KINETIC ANALYSIS OF HORIZONTAL PLYOMETRIC EXERCISE INTENSITY

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This study assessed the multi-planar kinetic characteristics of a variety of plyometric exercises that have a horizontal component. Ten men and ten women performed a variety of plyometric exercises including the double leg hop, standing long jump, single leg standing long jump, bounding, skipping, power skipping, cone hops and the hurdle hop (45.72 cm). Subjects also performed the countermovement jump. All plyometric exercises were performed on a force platform. Landing peak ground reaction forces (GRF) and rate of force development (RFD) were analyzed for three planes of movement. A number of differences were found between plyometric exercises. Quantification of plyometric exercises based on the analysis of GRF and RFD assists practitioners in the design of programs based on known intensity of these exercise

KEY WORDS: stretch shortening cycle, jump, force platform, specificity

INTRODUCTION: Plyometrics exercises are used to improve explosive power and prevent injury (deVillarreal, et al., 2009). Understanding the differences in plyometric exercise intensity is necessary for the progression of these exercises in performance enhancement and rehabilitation programs. Plyometric intensity has been defined as the amount of stress placed on involved muscles, connective tissues, and joints, and is dictated by the type of plyometric exercise performed (Potach & Chu, 2008). As a result, previous research has quantified the intensity of a variety of plyometric exercises that are performed primarily in the vertical plane. No study has comprehensively assessed the intensity of horizontal plyometric exercises. However, the benefits of plyometric exercise are biomechanically specific to the plane in which they are performed (Brughelli, et al., 2008).
Previous research examined a variety of kinetic characteristics of plyometric exercises performed primarily in the vertical plane. For example, ground reaction forces (GRF) and joint reaction forces have been assessed for a limited number of plyometric exercises (Tsarouches, et al., 1995). Research assessing the intensity of a larger number of plyometric exercises is limited to studies quantifying joint mechanical output of plyometric exercises (Sugisaki, et al., 2013), impulse and GRF (Jensen & Ebben, 2007; Jensen, et al., 2008), knee joint reaction forces (Jensen & Ebben, 2007), and electromyography (Ebben et al., 2008). Other comprehensive studies evaluated the take off and landing kinetic characteristics of eight different plyometric exercises performed primarily in the vertical plane (Ebben, at al., 2011).
Vertical plane exercise demonstrates limited value for sprinting and change of direction performance often referred to as agility (Brughelli, et al., 2008). Training programs that incorporate horizontal plyometrics improve average sprinting performance more than those that do not (Singh & Singh, 2013). To date, no known study has assessed the kinetic characteristics of a variety of horizontal plane plyometric exercises or assessed the sagittal or frontal plane kinetic characteristics of plyometric exercises. Therefore, the purpose of this study was to quantify horizontal plyometric exercise intensity in all three planes.

METHODS: Ten men (mean ± SD; age 28.50 ± 5.29 yr; body mass 87.87 ± 15.62 kg) and 10 women (mean ± SD; age 22.90 ± 4.91 yr; body mass 68.46 ± 8.22 kg) served as subjects. The study was approved by the institution's internal review board and all subjects provided written informed consent.
All subjects were habituated to the exercises. Subjects were given instruction, a demonstration, and practiced the correct performance of the plyometric exercises to be

tested. The plyometric exercises included the double leg hop (DLH), standing long jump (SLJ), single leg standing long jump (SLSLJ), bounding (BND), skipping (SKP), power skipping (PSKP), cone hops (CH), and the hurdle hop (HH) (45.72 cm). These plyometric exercises were included in this study since they represent a variety of commonly described and used plyometric exercises that include a horizontal component (Potach & Chu, 2008). Subjects also performed the countermovement jump (CMJ) for the purpose of including a commonly performed and studied (Ebben, et al., 2011; Jensen & Ebben, 2007) vertical plyometric exercise for comparison.

Prior to testing, each subject warmed up and performed dynamic stretching and jumping. Subjects then performed 2 repetitions of each of the plyometric test exercises in a randomized order with 1 minute rest between each exercise. The test exercises were assessed with 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.

Dependent variables were selected in order to evaluate the rate of force development (RFD) and peak GRF during the landing phase of each plyometric exercise, in each plane. These variables were calculated from the force time records of each plyometric exercise consistent with methods previously used (Jensen & Ebben, 2007; Ebben, et al., 2011). Jump height (JH) was calculated based, in part, on flight time using previously published equations (Moir, 2008). The RFD in each plane was defined as the first peak of GRF, minus the initial GRF upon landing, divided by the time to the first peak of GRF, minus the time of initial ground reaction force, and normalized to one second (Jensen & Ebben, 2007; Ebben, et al., 2011). Peak GRF was defined as the highest GRF value attained during the landing phase of the plyometric exercise (Jensen & Ebben, 2007). The average for two trials for each plyometric exercise was used for analysis.

The statistical analyses were undertaken with SPSS 20.0. A two way mixed ANOVA with repeated measures for plyometric exercise type was used to evaluate the main effects for plyometric exercise type and the interaction between plyometric exercise type and gender, for each dependent variable. Dependent variables included GRF in the vertical (GRF-V), sagittal (GRF-S) and frontal (GRF-F) planes, as well as the rates of force development in the vertical (RFD-V), sagittal (RFD-S) and frontal (RFD-F) planes. Bonferroni adjusted pairwise comparisons were used to identify the specific differences between the plyometric exercises. The trial to trial reliability of each dependent variable was assessed for each plyometric exercise using average measures intraclass correlation coefficient (ICC). In addition, a repeated measures ANOVA was used to confirm that there was no significant difference ($P > 0.05$) between trials of each plyometric exercise. Assumptions for linearity of statistics were tested and met. An *a priori* alpha level of $P \leq 0.05$ was used with post hoc power and effect size represented by d and η_p^2, respectively.

RESULTS: The analysis of GRF-V revealed significant main effects for plyometric exercise type ($P \leq 0.001$, $\eta_p^2 = 0.50$, $d = 1.00$). Analysis of GRF-S showed significant main effects for plyometric exercise type ($P \leq 0.001$, $\eta_p^2 = 0.62$, $d = 1.00$). Analysis of GRF-F also demonstrated significant main effects for plyometric exercise type ($P \leq 0.001$, $\eta_p^2 = 0.39$, $d = 1.00$).

Analysis of RFD-V showed significant main effects for plyometric exercise type ($P \leq 0.001$, $\eta_p^2 = 0.43$, $d = 1.00$). Analysis of RFD-S revealed significant main effects for plyometric exercise type ($P \leq 0.001$, $\eta_p^2 = 0.39$, $d = 1.00$). Finally, analysis of RFD-F showed significant main effects for plyometric exercise type ($P \leq 0.001$, $\eta_p^2 = 0.16$, $d = 0.97$). There was no significant interaction between plyometric exercise type and gender for any of the variables assessed. Results of Bonferroni adjusted pairwise comparisons for each dependent variable are presented in Tables 1 to 6. Intraclass correlation coefficients assessing the trial to trial reliability ranged from 0.40 to 0.99, with most ICC's over 0.80, for the plyometric exercises and dependent variables.

Table 1. Peak vertical plane ground reaction forces in Newtons (mean ± SD), for each plyometric exercise.

	SKP[a]	PSKP[b]	BND[b]	SLSLJ[a]	CH[c]	CMJ[d]	DLH[e]	HH[f]	SLJ[a]
Mean	414	542	550	646	754	755	787	798	909
SD	84	187	164	188	271	291	355	310	305

[a] Different ($p \leq 0.05$) than all other plyometrics
[b] Different ($p \leq 0.05$) than all plyometrics except for the BND
[c] Different ($p \leq 0.05$) than all other plyometrics except for CMJ, DLH, and HH.
[d] Different ($p \leq 0.05$) than all other plyometrics except for CH, DLH, and HH.
[e] Different ($p \leq 0.05$) than all other plyometrics except for CH, CMJ, and HH
[f] Different ($p \leq 0.05$) than SKP, PSKP, BND, and SLSLJ

Table 2. Peak sagittal plane ground reaction forces in Newtons (mean ± SD), for each plyometric exercise.

	SKP[a]	PSKP[b]	CH[c]	CMJ[d]	HH[e]	BND[b]	DLH[a]	SLSLJ[a]	SLJ[a]
Mean	82	134	139	160	171	180	246	285	345
SD	16	58	40	78	56	106	123	124	139

[a] Different ($p \leq 0.05$) than all other plyometrics
[b] Different ($p \leq 0.05$) than all plyometrics except for the CH, CMJ, and HH.
[c] Different ($p \leq 0.05$) than all other plyometrics except for PSKP, CMJ, and BND.
[d] Different ($p \leq 0.05$) than SKP, DLH,SLSLJ, and SLJ
[e] Different ($p \leq 0.05$) than all other plyometrics except for CMJ and BND

Table 3. Peak frontal plane ground reaction force in Newtons (mean ± SD), for each plyometric exercise.

	CH[a]	SKP[b]	HH[a]	CMJ[c]	PSKP[d]	DLH[e]	SLSLJ[f]	SLJ[g]	BND[h]
Mean	25	29	34	55	55	61	70	71	78
SD	12	10	17	42	35	37	24	45	46

[a] Different ($p<0.05$) than all other plyometric other than the SKP
[b] Different ($p<0.05$) than all other plyometrics other than the CH and HH.
[c] Different ($p<0.05$) than all other plyometrics except the PSKP, DLH, and SLSLJ.
[d] Different ($p<0.05$) than all other plyometrics other than the CMJ and DLH
[e] Different ($p<0.05$) than CH, SKP, HH, and BND
[f] Different ($p<0.05$) than CH, SKP, HH, and PSKP
[g] Different ($P<0.05$) all other plyomtrics except the DLH, SLSLJ, and BND.
[g] Different ($P<0.05$) all other plyomtrics except the SLSLJ and SLJ.

Table 4. Vertical plane rate of force development in N·m/s (mean ± SD), for each plyometric exercise.

	SKP[a]	CH[b]	PSKP[c]	CMJ[c]	HH[b]	BND[c]	SLSLJ[d]	DLH[e]	SLJ[a]
Mean	21819	62052	64000	65656	71556	78273	92979	121947	168719
SD	36915	44840	119176	48191	48257	59273	45076	107658	75197

[a] Different ($p \leq 0.05$) than all other plyometrics.
[b] Different ($p \leq 0.05$) than SKP, SLSLJ, DLH, and SLJ.
[c] Different ($p \leq 0.05$) than SKP, DLH, SLJ.
[d] Different ($p \leq 0.05$) than SKP, CH, CMJ, HH, and SLJ.
[e] Different ($p \leq 0.05$) than all other plyometrics except for SLSLJ

Table 5. Sagittal plane rate of force development in N·m/s (mean ± SD), for each plyometric exercise.

	SKP[a]	CMJ[b]	CH[c]	PSKP[d]	BND[e]	DLH[e]	HH[f]	SLSLJ[g]	SLJ[h]
Mean	5927	18670	20340	22489	29042	32048	39137	42091	47188
SD	7314	21166	14094	23595	18800	25206	29177	24505	28261

[a] Different ($p \leq 0.05$) than all other plyometrics
[b] Different ($p \leq 0.05$) than all other plyometrics except for the PSKP and CH
[c] Different ($p \leq 0.05$) than the SKP, HH. SLSLJ, and SLJ
[d] Different ($p \leq 0.05$) than SKP, HH, SLSLJ, SLJ
[e] Different ($p \leq 0.05$) than SKP, CMJ, SLSLJ, SLJ
[f] Different ($p \leq 0.05$) than all other plyometric except for the DLH, SLSLJ, and SLJ
[g] Different ($p \leq 0.05$) than all other plyometric except for the HH and SLJ.

Table 6. Frontal plane rate of force development in N·m/s (mean ± SD), for each plyometric exercise.

	SKP[a]	CH[a]	CMJ[b]	PSKP[c]	BND[d]	HH[c]	SLSLJ[d]	SLJ[e]	DLH[d]
Mean	1944	4171	9252	9975	10064	10085	10127	12865	13023.35
SD	1573	2761	9527	15553	7957	15765	5595	9650	16646.56

[a] Different ($p \leq 0.05$) than all other plyometrics
[b] Different ($p \leq 0.05$) than SKP, CH, and SLJ.
[c] Different ($p \leq 0.05$) than the SKP.
[d] Different ($p \leq 0.05$) than the SKP and CH.
[e] Different ($p \leq 0.05$) than the SKP, CH, and CMJ

DISCUSSION: This is the first study to comprehensively assess the intensity of a variety of horizontal plyometric exercises and demonstrates a number of differences in the GRF and RFD produced by these exercises. This finding is consistent with previous studies that demonstrated a number of differences in the intensity of plyometric exercises performed primarily in the vertical plane (Ebben, et al., 2008; Ebben, et al., 2011; Jensen & Ebben, 2007; Sugisaki, et al., 2013). This study is also the first to assess these kinetic variables for the frontal and sagittal plane.

The quantification of plyometric intensity via the analysis of GRF and RFD assists practitioners in the design of programs based on known intensity of these exercises, as has been recommended (Ebben, et al., 2008; Ebben, et al., 2011). Many previous recommendations have been anecdotal (Potach & Chu, 2008).

The highest GRF of these plyometric exercises are up to 4.2 times greater than the plyometric exercises with the lowest values, demonstrating large differences in the intensity of these exercises. It is interesting to note that many of these horizontal plyometric exercises produced GRF-V that were higher than the maximal CMJ, which has been shown to be a relatively high intensity vertical plyometric exercise (Ebben, et al., 2011). The plyometric exercises with the highest RFD values ranged from approximately 6.7 to 7.7 times greater than those exercises with the lowest RFD values.

Training and rehabilitation programs should progress the intensity and should be biomechanically specific to the demand of the athlete. For example, if a training or rehabilitation goal is to attenuate frontal plane instability, plyometric exercise with increasing frontal plane kinetic demands should be prescribed over the course of the program. Additionally, with these data, programs can be created which are sport specific to activities that require frontal and sagittal plane horizontal power such as running, as has been recommended (Brughelli, et al., 2008), and shown to be most effective due to training specificity (Singh & Singh, 2013).

CONCLUSION: Data from the present study show the existence of a continuum of plyometric intensity. There are substantial differences in intensity of plyometric exercises and practitioners should be aware of the training stimulus which they prescribe.

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