GROUND AND KNEE JOINT REACTION FORCES DURING VARIATIONS OF PLYOMETRIC EXERCISES

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Six Division-I athletes, who routinely used plyometric exercises, performed drop jumps from 46 and 61 cm, a pike jump, tuck jump, single leg jump, counter movement jump, squat jump, and a squat jump holding dumbbells equal to 30% of 1 RM squat. GRF obtained via an AMTI force plate and video analysis of markers placed on the left hip, knee, lateral malleolus, and fifth metatarsal were used to estimate reaction forces on the knee joint (KRF) and average rate of eccentric force development (ERFD). One-way Repeated Measures ANOVA indicated ERFD, KRF, and KRF relative to body weight were different across conditions ($p < 0.05$), but peak GRF and GRF relative to body weight were not ($p > 0.05$). Results indicate that although peak GRF forces of landing from plyometric exercise may not differ, the KRF do possibly due to variability in landing techniques.

KEY WORDS: knee joint reaction forces, landing techniques, stretch shortening cycle

INTRODUCTION: Plyometric exercises are widely used to augment explosiveness of athletic movements. There have been suggestions that these exercises may increase the possibility of joint injury and indeed drop jumps above 46 cm are not recommended for individuals weighing more than 100 kg and those under 14 or over 60 years of age (Potach, 2004). On the other hand, Milgrom and coworkers (2000) found that drop jumps up to 52 cm resulted in less force on the tibia than running at 17 km · hr^{-1}.
Plyometric training has also been suggested to be beneficial to strengthening bone and/or joints. Bauer and colleagues (2001) have suggested that joint reaction forces from drop jumps may result in forces that increase the mass of bones surrounding active joints. Furthermore plyometric training has been shown to alter neuromuscular activation during jumping and landing (Chimera et al., 2004; Wilkerson et al., 2004). However, these training programs were quite limited in variety, including only one or two types of jumps or drops from a single height.
Ground reaction forces of plyometric exercises have been shown to vary depending on the type of exercise performed or the height of a drop jump (Jensen & Ebben, 2002). However, the forces on the joints while performing variations of plyometric exercises have not been extensively studied. Understanding these forces is important in order to quantify the intensity of plyometric exercises. Therefore the purpose of the current study was to examine peak ground reaction forces and knee joint reaction forces while performing a variety of plyometric exercises.

METHODS: Six NCAA Division I athletes (four female and two male; mean ± SD; age = 20.3 ± 1.0 years, body mass = 78.9 ± 12.2 kg, 1RM squat = 143.6 ± 55.6 kg), (track and field, volleyball and wrestling) volunteered to serve as subjects for the study. All subjects used the studied exercises in their regular resistance-training regimen. Subjects completed a Physical Activity Readiness-Questionnaire and signed an informed consent form prior to participating in the study. Approval for the use of Human Subjects was obtained from the institution prior to commencing the study. Subjects had performed no strength training in the 48 hours prior to data collection.
Warm-up prior to the plyometric exercises consisted of at least 3 minutes of low intensity work on a cycle ergometer. This was followed by static stretching including one exercise for each major muscle group with stretches held from 12-15 seconds. Following the warm-up and stretching exercises, the subjects were allowed at least 5 minutes rest prior to beginning the plyometric exercises. The order of plyometric exercises was randomly assigned and

consisted of drop jumps (DJ) from 46 and 61 cm, a pike jump (pike), tuck jump (tuck), single leg jump (off the left leg) (SLJ), counter movement jump (with arm swing) (CMJ), squat jump (with hands on top of the head) (SJ), and a squat jump holding dumbbells equal to 30% of 1 RM squat (SJ30) (Potach, 2004). A one minute rest interval was maintained between each exercise.

The plyometric exercises were performed by taking off from and landing on a 2 cm thick aluminum plate (76 X 102 cm) bolted directly to a force platform (OR6-5-2000, AMTI, Watertown, MA, USA). Attachment of the plate resulted in a natural frequency of not less than 142 Hz, within limits recommended for this data collection (AMTI). Ground Reaction Force (GRF) data were collected at 1000 Hz, real time displayed and saved with the use of computer software (BioSoft 1.0, AMTI, Watertown, MA, USA) for later analysis. Peak GRF was the highest value attained during the movement and occurred during the landing. The average rate of eccentric force development (ERFD) was defined as the first peak of GRF divided by the time from onset of landing force to the first peak of GRF (Bauer et al., 2001).

Video of the exercises was obtained at 60 Hz from the left side using 1 cm reflective markers placed on the greater trochanter, knee joint center, lateral malleolus and the fifth metatarsal. Markers were digitized using Motus 5.2 (Peak Performance Technologies, Englewood, CO) and acceleration of the joint segment center of mass was determined after data was smoothed using a fourth order Butterworth filter (Winter, 1990).

To synchronize data a signal was used to initialize kinetic data collection which also displayed a light in the view of the camera. Data were then combined into a single file and splined to create a file of equal length at 60Hz. Knee joint reaction forces (KRF) were estimated according to Bauer et al (2001). Because GRF for all but the SLJ would have been distributed across both feet (and therefore both knees) GRF values for all but the SLJ were divided by two prior to calculation of KRF.

Statistical treatment of the data was performed using a One-Way (type of plyometric exercise) Repeated Measures ANOVA for average ERFD, GRF, GRF divided by body weight (GRF/BW) and KRF and KRF divided by body weight (KRF/BW).

RESULTS AND DISCUSSION: Peak ground reaction forces during plyometric exercises occurred during the landing portion of the exercises, as noted by previous authors (Jensen and Ebben, 2002; Potach, 2004). Peak GRF and GRF/BW were not statistically different ($p>0.05$) across the eight conditions (see Table 1). This finding is in contrast to previous work by Jensen and Ebben (2002) who found differences in impulse when comparing a variety of lower body plyometric exercises. It is possible that the difference in findings may be due to lack of statistical power in the current study as a result of a smaller number of subjects and the relatively large variability in plyometric performance.

Table 1 Peak ground reaction force (GRF), peak GRF relative to body weight (GRF:BW), and average rate of loading (mean ± SD) for eight variations of plyometric exercises (n=6).

	DJ46	DJ61	CMJ	SJ	SJ30%	SLJ	pike	tuck
GRF (N)	2570 ± 979	3056 ± 960	2879 ± 892	2389 ± 437	2966 ± 1112	2261 ± 697	2772 ± 767	2937 ± 1409
GRF:BW ($N\cdot Kg^{-1}$)	3.25 ± 0.74	3.91 ± 0.80	3.71 ± 0.95	3.16 ± 0.84	3.74 ± 0.77	2.92 ± 0.81	3.70 ± 1.18	3.66 ± 1.33

Table 2 Average rate of eccentric force development (mean ± SD) for eight variations of plyometric exercises (n=6).

	DJ46	DJ61	CMJ	SJ	SJ30%	SLJ	pike	tuck
ERFD (N/s)	741 ± 347	975 ± 313	843 ± 357	505 [a] ± 226	424 [a] ± 168	718 ± 293	651 ± 232	804 ± 224

[a] Significantly different ($p<0.05$) from DJ 46, DJ61, CMJ, SLJ, tuck

On the other hand, differences were found in the ERFD up to the point of the first peak GRF associated with variations of plyometric exercises. The first peak GRF (see Figure 1) has been previously described as the contact of the toe followed by heel contact at peak 2 (Bauer et al., 2001). In the present study, the ERFD was lower ($p < 0.05$) for squat jump and squat jump with 30% of 1RM squat than either of the drop jumps, the counter movement jump, single leg jump and the tuck jump (see Table 2).

These differences in the ERFD across the jumping conditions appear to indicate variability among plyometric exercises, thus differences in their relative intensity level. These differences in ERFD are perhaps a function of landing techniques, which is likely influenced by the nature of the plyometric exercise itself, and includes factors such as jump height, unilateral versus bilateral landing, added external load, and the degree to which forceful hip and knee extension is required in order for subjects to prepare their legs for landing such as with the tuck and pike jump. Researchers have suggested that a threshold ERFD was necessary to optimally activate the stretch shortening cycle (Ebben et al., 1999). While determining the threshold is elusive, the current data may be used to determine the progression of plyometric exercises via an increasing ERFD.

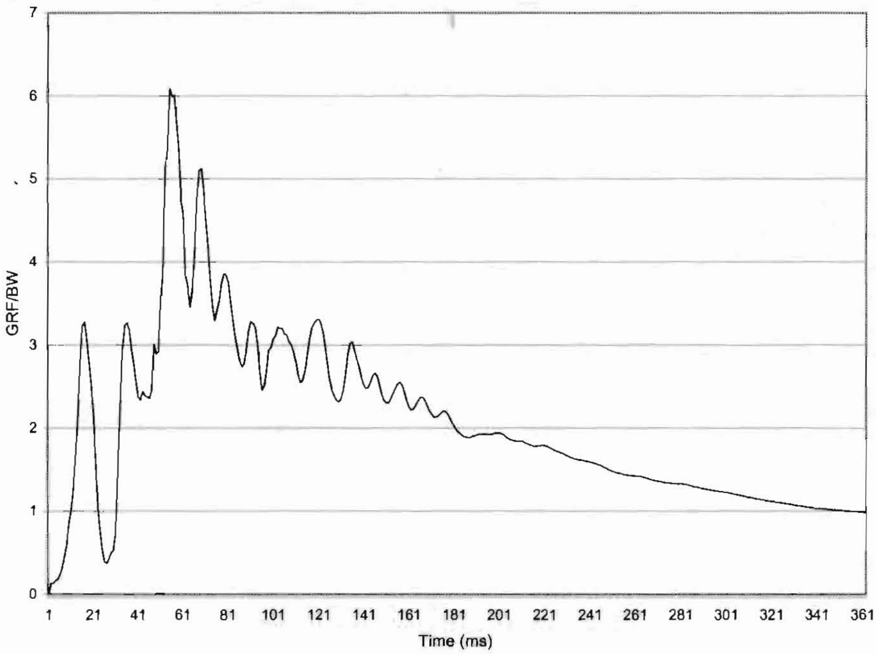

Figure 1 Ground reaction force relative to Body mass for Subject 3 during the landing of a Drop Jump from 61 cm.

In contrast to the ground reaction forces, but consistent with ERFD, peak KRF and KRF/BW also varied across the different types of jumps ($p < 0.05$) as shown in Table 3. Variations in KRF, and KRF/BW, associated with different plyometric exercises, suggest that the relative intensity of these plyometric exercises can be empirically determined to some degree through this variable as well. Of particular interest is the variability in forces on the knee relative to body weight, with some plyometric exercises such as the pike and tuck jumps producing KRF nearly 10 times BW, likely due to the subjects' active concentric activation of the knee and hip extensors in order to get the feet in a position for landing, after the high degree of hip flexion associated with the initial part of these exercises. The single leg jump also exhibited high KRF/BW values which were likely due to the fact that all of the reaction force is unilaterally distributed and unilateral jump heights are typically more than 50% of the bilateral equivalent (van Soest et al., 1985). Exercises with added load resulted in lower jump heights and therefore somewhat lower KRF and KRF/BW as the acceleration due to gravity was less. The higher KRF and KRF/BW associated with the tuck, pike, and single leg jumps suggest that these exercises should be progressed later in the development of a plyometric program as a way to increase plyometric intensity. Furthermore, these exercises should be used sparingly, or progressed gradually with individuals during the early stages of recovery from knee injury. Further study is recommended to investigate the forces taking place during plyometric activities.

Table 3 Peak knee reaction force (KRF) and peak KRF relative to body weight (mean ± SD) for eight variations of plyometric exercises (n=6).

	DJ46	DJ61	CMJ	SJ	SJ30%	SLJ	pike	tuck
KRF (N)	4694 [b] ± 1348	4620 ± 1133	3974 [a] ± 1265	5232 ± 3701	3616 [b] ± 948	6638 ± 1863	7489 ± 1822	7566 ± 1947
KRF:BW ($N \cdot Kg^{-1}$)	5.98 [c] ± 1.26	5.97 ± 1.14	5.11 [a] ± 1.21	7.07 ± 5.63	4.80 [b] ± 1.33	8.54 ± 1.63	9.68 ± 1.95	9.94 ± 2.42

[a] Significantly different ($p < 0.05$) from pike, tuck, SLJ
[b] Significantly different ($p < 0.05$) from pike, tuck
[c] Significantly different ($p < 0.05$) from pike, SLJ

CONCLUSION: Quantifying intensity of resistance training with machines or free weights is relatively easy and determined in part by the loads that are typically labeled on machines or weight plates. For plyometrics, the best way to quantify exercise intensity may be to understand variables such as peak GRF, peak GRF/BW, KRF, KRF/BW and ERFD. Enhanced understanding of these intensity variables is important to allow practitioners to progress plyometric intensity from low to high over the course of the program.

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