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This study evaluated and compared the peak vertical ground reaction force (GRF) and rate of force development (RFD) for the eccentric and concentric phases of 4 lower body resistance training exercises, including the back squat, deadlift, step-up, and forward lunge. Sixteen women performed 2 repetitions of each of the 4 exercises at a 6 repetition maximum load. Kinetic data were acquired using a force platform. A repeated measures ANOVA was used to evaluate the differences in GRF between the exercises. Results revealed significant main effects for GRF both the eccentric ($p \leq 0.001$) and concentric ($p \leq 0.001$) phases. Significant main effects were also found for RFD for the eccentric ($p \leq 0.001$) and concentric phases ($p \leq 0.001$). Force and power requirements and osteogenic potential differ between these resistance training exercises.

Keywords: resistance training, ground reaction force, rate of force development

Introduction

Quantification of the intensity of training stimuli enables practitioners to select optimal exercises to elicit adaptations based on individual needs. The magnitude of muscle activation and the amount and rate of force development are of particular interest because these variables provide insight into the physical demands of resistance training exercises. Surface electromyography (EMG) and force platforms are two frequently utilized instruments that measure these variables of lower body resistance training exercises.

Surface electromyography has been used to evaluate single lower body resistance training exercises and variations therein (Ebben & Jensen, 2002; Schwanbeck et al., 2009), as well as multiple lower body exercises (Ekstrom et. al, 2007; Ebben, 2009; Ebben et al., 2009). While EMG is a valid and reliable tool for quantifying muscle activity, the amplitude of the EMG signal cannot be assumed to be equal to force production of the muscle due to several physiologic and technical factors (Neumann, 2010). However, other instruments, such as a force platform, are able to quantify kinetic variables.

Kinetic data demonstrate the magnitude of forces applied and received by the body and how quickly these forces are generated. The magnitude and rate of force generation are components of power production, which is a key determinant of athletic success for many sports (Stone, 1993). Additionally, the magnitude and rate of loading of the axial skeleton are essential determinants of the osteogenic potential of an exercise (Skerry, 1997). Exercises that promote osteogenesis are of particular importance to female athletes, who are at increased risk of impaired bone health associated with prolonged periods of amenorrhea, compared to male and eumenorrheic female counterparts (Jurimae & Jurimae, 2008).

Previously, kinetic analysis has been used to assess variations of a single exercise (Wallace et al., 2006; Wilson et al., 2008), and multiple modes of exercises, such as resistance training, plyometrics, and aerobic exercise (Ebben et al., 2009b; Morrissey et al., 1998). However, no previous study has performed a kinetic analysis of multiple variations of a single exercise mode, such as resistance training. Therefore, the purpose of the present study was to measure and compare the ground reaction force (GRF) and rate of force development (RFD) for both the eccentric and concentric phases of 4 resistance training exercises, including the back squat, deadlift, step-up, and forward lunge.

Methods

Subjects included 16 university women whose descriptive statistics are presented in Table 1. Inclusion criteria consisted of women subjects who were 18-27 years old and were either NCAA Division I or club sports athletes, or recreationally fit, and participated in lower body resistance training for at least two days a week for at least 6 weeks. Exclusion criteria included any orthopedic lower limb pathology that restricted athletic functioning, known cardiovascular pathology, and 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.

Table 1. Descriptive data (mean ± SD)

	Subjects (N=16)
Age (years)	21.19 ± 2.17
Height (cm)	169.39 ± 7.54
Body weight (kg)	66.08 ± 9.91
High school sports participation (years)	3.91 ± 0.38
College sports participation (years)	1.25 ± 1.91
Plyometric training participation (days/week)	0.94 ± 1.23
Resistance training participation (days/week)	2.72 ± 0.48
Aerobic training participation (days/week)	4.09 ± 2.08

Subjects attended two sessions, including one pre-test habituation session and one testing session. At the beginning of the each session, subjects participated in a standardized general and dynamic warm-up. During the pre-test habituation session, subjects were familiarized with and performed each of the 4 test exercises, including the back squat, deadlift, step-up using a 45.72 cm box, and forward lunge, in order to determine their 6 repetition maximum (RM). Approximately 1 week after the pre-test habituation session, subjects returned for the testing session. Subjects performed 2 full range of motion repetitions using their previously determined 6 RM loads, for each of the test exercises. Randomization of the exercises, limited repetitions, and 5 minutes of recovery were provided between test exercise in order to reduce order and fatigue effects. All exercises were performed according to the methods previously described (Earle & Baechle, 2000) with the exception that the step-up began on top of the box so that all exercises consistently started with the eccentric phase and ended with the concentric phase.

All exercises were performed on a force platform (Advanced Mechanical Technologies Incorporated, Model BP6001200) that was mounted flush with a weightlifting platform to minimize risk of injury. Kinetic data were analyzed for GRF and RFD for both the eccentric and concentric phases of each of the 4 exercises. Rate of force development was calculated as the difference between the peak GRF and the GRF from a point 100 ms before the peak, divided by 100 ms. All values were averaged using the 2 test trials.

Data were evaluated with SPSS 16.0 for Windows (Microsoft Corporation, Redmond, WA, USA) using a repeated measures ANOVA to determine statistical differences in kinetic data between the exercises. 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 showed significant main effects for both the eccentric ($p \leq 0.001$, $d = 1.00$, $\eta^2 = 0.838$) and concentric ($p \leq 0.001$, $d = 1.00$, $\eta^2 = 0.479$) phases, indicating differences in force requirements between the exercises. Significant main effects were also found for the RFD data for both the eccentric ($p \leq 0.001$, $d = 1.00$, $\eta^2 = 0.426$) and concentric ($p \leq 0.001$, $d = 1.00$, $\eta^2 = 0.391$) phases, indicating differences in power production among the exercises. Post hoc analysis identified the specific differences between the exercises as assessed by GRF and FRD data (Table 2).

Table 2. Kinetic data (mean ± SD)

	Squat	Deadlift	Step-Up	Lunge
Eccentric GRF (N)	1473.70 ± 293.61^{c***,d**}	1416.48 ± 253.64^{c***,d**}	944.59 ± 165.74^{a***,b***,d***}	1322.50 ± 195.12^{a**,b*,c***}
Eccentric RFD (N·sec^{-1})	953.78 ± 759.29^{d*}	793.16 ± 570.20^{d**}	574.36 ± 252.85^{d**}	1909.65 ± 1124.69^{a*,b**,c**}
Concentric GRF (N)	1580.73 ± 361.08^{c**,d**}	1520.48 ± 276.45^{c**,d**}	1202.39 ± 216.38^{a**,b**,d*}	1399.00 ± 207.33^{a**,b**,c*}
Concentric RFD (N· sec^{-1})	714.86 ± 630.76^{c**,d**}	893.50 ± 456.63^{c*,d**}	2496.00 ± 1802.58^{a**,b*}	1441.69 ± 509.71^{a**,b**}

GRF = ground reaction force; RFD = rate of force development; a = significantly different from squat; b = significantly different from deadlift; c = significantly different from step-up; d = significantly different from lunge; * = $p \leq 0.05$; ** = p 0.01; *** = $p \leq 0.001$

Discussion

This is the first known study to assess the GRF and RFD of several lower body resistance training exercises. Significant differences in GRF and RFD were found among the squat, deadlift, step-up, and lunge. The present study revealed differences in the force demands for both eccentric and concentric phases of the exercises, as assessed by GRF. Specifically, GRF data were greatest for the squat and deadlift, followed by the lunge, and the step-up. Previous research evaluating kinetic data during maximal isometric squats found peak GRF values of 2186.95 ± 377.34 N and RFD values of 2689.32 ± 804.80 N/s, which were higher than the values obtained in the current study (McBride et. al, 2006). This may be attributed to differences in the relative intensity of the squat between the two studies. Specifically, the previous study evaluated the squat under a maximal load, while the present study used a 6 RM load. Additionally, the RFD of the eccentric phase of the lunge was significantly greater than that of all the other exercises. This latter finding is somewhat consistent with previous research demonstrating that plyometric exercises, such as the depth jump, and loaded jumps such as the squat jump, yield greater RFD data than the squat (Ebben et al., 2010). This finding is potentially due to the eccentric or weight acceptance phase of the lunge, which is characterized by a rapid loading in the transition from non-weight bearing to weight bearing on the lead leg as the subject lunges forward. The RFD during the concentric phase of the step-up was significantly greater than that of the squat and deadlift, and trended to be greater than that of the lunge. Thus, the step-up and lunge provide a greater RFD stimulus than the squat and deadlift. The large force demands of the squat and deadlift may provide a more intense training stimulus in terms of GRF, though athletic power may be augmented by training with the lunge and step-up, due to the greater RFD component of these exercises during the eccentric and concentric phases, respectively.

Each of these exercises may have value as an osteogenic stimulus either through relatively high GRF or relatively high RFD, which may approximate the magnitude and rate of overload which are believed to be important osteogenic stimuli (Skerry, 1997).

Previous research examining similar resistance training exercises has also shown differences in muscle activation between the 4 exercises assessed (Ebben et al., 2009). This electromyographic data along with the kinetic data from the present study enhances the understanding of the characteristics of these exercises.

Conclusion

Of the 4 exercises assessed, the squat and deadlift yielded the greatest GRF, while the lunge and step-up had the greatest RFD demands. Training with a combination of these exercises may be ideal for obtaining adaptations along the force velocity continuum and for promoting osteogenesis.

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