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Intensity rankings of plyometric exercises using joint power absorption

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ABSTRACT

Background: Athletic trainers and physical therapists often progress patients through rehabilitation by selecting plyometric exercises of increasing intensity in preparation for return to sport. The purpose of this study was to quantify the intensity of seven plyometric movements commonly used in lower-extremity rehabilitation by joint-specific peak power absorption and the sum of the peak power.

Methods: Ten collegiate athletes performed submaximal plyometric exercises in a single test session: vertical jump, forward jump, backward jump, box drop, box jump up, tuck jump, and depth jump. Three-dimensional kinematics and force platform data were collected to generate joint kinetics. Peak power absorption normalized to body mass was calculated at the ankle, knee, and hip, and averaged across repetitions. Joint peak power data were pooled across athletes and summed to obtain the sum of peak power. Movements were ranked from 1 (low) to 7 (high) based on the sum of peak power and joint peak power (ankle, knee, hip).

Findings: The sum of peak power did not correspond with standard low, medium, and high subjective intensity ratings or joint peak power in all joints. Mixed model analyses revealed significant variance between the sum of peak power and joint peak power ranks in the forward jump, backward jump, box drop, and depth jump ($P < 0.05$), but not in the vertical jump, box jump up, and tuck jump.

Interpretation: Results provide intensity rankings that can be used directly by athletic trainers and physical therapists in developing protocols for rehabilitation specific to the injured joint.

1. Introduction

Plyometric exercise, a well-established tool used to improve sports performance and to prevent injury, has recently been adapted for lower-extremity rehabilitation (Chmielewski et al., 2006). Regardless of application, common recommendation is to gradually increase the intensity of the plyometric exercises to avoid setbacks (Chmielewski et al., 2006; Ebben, 2007). In rehabilitation, this progression assists the redevelopment of neuromuscular function while also simulating movements similar to competition (Chmielewski et al., 2006). In addition, the landing phase of plyometric exercises, where most injuries occur (Kipp and Palmieri-Smith, 2012), requires lower-extremity joints to dynamically stabilize (Ebben et al., 2010; Petushek et al., 2010). This dynamic stabilization can assist healing when applied at the appropriate intensity. However, programming the particular movements and sequencing can be challenging given the wide variety of plyometric exercises available and the subjective nature of "plyometric intensity". Potach and Chu (2000) define plyometric intensity as "the amount of stress placed on involved muscles, connective tissues, and joints" and assign standard low, medium, and high rankings to exercises. This definition of intensity indicates that biomechanical measures may be best to quantify and rank plyometric exercises.

A variety of biomechanical measures have been used to quantify differences between plyometric exercises. Most measures were taken directly from the ground reaction force during landing such as peak vertical ground reaction force (Wallace et al., 2010), rate of force development (Jensen and Ebben, 2007), and time to stabilization (Ebben et al., 2010). Jensen and Ebben (2007) also examined knee joint reaction forces to assess the stresses placed on muscles, connective tissues, and joints. A "reactive strength index" combined ground contact time with jump height to measure explosive strength and gauge an athlete's ability to develop force quickly (Ebben and Petushek, 2010). Differences between plyometric exercises were also quantified using integrated electromyographic signal from the gastrocnemius and the quadriceps (Ebben et al., 2008). A straightforward comparison between the investigations is difficult because of the large variety in exercises chosen (Table 1). Among these investigations, only Ebben et al. (2010) focused specifically on rehabilitation applications.

Because plyometric exercises place different demands on each joint, generic intensity rankings may not be adequate for developing exercise progression in lower-extremity rehabilitation. Motor unit recruitment recorded from individual muscles does not correlate well with typical intensity rankings (Ebben et al., 2008). Mechanical outputs vary across

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Table 1
A summary of previous literature demonstrates the limited number of common exercises. Exercises are ordered from low intensity to high intensity (bottom to top) based on peak ground reaction force relative to body weight (PGRF/BW), rate of eccentric force development (E-RFD), knee joint reaction force relative to body weight (KRF/BW), integrated electromyography (EMG) in the quadriceps and gastrocnemius muscle groups, and time to force stabilization for men and women. Ranking trends in depth jump from a height of 61 cm, squat jump, and tuck jump are noted in black boxes, light gray, and dark gray respectively.*

Method	PGRF/BW (Wallace et al. 2010)	E-RFD (Jensen & Ebben 2007)	KRF/BW (Jensen & Ebben 2007)	EMG gastrocnemius (Ebben et al. 2008)	EMG quadriceps (Ebben et al. 2008)	Time to stabilization men (Ebben et al. 2010)	Time to stabilization women (Ebben et al. 2010)
				Vertical jump ‡	Cone hop		
High intensity	Depth drop 90 cm	Depth jump 61 cm	Tuck jump	Cone hop	Box jump 61 cm	Single-leg jump	DB countermovement
	Depth jump 90 cm	Countermovement	Pike jump	Tuck jump	Tuck jump	Tuck jump	Single-leg jump
	Depth drop 60 cm	Tuck jump	Single-leg jump	Squat jump †	Vertical jump ‡	Countermovement	Tuck jump
	Standing long jump	Depth jump 46 cm	Squat jump	Pike jump	DB squat jump	DB countermovement	Squat jump
↕	Depth jump 60 cm	Single-leg jump	Depth jump 46 cm	Box jump 61 cm	Squat jump †	Squat jump	Countermovement
	2 consecutive jump	Pike jump	Depth jump 61 cm	Db squat jump	Pike jump	Cone hop	Cone hop
	Vertical jump	Squat jump	Countermovement	Single-leg jump ‡	Single-leg jump ‡	Line hop	Line hop
Low intensity	Depth drop 30 cm	DB squat jump	Db squat jump	Depth jump 30 cm	Depth jump 30 cm		
	Depth jump 30 cm			Depth jump 61 cm	Depth jump 61 cm		

* DB = dumbbell. † Referred to as two-foot ankle hop by Ebben et al. (2008). ‡ Referred to as double-leg vertical jump and reach (Vertical Jump) and single-leg vertical jump and reach (Single-Leg Jump) by Ebben et al. (2008).

joints in performance-oriented exercises due to significant variations in joint muscle recruitment (Sugisaki et al., 2013). Of the six mechanical metrics examined, peak negative power contained significant interaction between the joint and exercise in all joints. Power indicates the amount of energy that was exerted (positive) or absorbed (negative). Because intensity correlates to the stretch load (kinetic energy) applied through the exercise (Chmielewski et al., 2006), peak negative power may be an effective metric to quantify the intensity of plyometric exercises.

The objective of this investigation was to quantify and rank the intensity of seven plyometric exercises commonly used in lower-extremity rehabilitation. Joint-specific intensity was quantified with peak negative power measured at each joint in the lower extremity, and overall intensity was quantified by the sum of the peak powers from each joint. We hypothesized that the general intensity rankings would reflect previously published rankings, but that joint-specific intensity rankings will result in differences based on the joint of interest. We anticipate that these data will assist athletic trainers and physical therapists when developing progressive rehabilitation protocols that can be tailored to the injury site.

2. Methods

This single cohort repeated measures study was approved by the University of Denver (DU) Institutional Review Board prior to initiation. Ten collegiate athletes from DU swimming, soccer, and lacrosse (3 males, 7 females, 20.8 (SD: 0.75) years) participated in this investigation. Each athlete, recruited through advertisements within the DU Athletic Department, had prior experience with plyometric exercises through regular strength and conditioning training. Prior to enrollment in the study, athletes were screened for lower-extremity injury and gave informed written consent. Each athlete visited the DU Human Dynamics Laboratory for a single two-hour session that included a warm up, instrumentation, and execution of a series of bilateral plyometric exercises. Each athlete wore compression shirts and shorts and used their own athletic shoes during the data collection.

The standardized warm up consisted of five repetitions of seven dynamic exercises (bilateral body-weight squats, left and right single-leg squats, left and right forward lunges, and left and right side lunges) that correlate to lower-extremity plyometrics. The warm up was followed by coached stretching of the major muscle groups in the lower extremities and hips; each stretch was held for approximately 15 s. After stretching, the athlete rested for five minutes before beginning the data collection.

Each athlete was instrumented with 34 reflective markers placed on the hips and lower extremities. Three-dimensional marker positions were collected through Vicon Nexus (Peak Performance Technologies, Centennial, CO, USA). Ground reaction forces (GRFs) and moments in three degrees of freedom were collected with force platforms (Bertec, Columbus, OH, USA). The force platforms were arranged so that GRFs for each limb could be independently collected during the landing phase of each plyometric exercise.

Each athlete performed a series of seven submaximum bilateral plyometric exercises that are routinely used for lower-extremity rehabilitation in the DU sports medicine program. The series consisted of a countermovement vertical jump (VertJ), forward jump (ForwJ), backward jump (BackJ), box drop (BoxD), box jump up (BoxJ), tuck jump (TuckJ), and depth jump (DepthJ), presented in random order.

Instructions and jump height were standardized for each athlete. Prior to performance, each athlete watched a video that demonstrated correct technique with verbal instructions. Several exercises required a hurdle (forward jump) or a plyometric box (box jump up, box drop, and depth jump). Jump height or drop height was controlled with five boxes (20 cm, 25 cm, 30 cm, 40 cm, and 45 cm) designed to rigidly mount to the force platform. The hurdle height and plyometric box height were set as one quarter and one half the vertical distance from the lateral epicondyle of the knee to the ground, respectively (Fig. 1).

For each exercise, each athlete performed four practice repetitions followed by three trial repetitions. The practice repetitions were separated by 10-second rest periods. After a 45-second rest period, the athlete performed three trial repetitions with 30-second rest periods between each repetition. To minimize fatigue, the athlete rested for two minutes between consecutive plyometric exercises. To monitor fatigue, each athlete rated their exertion level between the practice repetitions and the trial repetitions. If exertion level exceeded three (on a 10-point scale), an additional two minutes of rest was given between exercises.

Data were processed into joint kinetic variables using Visual 3D Standard (C-Motion, Germantown, MD, USA). Marker position and force platform data were filtered with a fourth-order zero phase lag low-pass Butterworth filter with cutoff frequency equal to 25 Hz (Bisseling and Hof, 2006). Peak power absorption normalized to body mass was calculated at the ankle, knee, and hip for each repetition, and averaged across repetitions to provide a point estimate for joint peak power (JPP). The JPPs from each lower extremity joint were summed within an exercise to obtain the sum peak power (SPP), which serves as an estimate for overall intensity. Exercises were ranked based on SPP and each JPP (ankle, knee, hip) from low to high (1 to 7) and compared to standard subjective intensity ratings of low, medium, and high from Potach and Chu (2000).

SPP, JPP, and their associated ranks (dependent variables) were statistically analyzed with respect to exercise, joint, and subject (independent variables). To assess the differences in peak power absorbed between exercises, a mixed-model analysis with random effect of