for squat condition or the interaction of load and squat condition ($p > 0.05$). Analysis of anterior-posterior (A-P) GRF revealed significant main effects for exercise load ($p \leq 0.05$), squat condition ($p \leq 0.001$), and the interaction between load and condition ($p \leq 0.05$). Analysis of medial-lateral GRF revealed no main effects ($p > 0.05$). Compared to the T-BS, the SM-BS, offers an A-P resistance against which approximately 76-83% greater force can be produced in that plane.

Keywords: resistance training, ground reaction force, frontal plane, sagittal plane

INTRODUCTION: Lower body resistance training exercises such as the back squat are commonly prescribed for training and rehabilitation. Consumer publications have recommended variations of this exercise, including the traditional barbell back squat (T-BS) and the Smith machine back squat (SM-BS) (Stoppani, 2008).

Differences in Smith machine design, typified by variation in sagittal plane absolute angle relative to the ground, have been studied (Biscarini et al., 2013). Other biomechanical studies examined the influence of trunk and foot position and weight distribution on subsequent joint torques (Biscarini et al., 2011), while researchers also examined variation in SM-BS loading mechanisms (Arandjelovic, 2012).

Researchers evaluated the one repetition maximum load that could be used for the SM-BS and T-BS, for the purpose of load prediction from one mode to the other (Cotterman et al., 2005). Other biomechanical studies compared these two training exercises. The kinematics of the T-BS and SM-BS were assessed with three dimensional video analyses. Results reveal that the T-BS resulted in a larger range of motion than the SM-BS, for all joints assessed. Additionally, it was shown that subjects position their feet more anteriorly during the SM-BS than the T-BS, due to the vertical restriction of the Smith machine, resulting in a larger moment of resistive force at the knee joint (Gutierrez and Bahamonde, 2009). Muscle activation of the prime movers and stabilizers was also assessed during the performance of each of these exercises. Muscle activation was statistically higher during the T-BS in the gastrocnemius, biceps femoris, and vastus medialis. Though not statistically significant, all other lower body and core muscles assessed produced 43% more activity during the T-BS compared to the SM-BS (Schwanbeck et al., 2009), yielding evidence that according to these variables, the T-BS may be the superior training stimulus for muscle activation. However, no research has assessed the multi-planar kinetics of these exercises or the influence of load in the performance of the T-BS and SM-BS. Questions remain about the multi-planar demands of these exercises and thus the potential each has for developing or limiting multi-planar strength. Since the T-BS and the SM-BS are commonly prescribed lower body exercises for rehabilitation and performance enhancement, it is necessary to understand the characteristics of the exercises in order to know the nature of the training stimulus and potential exercise progression for exercise prescription. Therefore, the purpose of this study was to examine the vertical (V), anterior-posterior (A-P), and medial-lateral (M-L) ground reaction forces (GRF) produced during the performance of T-BS and SM-BS at a variety of exercise intensities.

METHODS: Ten men served as subjects for this study (age = 21.40 ± 2.17 years). Additional subject descriptive data are shown in Table 1. The subjects were informed of the risks associated with the study and provided informed written consent. The study was approved by the Institutional Review Board.

Subjects participated in two research sessions. Prior to each session, subjects performed dynamic stretching and an activity specific warm-up. The first session was designed to habituate the subjects to the test exercises and determined their five repetition maximum (5RM) for both the T-BS and the SM-BS. Subjects performed three warm-up sets for both the T-BS and the SM-BS. These warm-up sets were conducted at 50%, 75%, and 90% of the subject's estimated 5RM for 2 repetitions each. After five minutes of rest, the subjects performed their baseline 5 RM test for the T-BS and SM-BS.

After approximately four days of recovery, the subjects returned for the testing session, during which time they were tested in six different test conditions including the T-BS at 50%, 80%, and 100% of their 5RM load, and the SM-BS at 50%, 80%, and 100% of their 5RM load. The testing order was randomized for squat test type and load condition. Subjects performed five repetitions of each test with five minutes of recovery allowed between each.

All test exercises were performed on a 30x40 force platform (Accupower, Advanced Mechanical Technologies Inc., Watertown, MA) which was mounted flush to the floor. The force platform was calibrated prior to the testing and kinetic data were collected at 600 Hz and real-time displayed and analyzed using proprietary software (Accupower, Advanced Mechanical Technologies, Inc., Watertown, MA). Peak GRF in the V, A-P, and M-L planes were assessed for each exercise type and load condition. Data were analyzed with statistical software (SPSS 25.0, International Business Machines Corporation, Armonk, New York). A 2 x 3 ANOVA with repeated measures for exercise type and load condition was used. Bonferroni adjusted pairwise comparison were conducted when main effects were present. A paired samples *t*-test was used to identify the differences in the 5RM for each exercise condition. The reliability of the trials was assessed using intraclass correlation coefficients (ICC), for each of the dependent variables and coefficients of variation were calculated. Assumptions for linearity of statistics were tested and met. Statistical power (d) and effect size (η_p^2) are reported and all data are expressed as means ± SD. The η_p^2 values of .0099, .0588, and .1379 represent small, medium, and large effect sizes (Richardson, 2011). The *a priori* alpha level was set at $p \leq 0.05$.

Table 1. Subject Descriptive Information (Mean ± Standard Deviation)

Height measured in centimeters	180.79 ± 9.03
Mass measured in kilograms	88.95 ± 14.12
Years of high school sport participation	3.80 ± 0.63
Years of collegiate sport participation	2.05 ± 1.52
Smith machine back squat experience	2.70 ± 2.58
Traditional back squat experience	6.80 ± 1.87

RESULTS: In the analysis of V GRF, results revealed significant main effects for exercise load ($p \leq 0.001$, $d = 0.99$, $\eta_p^2 = 0.72$) but not for exercise type ($p > 0.05$) or the interaction of exercise type and load ($p > 0.05$). Mean data are shown in Table 2. In the analysis of A-P GRF, results revealed significant main effects for exercise load ($p \leq 0.05$, $d = 0.72$, $\eta_p^2 = 0.35$) exercise type ($p \leq 0.001$, $d = 0.98$, $\eta_p^2 = 0.70$), and the interaction between load and type ($p \leq 0.05$, $d = 0.79$, $\eta_p^2 = 0.38$). Data and results from the Bonferonni adjusted post hoc analysis are shown in Table 3. The analysis of M-L GRF revealed no main effects ($p > 0.05$) for exercise load, exercise type, or the interaction between load and exercise type. Mean data are shown in Table 4.

The five RM testing loads were statistically different ($p = 0.027$) between the T-BS and the SM-BS. The mean T-BS and SM-BS five RM loads were 135.68 ± 27.12 kg and 127.50 ±

20.42 kg, respectively. Average measure Interclass correlation coefficients for the GRFs from each exercise test and load condition ranged from .66 to .99. Coefficients of variation for all V forces ranged from 12.69% to 15.68%, for all test conditions. Coefficients of variation for all A-P forces ranged from 22.73% - 56.15%, for all test conditions. Coefficient of variation for all M-L forces ranged from 55.2% to 74.9%, for all test conditions.

Table 2. Vertical Ground Reaction Force (Mean ± Standard Deviation)

	T-BS	SM-BS	% Difference*
50% 5 Repetition Maximum	452.04 ± 70.86	430.98 ± 67.17	4.66
80% 5 Repetition Maximum	498.97 ± 74.21	497.38 ± 64.87	0.32
100% 5 Repetition Maximum	581.78 ± 114.20	542.04 ± 68.76	6.83

T-BS= Traditional Back Squat; SM-BS= Smith Machine Back Squat
*No significant differences were found (p > 0.05).

Table 3. Anterior-Posterior Ground Reaction Force (Mean ± Standard Deviation)

	T-BS	SM-BS	% Difference
50% 5 Repetition Maximum	5.84 ± 3.31	24.49 ± 12.69	76.15*
80% 5 Repetition Maximum	5.82 ± 3.68	34.96 ± 18.80	83.35*
100% 5 Repetition Maximum	7.67 ± 3.08	36.52 ± 22.73	79.00*

T-BS= Traditional Back Squat; SM-BS= Smith Machine Back Squat
*Significantly different ($p \leq 0.001$).

Table 4. Medial-Lateral Ground Reaction Force (Mean ± Standard Deviation)

	T-BS	SM-BS	% Difference*
50% 5 Repetition Maximum	3.75 ± 3.45	2.56 ± 4.77	31.73
80% 5 Repetition Maximum	2.08 ± 4.50	2.86 ± 15.64	27.27
100% 5 Repetition Maximum	3.99 ± 3.85	0.01 ± 11.54	99.75

T-BS= Traditional Back Squat; SM-BS= Smith Machine Back Squat
*No significant differences were found (p > 0.05).

DISCUSSION: This is the first study to assess the multi-planar kinetics of the T-BS and SM-BS. This study shows that no kinetic differences between these exercises exist in the V and M-L plane. However, in the analysis of the A-P plane, the SM-BS condition resulted in the production of greater GRFs. Other research assessing kinetic differences of other back squat variations examined only the V GRF, also demonstrating no differences for the exercises assessed (Ebben and Jensen, 2002). The current study showed that significant differences were present for V GRF as a result of the load used. This result was predictable and supported by research which shows that progressed loads during resistance training exercises increases force (Jensen and Ebben, 2002).

In the present study, A-P GRFs also differed between the exercises, and as a function of the exercise load. This finding may be explained by previous research which demonstrated that during the SM-BS, the bar is restricted in the A-P plane and greater trunk and hip flexion is present (Gutierrez and Bahamonde, 2009). Therefore, the SM-BS seems to provide A-P stability, and the vertical slide rails serve as a resistance against which force can be developed. Additionally, foot placement during the SM-BS has been shown to affect weight distribution, and influence the absolute angle of the torso and joint reaction forces (Biscarini et al., 2011).

Despite the kinetic difference found in the present study, other research has demonstrated greater muscle activation in select posterior compartment, hamstring, and quadriceps muscles during the T-BS compared to the SM-BS (Schwanbeck, 2009). Furthermore, the T-BS allows a greater A-P range of motion at the knee joint, compared between the SM-BS. This difference in range of motion was believed to be due, in part, to variations in foot placement between these exercises (Gutierrez and Bahamonde, 2009).

In the present study, no kinetic differences were found between exercises for M-L GRF. This result is not surprising since during the SM-BS, the bar is restricted in the A-P direction

(Gutierrez and Bahamonde, 2009), resulting in greater forward inclination which effected joint torques (Biscarini et al., 2013). There was no evidence of altered joint or exercise motion in the M-L plane (Biscarini et al., 2011; Gutierrez and Bahamonde, 2009).
Finally, in the current study, the subject's T-BS 5RM was 6.03% greater than the SM-BS. This result is in contrast with previous research showing that subjects could handle greater 1 RM loads for the SM-BS than the T-BS (Cotterman et al., 2005.).

CONCLUSION: This study demonstrates that the primary kinetic differences between the SM-BS and the T-BS exist in the A-P plane. While the SM-BS restricts multi-planar movement, it allows greater A-P force production compared to the T-BS.

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