GROUND REACTION FORCE AND RATE OF FORCE DEVELOPMENT DURING LOWER BODY RESISTANCE TRAINING EXERCISES

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This study quantified the differences in the kinetic profiles of the back squat, deadlift, step-up, and lunge. Eleven subjects performed 2 repetitions of their 5 repetition maximum in each of the 4 exercises. Kinetic data were collected using a force platform. The exercises were compared based on their peak vertical ground reaction force (GRF_P) and rate of force development (RFD) in both the eccentric and concentric phase. A repeated measures ANOVA indicated differences ($p \leq 0.001$) in GRF_P attained for the different exercises in both the eccentric and concentric phase. No significant differences ($p \geq 0.05$) were found for RFD for any of the exercises in either the eccentric or concentric phase. Results can guide the development of training programs that are specific to strength, explosiveness, or osteogenesis.

KEYWORDS: kinetics, strength, explosiveness, osteogenesis

INTRODUCTION: Understanding the relative value of an exercise is important in the design of a training program for strength, explosiveness, or osteogenesis. In order to perform any exercise, a certain level of force must be applied. Therefore, ground reaction force (GRF) and its derivatives, peak GRF and RFD, have been used to compare exercise characteristics (Ebben et. al, 2009; Escamilla et. al, 2002; Jensen and Ebben, 2002; Salem et. al, 2004; Wilson et. al, 2008; Zink et. al, 2006).
Previous research has used GRF to analyze performance of single or variations of single resistance exercises such as the squat (Zink et. al, 2006), deadlift (Escamilla et. al, 2002), step-up (Salem et. al, 2004), and lunge (Wilson et. al, 2008).
Research has also evaluated two or more resistance training exercises in a single study. Kinetic analysis has been used to compare the hang clean and hang snatch (Jensen and Ebben, 2002). Multiple exercises have also been studied to determine training load predictions (Ebben et. al, 2008) and muscle activation during multiple lower body resistance exercises (Ebben, 2009). Research has also analyzed the GRF of multiple modes of exercise such as walking, running, plyometrics, and the back squat (Ebben et. al, 2009).
Resistance training is used for many purposes such as performance enhancement or rehabilitation. Peak GRF and rate of force development (RFD) can be used as an indicator of the exercise's potential to increase strength and explosiveness, respectively. A secondary effect of resistance training is the bone adaptation that results from high strains and magnitudes of resistance. While no research has produced precise prescription for osteogenesis, it has been proposed that higher magnitude and rate of loading produce greater adaptation (Skerry, 1997). Exercise GRF and RFD can be used to estimate the magnitude and rate of loading, respectively, of resistance training exercises (Ebben, et al, 2010).
No study has compared kinetic aspects of multiple resistance training exercises. Therefore, the purpose of this study is to compare the kinetic characteristics of the squat, deadlift, step-up, and lunge. Peak vertical GRF (GRF_P) and RFD during the eccentric and concentric phase of each exercise will be assessed. These results will help determine optimal exercises to be included in training focused on strength, explosiveness, or osteogenic potential.

METHODS: Eleven recreationally active subjects participated in this study (mean ± SD; age

= 22.45 ± 2.70 years; body mass = 83.12 ± 15.19 kg). Subjects included males who were 18-45 years old and participated in at least 6 weeks of lower body resistance training prior to testing. All subjects provided written informed consent and the study was approved by the university's internal review board.

A pre-test habituation session including assessment of 5 repetition maximum (RM) loads for back squat, deadlift, step-up, and lunge. After at least 48 hours of recovery, subjects returned for the test session and performed 2 repetitions of the subject's 5RM load in each of the randomly ordered test exercises with 5 minutes of rest between each set. Back squats were performed to the depth of a measured 90 degree knee angle. Step-ups were standardized to an 18 inch box. Lunges were performed to a length of 120 cm. All step-up and lunge sets were performed with only the right leg. The deadlift and step-up were performed with the eccentric muscle action first followed by the concentric muscle action. This was done in order to keep consistency in the order of muscle actions of all exercises being studied. Instructions were given to perform exercises at maximal velocity to enhance external validity.

Prior to the pre-test habituation and test sessions, a warm-up was performed consisting of 3 minutes on a cycle ergometer proceeded by dynamic stretching exercises including 5 repetitions of each of the following: slow and fast body weight squats, forward and backward lunges, and walking quadriceps and hamstring stretches. A 20 yard skip and 5 sets of 10 yard sprints gradually increasing in speed were also performed. Warm-up sets of 5 reps at 60% and 3 reps at 80% of a self-predicted 1 RM were completed for the first exercise to be performed. Warm-up sets were not performed for the rest of the exercises due to already being acclimated to high intensity loads and to minimize fatigue.

The test exercise modes were assessed with a 60 x 120 cm force platform (BP6001200, Advanced Mechanical Technologies Incorporated, Watertown, MA, USA) that was bolted to the laboratory floor and mounted flush in the center of a 122 x 244 cm weightlifting platform. The force platform 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. The GRF_P and RFD were calculated from the force-time records for both eccentric and concentric phases. All values were determined as the average of two repetitions for each exercise. The GRF_P was defined as the highest value attained. The RFD was defined as GRF_P minus the GRF 250 ms prior to the peak divided by the time elapsed between these two values (250 ms) and calculated consistent with methods previously used (Jensen et al, 2008; Ebben et al, 2010).

All data were analyzed with SPSS © (Version 16.0). A repeated measures ANOVA was used to determine possible differences in GRF_P and RFD during the eccentric and concentric phase between the exercise modes, as well as differences in estimated 1 RM. Significant main effects were further analyzed with Bonferroni adjusted pairwise comparison to identify the specific differences between the exercise modes. A Pearson's correlation coefficient was used to assess the relationship between the exercise load and the GRF_P and RFD. The *a priori* alpha level was set at $p \leq 0.05$. Power and effect sizes are listed as d and partial eta squared (η_p^2), respectively.

RESULTS: Analysis of GRF_P showed significant main effects for the eccentric ($p \leq 0.001$, d = 1.00, η_p^2 = 0.73) and concentric ($p \leq 0.001$, d = 1.00, η_p^2 = 0.91) phases, indicating differences in force requirements between the exercises. No significant main effects were found for the RFD during the eccentric (p = 0.78) or concentric (p = 0.51) phases. Significant main effects were also found ($p \leq 0.001$, d = 1.00, η_p^2 = 0.86) for estimated 1 RM. Post hoc analysis identified the specific differences in GRF_P and estimated 1RM between the exercises (Table 1 and 2). Descriptive RFD information is also presented in Table 3 and 4. Squat, deadlift and lunge eccentric and concentric GRF_P were correlated with exercise load ($p \leq 0.01$, R ranged from 0.76 to 0.93). Step-up eccentric and concentric GRF_P and RFD for all exercises were not correlated to exercise load.

Table 1. Eccentric and Concentric GRF_P in Newtons (N) (mean ± SD). N=11.

	Squat	Deadlift	Lunge	Step-Up
ECC	2440.19 ± 293.70*	2301.41 ± 371.18*	1714.87 ± 351.87**	1575.08 ± 490.75**
CON	2646.44 ± 391.16***	2539.07 ± 458.90***	1910.37 ± 428.82*	1587.34 ± 372.29*

* = Different than all other exercises; $p \leq 0.05$
** = Different than Squat and Deadlift; $p \leq 0.05$
*** = Different than Lunge and Step-Up; $p \leq 0.05$

Table 2. Estimated 1RM in kilograms (kg) (mean ± SD). N=11.

Squat	Deadlift	Lunge	Step-Up
169.99 ± 25.94*	163.00 ± 30.49*	76.99 ± 38.41**	75.13 ± 22.10**

* = Different than Lunge and Step-Up; $p \leq 0.001$
** = Different than Squat and Deadlift; $p \leq 0.001$

Table 3. Eccentric rate of force development ($N \cdot s^{-1}$) (mean ± SD). N=11.

Step-Up	Squat	Lunge	Deadlift
2312.96 ± 4857.66	2095.73 ± 3052.86	2022.97 ± 1240.32	1172.98 ± 363.27

Table 4. Concentric rate of force development ($N \cdot s^{-1}$) (mean ± SD). N=11.

Deadlift	Step-Up	Lunge	Squat
2373.98 ± 1900.19	2162.10 ± 2389.72	1950.02 ± 1923.76	1431.39 ± 723.24

DISCUSSION: This is the first study to kinetically quantify and compare multiple resistance training exercises, including the back squat, deadlift, step-up, and lunge. This study shows significant differences in GRF_P between exercises in both the eccentric and concentric phase. The concentric phase GRF_P was highest in the back squat followed by the deadlift. The lunge and step-up were significantly lower than the back squat and deadlift, but no differences existed between them. Significant differences were not found for either the eccentric or concentric RFD, although substantial mean differences were present.

Differences in GRF_P may be explained, in part, by the load used for each exercise. In this study, the squat and deadlift mean 1 RM were significantly higher than the lunge and step-up. In fact squat, deadlift, and lunge exercise load was significantly correlated with GRF_P.

It is noted that the exercises with higher GRF_P such as the squat and deadlift, are performed with bilateral weight distribution. Exercises with lower GRF_P such as the lunge and step-up are performed unilaterally. The unilateral component creates a smaller base of support and reduces maximal loading, consistent with previous research (McBride et. al; 2006), and ultimately reducing GRF_P in the present study.

Statistically significant differences did not occur in the RFD between the 4 exercises, although substantial mean differences exist. For example, the deadlift produced a 65.8% higher concentric RFD than the back squat. The step-up and lunge also have a 51.0% and 36.3% higher mean RFD than the back squat, respectively, potentially due to the unilateral nature and the bilateral deficit phenomenon (Hay et. al, 2006).

While the back squat produces the greatest concentric GRF_P it also has the slowest mean concentric RFD. The relationship between GRF_P to RFD is consistent with the force velocity curve, which estimates that the greater the load lifted, the slower the movement of the exercise (Kraemer & Spiering, 2006). The greater motor unit recruitment resulting from slower movements results in maximal strength development (Campos et. al, 2002). Therefore, strength focused training should prioritize the back squat over exercises such as the lunge and step-up.

Training exercises should also simulate the sport being trained for. Sport-specific simulation includes the relative speed of the exercise for muscle adaptation (Kraemer & Spiering, 2006) as well as similar movements for neural adaptation (Behm, 1995). While the step-up and lunge do not allow for the use of comparatively high loads, they may still be valuable due to a high RFD and their unilateral nature. Unilateral exercises such as steps have relatively high mean concentric RFD and may be useful for training athletic activities such as sprinting. Training for powerful bilateral movements such as vertical jumping in basketball or volleyball should incorporate deadlifts for a bilateral high concentric RFD exercise.

The results of this study provide some insight into the potential of osteogenesis from these exercises. The squat's high GRF_P estimates a high magnitude of load, and the deadlift's high concentric RFD approximates a greater rate of loading, both of which are believed to be important for osteogenesis (Skerry, 1997). Therefore, a combination of these exercises should be included in programs designed to promote osteogenesis

CONCLUSION: This study shows that the back squat has the highest mean GRF_P followed by the deadlift, lunge, and step-up. Mean eccentric RFD is highest in the step-up followed by the squat, lunge, and deadlift. Mean concentric RFD is highest in the deadlift followed by the step-up lunge and squat. High GRF_P is necessary for strength training while high RFD is essential for explosive training. Many sports will require both strength and explosiveness.

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