THE OSTEOGENIC POTENTIAL OF SUPERMAXIMAL SQUAT LOADS

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This study evaluated the ground reaction force (GRF) and rate of force development (RFD) of the back squat at 3 different loads. Twelve subjects performed the back squat with 80%, 100%, and 120% of their 1 repetition maximum (RM) on a force platform. A two way repeated measures ANOVA revealed significant main effects for GRF for both the eccentric ($p \leq 0.001$) and concentric ($p \leq 0.001$) phases but no interaction between phase and GRF or RFD ($p < 0.05$). No significant main effects were found for RFD for the eccentric ($p = 0.09$) and concentric phases ($p = 0.38$). Post hoc analyses demonstrated that back squats at 120% produced the highest GRF in the eccentric and concentric conditions. Mean RFD was highest, and trending toward significance, during the eccentric phase at 100% of 1 RM condition.

KEYWORDS: resistance training, compressive loading, bone development, strain

INTRODUCTION: The back squat is a common resistance training exercise that is believed to increase athletic ability, strength, and enhance ligament and bone strength (Chandler & Stone, 1991). Exercises that promote osteogenesis are of particular importance to those who are at increased risk of impaired bone health (Jurimae & Jurimae, 2008). Recently, the back squat has been compared to other modes of training including loaded squat jumps, depth jumps, running, and walking in an attempt to quantify the kinetic osteogenetic potential (Ebben et al., 2010). Osteogenic protential of exercise has been proposed to be a function of the magnitude and rate of force development (RFD) (Skerry, 1997) and has been assessed via vertical peak ground reaction forces (GRF) and eccentric RFD, respectively (Ebben et al., 2010).

During dynamic exercises, the external torque is a function of the magnitude of the external load and the moment arm through which the load is expressed. The moment arm changes throughout the range of motion of dynamic exercise (Harman, 2008). For example, during the back squat, the knee joint moment is approximately longest when the knee flexion angle is the greatest (Gullett et al., 2009). Thus, the external torque is greatest during the deeper portion of the squat. This observation, as well as anecdotal clinical observation demonstrate that subjects can handle less load when performing the back squat with greater compared to less depth. Thus, the magnitude of the load, and therefore osteogenic potential, may be limited by the squat depth. The kinetic characteristics of some variations of the back squat exercise have been previously evaluated (Ebben & Jensen, 2002; Gullett et al., 2009). However, no study has compared exercise load, including those that exceed the 1 RM, in order to assess the osteogenic potential.

Therefore, the purpose of this study was to assess the peak vertical GRF, GRF normalized to body weight, and RFD for both the eccentric and concentric phases of the back squat at 80%, 100%, and 120% of the subject's 1 repetition maximum (RM), in order to assess the osteogenic potential of these back squat loading variations.

METHODS: Subjects included 12 men (mean ± SD; age = 22.42 ± 2.54 years; height = 175.05 ± 7.18 cm; body mass = 83.75 ± 15.25 kg; squat 1 RM = 157.10 ± 28.61 kg). Inclusion criteria consisted of men who regularly participated in lower body resistance training. Exclusion criteria included any orthopedic lower limb pathology that restricted athletic functioning, known cardiovascular pathology, or inability to perform exercises with maximal effort. All subjects provided informed consent prior to the study, and the university's internal review board approved the study.

Subjects participated in a habituation and test session. Before each, subjects warmed up for 3 minutes on a cycle ergometer. Subjects also performed 5 slow bodyweight squats, 10 yard forward walking lunge, 10 yard backward walking lunge, 10 yard walking hamstring stretch, 10 yard walking quadriceps stretch, 20 yard skip, and 5 countermovement jumps of increasing intensity. Subjects then rested for 2 minutes.

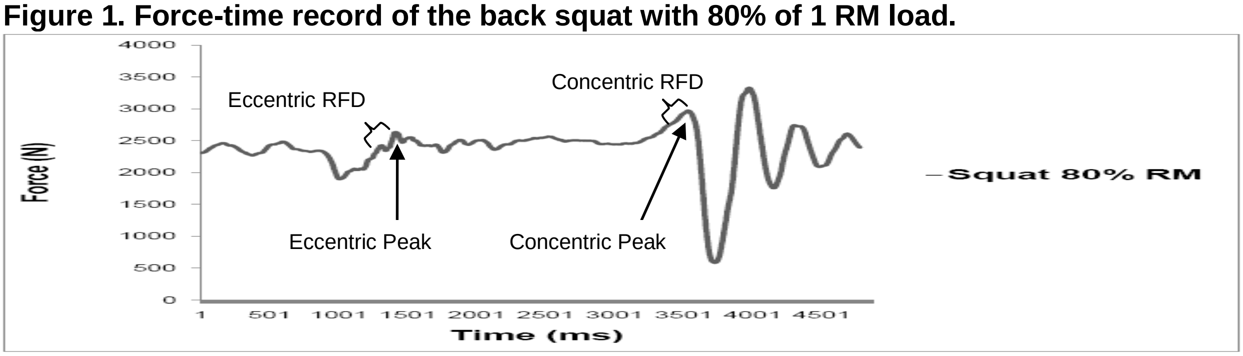
During the habituation session, the subject's age, body mass, height, and history of athletic participation was assessed. Subjects also performed their back squat 5 repetition maximum (RM) down to a knee angle of 90 degrees in order to determine their testing load during the primary testing session. Prior to the 5 RM test, subjects performed 2 sets of 3 reps at approximately 75% and 90% of their self assessed maximum ability. Subjects also perform 2 sets of 1 repetition in the supermaximal (120% of 1 RM) condition at a knee angle of 65 degrees to become familiar with this testing condition.

Subjects then returned for the testing session. During this time, they warmed up using the same warm up protocol as the one used in the habituation session. After 5 minutes of rest, subjects performed 2 sets of 1 repetition of the back squat in the randomly ordered test conditions with 5 minutes rest between sets and exercises. Test conditions included the back squat performed at 80%, 100% and 120% of the subjects estimated 1 RM. The subjects performed the sets of 80% and 100% of the subject's estimated 1 RM loads at approximately 90 degrees of knee flexion. The set at 120% of estimated 1 RM load was performed at 65 degrees of knee flexion, since it was not possible to perform the exercise to 90 degrees of knee flexion with the supermaximal load.

All exercises were performed on a force platform (BP6001200, Advanced Mechanical Technologies Incorporated, Watertown, MA, USA) which was calibrated with known loads to the voltage recorded prior to the testing session. Kinetic data were collected at 1000 Hz, real time displayed and saved with the use of computer software (BioAnalysis 3.1, Advanced Mechanical Technologies, Inc., Watertown, MA USA) for later analysis.

Kinetic data were analyzed for GRF, GRF normalized to body weight, and RFD for both the eccentric and concentric phases of each back squat condition. All values were averaged using 2 test trials. Peak vertical GRF was defined as the highest value attained during the eccentric and concentric phase of each exercise. The RFD was defined as the peak vertical GRF minus the vertical GRF occurring 100 ms prior to the peak vertical GRF and normalized to a second for both the eccentric and concentric phases. Figure 1 shows a sample force-time record for the squat performed in the 80% condition.

Figure 1. Force-time record of the back squat with 80% of 1 RM load.



Data were evaluated with SPSS 18.0 for Windows (Microsoft Corporation, Redmond, WA, USA) using a two way repeated measures ANOVA to determine statistical differences in kinetic data between the exercises and the interaction between GRF and RFD and the eccentric and concentric phase. Significant main effects were further evaluated using Bonferroni adjusted pairwise comparisons. Assumptions for linearity of statistics were tested and met. Statistical power (*d*) and effect size (η^2) are reported, and all data are expressed as means ± SD.

RESULTS: Analysis of GRF demonstrated significant main effects for both the eccentric ($p \leq 0.001$, $\eta^2 = 0.92$, $d = 1.00$) and concentric ($p \leq 0.001$, $\eta^2 = 0.93$, $d = 1.00$) phases, indicating differences in GRF, among the 3 squat loading conditions. There was no significant interaction between GRF and eccentric and concentric phase ($p = 0.11$, $\eta^2 = 0.10$, $d = 0.46$). Analysis of GRF normalized to body weight demonstrated significant main effects for both the eccentric ($p \leq 0.001$, $\eta^2 = 0.91$, $d = 1.00$) and concentric ($p \leq 0.001$, $\eta^2 = 0.91$, $d = 1.00$) phases, indicating differences in GRF normalized to body weight among the 3 squat loading conditions. There was no significant interaction between GRF normalized to body weight and eccentric and concentric phase ($p = 0.17$).
Analysis of RFD demonstrated no significant main effects for the eccentric ($p = 0.09$, $\eta^2 = 0.20$, $d = 0.48$) and concentric ($p = 0.38$, $\eta^2 = 0.08$, $d = 0.20$) phases, indicating no differences in RFD among the 3 back squat load conditions, though the eccentric RFD was approaching significance. There was no significant interaction between GRF and eccentric and concentric phase ($p = 0.33$, $\eta^2 = 0.10$, $d = 0.23$). Significant main effects were further evaluated for both the eccentric and concentric phase and are described in Table 1 and 2. Descriptive RFD data are shown in Table 3.

Table 1. Ground reaction force (GRF) data from the eccentric and concentric phases of 3 squat loading conditions (mean ± SD). (N=12).

	Squat 80% RM	Squat 100% RM	Squat 120% RM
Eccentric GRF (N)	2230.35 ± 316.81*	2625.80 ± 407.55*	2868.30 ± 391.22*
Concentric GRF (N)	2598.16 ± 379.72*	2935.53 ± 390.40*	3306.61 ± 455.20*

*Significantly different than all other squat conditions ($p \leq 0.001$)

Table 2. Ground reaction force (GRF) data normalized to body weight from the eccentric and concentric phases of 3 squat loading conditions (mean ± SD). (N=12).

	Squat 80% RM	Squat 100% RM	Squat 120% RM
Eccentric GRF (BW)	2.77 ± 0.47*	3.26 ± 0.60*	3.57 ± 0.66*
Concentric GRF (BW)	3.23 ± 0.55*	3.65 ± 0.62*	4.12 ± 0.75*

*Significantly different than all other squat conditions ($p \leq 0.001$)

Table 3. Mean rate of force development (RFD) data from the eccentric and concentric phases of 3 squat loading conditions (mean ± SD). (N=12).

	Squat 80% RM	Squat 100% RM	Squat 120% RM
Eccentric RFD ($N \cdot sec^{-1}$)	2844.02 ± 2368.89	3443.69 ± 3056.63	2998.41 ± 1631
Concentric RFD ($N \cdot sec^{-1}$)	1672.63 ± 880.63	1993.69 ± 795.07	1766.28 ± 881.82

DISCUSSION: This study demonstrates that performing the back squat with supermaximal loads of 120% of the estimated 1RM, through 65 degrees range of motion develops higher GRF than performing the back squat with maximal or submaximal loads. Thus, performing this exercise with supermaximal loads may be useful for bone development since the magnitude of the load is believed to be osteogenic (Skerry, 1997). In the present study, a mean increase in back squat load of 20% resulted in a mean increase in eccentric and concentric GRF of 9% and 13%, respectively. While the relationship between squat load and peak GRF may be intuitive, it has not been previously investigated across a loading continuum

or during supermaximal loading conditions. In fact, previous research demonstrated that high load squats offered less GRF than lower load exercises such as jump squats (Ebben et al., 2010). In the present study, squat range of motion, and the likely increase in lengths of the moment arm of the resistance force, likely reduced the possible training load since the moment arm of the resistance is greatest at greater degrees of knee joint flexion (Gullett et al., 2009). Programs designed to optimize osteogenesis should include supramaximal squats as well as loaded squat jumps and depth jumps which have been shown to produce high GRF and RFD (Ebben et al., 2010). From the perspective of sport specificity, it is recognized that training for athletic development may require squatting with greater than 65 degrees of knee flexion for sports that require athletes to function in lower positions (Chandler & Stone, 1991)
Rate of force development was not significantly different between exercise conditions. Significant subject variability exists with respect to the speed of the eccentric and concentric phases despite the fact that all subjects were instructed to perform each as quickly as possible. Nonetheless, the eccentric RFD approached significance during the back squat, with the 100% of the estimated 1 RM demonstrating the highest mean value. The concentric RFD demonstrated a similar mean pattern typified by the highest mean RFD during the 100% of the estimated 1 RM. The supermaximal squat condition at 120% of the estimated 1 RM demonstrated mean RFD values that were slightly greater than the condition at 80% of the estimated 1 RM. These data suggest that the RFD may not be associated with the lightest load. Previous research demonstrated that eccentric RFD was greatest during depth jump landings and progressively lower during jump squats at 30% of the subject's back squat 1 RM and back squat at 5RM load (Ebben et al., 2010).

CONCLUSION: Performing the back squat at supermaximal loads, accomplished with reduced range of motion, results in the highest GRF, and thus should be included in programs designed to promote osteogenesis.

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