Hubble RP, Wang H, Nagelkirk P, Avedesian JM, Wilkinson R, Dickin DC. Influence of Whole Body Vibration on Drop Jump Landings and Knee Loading Mechanics. J Orthopedics & Orthopedic Surg. 2022;3(1):5-11

Journal of Orthopedics and Orthopedic Surgery

Research Article **Open Access**

Influence of Whole Body Vibration on Drop Jump Landings and Knee Loading Mechanics

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Article Info

Article Notes
Received: November 13, 2021
Accepted: February 01, 2022

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Keywords:
Kinetics
Kinematics
Landing
Plyometric
Sex differences
Knee abduction

Abstract

Plyometric training is one commonly used method of improving jump performance through improving explosive power generation. Research has also demonstrated that whole body vibration (WBV) can improve jumping and enhance explosive strength especially when supplementing resistance and plyometric training programs. With the drop jump being a common training skill, proper lower extremity landing mechanics are important to consider. Limited evidence suggests that WBV may reduce ground reaction forces and improve knee stability however, its influence on knee loading have not been reported. This study sought to examine the effects of WBV on ground reaction forces and knee valgus during a drop jump. 19 participants (10 female) completed drop jumps pre, immediately post, 10 & 20 minutes post WBV. Results were analyzed by repeated measures ANOVA. Main findings indicated that valgus knee angle increased significantly (p=0.011) post vibration and remained elevated across the 10 & 20 minute post vibration time intervals. Significant differences between sexes revealed that females demonstrated greater internal knee abduction moments (p=0.038). Findings that WBV increases knee valgus angle, a position linked to anterior cruciate ligament injury, suggest further investigation understand the effects of WBV on neuromuscular control and eccentric loading. Strength and conditioning professionals should exercise caution when incorporating WBV into plyometric protocols.

Introduction

Jump performance is a trait that benefits athletes across numerous sports. Plyometric training is a commonly used method to improve jump performance and incorporates varying drop jump heights[1]. Whole body vibration (WBV) involves standing on a platform that causes a vertical (or vertical plus anteroposterior and/or mediolateral motion) displacement of an individual's center of gravity, altering the gravitational forces on the body[2]. Exposure to WBV, and more recently an individualized frequency vibration (i.e., specific vibration frequency that elicits highest level of electromyographic activation in a muscle), has been shown to improve explosive and reactive strength when added to a strength training protocol over that of isolated strength training[3]. Additionally, WBV has been shown to improve jump height in multiple studies[3-8]. The specific mechanism has not been determined but studies have suggested increased efficiency of the muscle spindles or eliciting effects similar to post-activation potentiation in response to muscle activation[9-11]. Given these potential benefits, strength and conditioning professionals may consider WBV as a tool to supplement plyometric training programs. While improvements in jump height may be beneficial for athletes, examining the effects of WBV on landing from drop jumps should be investigated further to better understand how landing mechanics are impacted by the vibration exposure and the increases in jump height facilitated by the vibration exposure.

As jump height increases (as reported in response to WBV or through other forms of training), the ground reaction forces (GRFs) experienced during the landing will also increase[12]. Additionally, greater GRFs have been associated with increased anterior cruciate ligament (ACL) injury risk[13,14], and an even greater risk in females[15,16]. It is also important to consider joint position(s) when an athlete lands, as landing with a knee in a valgus position or increased frontal plane (i.e., valgus) knee moments are major contributing factors to ACL rupture[17-20]. Considering the potential risk of ACL injury associated with the combined effects of increased GRFs and valgus knee angles, and the sex of the performer it would be beneficial to investigate the influence of WBV on these risk factors during landings, especially in light of the reported improvements in jump height following WBV exposure. While WBV research has examined explosive power measures of jumping maneuvers, limited and equivocal research has assessed the impact of WBV on landing mechanics[21-23]. Following WBV, researchers have demonstrated enhancements in knee neuromuscular control[21] and improved dynamic stability and flexibility[24], potentially attributed to improved knee joint proprioception following vibration exposure[21]. However, the aforementioned studies did not include measures related to knee valgus or the effects of an individualized vibration frequency. As such, the purpose of this study was to examine the effect of an individualized frequency WBV training program on GRFs, lower limb mechanics and the differences associated with the sex of the individual during the landing phase of a drop jump. It was hypothesized that GRFs, loading rates, valgus knee moment and valgus knee angles would show an acute decrease in non-sedentary individuals following an individualized frequency WBV training session as a result of the potential changes in proprioception following the vibration exposure[23,25]. Additionally, it was hypothesized that WBV would not differentially alter performance based on the individual's sex.

Materials and Methods

Experimental Approach to the Problem

To examine the hypotheses for this study, subjects were recruited and tested on two separate days. During the first day we determined the individualized vibration frequency to be used during the participants second testing session which was conducted ~48 hours (two days) later. On the second visit, the participants completed drop jumps and then performed the vibration training program outlined below. Following vibration, subjects completed additional drop jumps immediately, 10 and 20 minutes post-WBV to examine the effects of vibration and short-term recovery on drop jump mechanics. Participants were allowed to sit or stand during the recovery period but not engage in any activity. Ground reaction forces, loading rates, knee moment and valgus knee angles were examined.

Subjects

Twenty non-sedentary young adults (10 male, 10 female) were recruited for this study. Participants were required to be participating in at least 30-minutes of moderate exercise at least three days a week to help ensure that the drop jump movements could be performed without injury. One male withdrew from participation due to a knee injury sustained during an activity unrelated to the study, resulting in 19 participants (9 male, 21.40±2.87years, 78.68±13.89kg, 1.75±0.09m; 10 female, 21.40±3.13years, 63.48±12.21kg, 1.66±0.06m). Participants were excluded if they had any lower extremity neuropathies, recent knee, hip or ankle injuries, lower extremity surgeries within the previous year or a recent or history of concussions. All participants reported as right leg dominant which was defined as the leg they would use to kick a ball. This study was approved by a university Institutional Review Board in accordance with the Declaration of Helsinki (Protocol# 291208-2) and informed consent was obtained from all subjects involved in the study signed prior to participation and study familiarization.

Procedures

The first visit was used to establish the individualized WBV (iWBV) frequency protocol and to practice the drop jump task. Electromyographic (EMG) activity of the right vastus lateralis via surface electrodes (Bagnoli DE 2.1 - Delsys, Boston, MA) was sampled at 2000 Hz and used to monitor peak muscular activation during multiple brief WBV exposures. Skin preparation for electrode placement included hair removal with a razor, mild skin abrasion with fine grit sandpaper and cleansed with gauze pads and rubbing alcohol. The longitudinal axis of the electrode was placed on the skin directly above the muscle following the direction of the underlying muscle fibers. An individualized frequency protocol[3,4] required the participants to stand barefoot with knees flexed to approximately 15 degrees[2] on a 0.8 x 1.01m synchronous vibration plate (Pneu-VibePro, Sandpoint, ID) vibrating with a peak-to-peak amplitude of 2mm. Participants completed a baseline (no vibration) trial immediately followed by 10 seconds of vibration at randomized frequencies of 20, 25, 30, 35, 40, 45, 50 or 55 Hz (1.61 g – 12.2 g). Between each vibration exposure four-minutes of rest was provided to limit the effects of fatigue or crossover from the previous vibration exposure resulting in eight vibration exposures during the first session. Peak root-mean-square (RMS) values of the electromyographic activity were calculated (additional detail for the calculation can be found in the *Data Analysis* section below) to determine the vibration frequency that elicited the greatest neuromuscular response. Following the vibration protocol, participants were asked to perform 10 practice drop jumps from a 0.60 m box[26] to reduce the learning effect on the task on the second visit. Participants were asked to step off the box and land and jump as high as possible immediately following the landing. Only trials in which each foot landed completely on separate 0.46 m x 0.51 m force plates (AMTI OR6-7-1000, Watertown, MA; sampling at 2000 Hz) were used for the analysis. To remove the influence of arm swing on jump height, all participants were fitted with the same lightweight strap-based harness typically used in rock-climbing and were instructed to grasp the straps during all trials. After practicing the jump protocol, participants were asked to refrain from strenuous physical activity before attending the second testing session which occurred ~48 hours following the first session.

For the second testing session, three-dimensional kinematic data was captured at 200 Hz with a 12-camera Vicon MX-F40 system (Vicon, Oxford Metric Ltd., Oxford, UK) utilizing a modified plug-in gait marker set[27]. Retro-reflective markers were placed bilaterally on the lateral malleolus of the ankle, lateral knee, anterior superior spine, posterior superior iliac spine, acromion processes, and four-marker clusters on the lateral aspect of the thighs and shanks. Additional markers were placed on the manubrium, 7th cervical and 12th thoracic vertebrae to create the 3D model for analysis[27,28]. Participants wore the same body harness used in the initial testing session. Following marker placement, participants completed five-minutes of self-selected pace walking on a treadmill. Following the warm-up, five baseline drop jump trials were completed. A successful landing consisted of all markers being recorded while the participant landed with each foot completely on their assigned force plate. A rest period of 30-seconds was provided between trials to reduce fatigue. After completing five successful baseline drop jumps, the participant then completed the WBV protocol consisting of 10, individualized frequency one-minute vibration sessions with one-minute rest between each trial, and a four-minute rest period following the fifth trial[3,4]. During the WBV exposure participants maintained a semi-squat position with feet approximately shoulder-width apart[29] and approximately 15 degrees of knee flexion to maximize the effects of the vibration to the legs and help reduce residual vibrations to the head[30]. Drop jump landings were also assessed immediately following WBV and again at 10 and 20 minutes post vibration.

Data Analysis

Electromyographic data for the individualized frequency were acquired and processed with Delsys EMG Works software (version 3.6). Raw data were full-wave rectified and smoothed using a root-mean-square (RMS) calculation with a 0.125s window length and a 0.0625s overlap over the course of each 10 second vibration exposure[31]. The peak from the resulting RMS curve was used to indicate the neuromuscular response for each WBV frequency. Subsequently, the frequency with the highest peak value was considered the individualized frequency for the second day.

All data were collected and exported using Vicon Nexus software and subsequently processed using Visual 3D (V4) software (C-Motion, Germantown, MD). Kinematic and kinetic data were filtered using a dual-pass zero-phaseshift Butterworth filter using 8 Hz and 40 Hz cutoffs, respectively[32]. Data from the dominant leg was assessed from initial ground contact to peak knee flexion during the landing. The variables of interest for examination included peak GRFs, peak loading rate, peak knee varus/valgus angle, peak valgus knee moments and jump height. The GRF was normalized to each participants weight and expressed in body weights (BWs) while peak loading rate was calculated from initial ground contact to maximum GRF and taken as the first derivative of the vertical GRF and expressed as body weights per second (BW/s)[33]. A Cardan coordinate

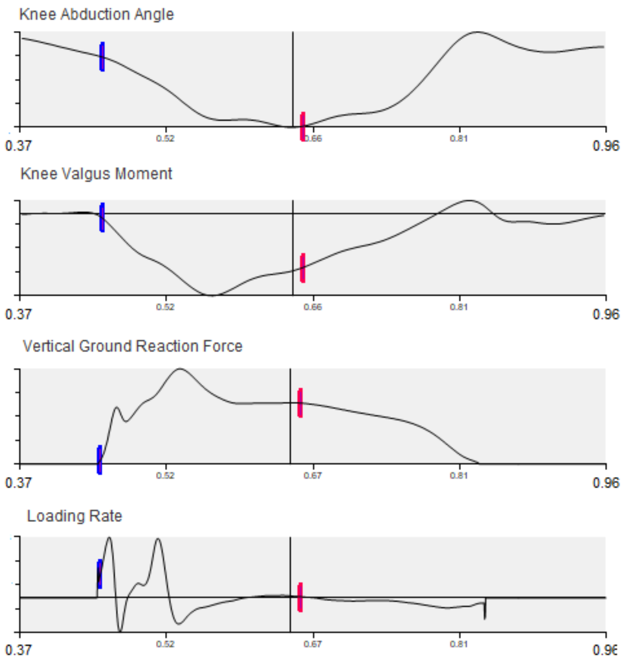

Figure 1: Exemplar knee angle and moment and vertical ground reaction force and loading rate graphs during the landing maneuver. Initial contact (blue vertical line) and peak knee flexion (red vertical line) indicate the period of the landing used to calculate the respective measures.

system (X, Y, Z) was used to create a 3D model relative to the participant/joints and used to calculate internal joint moments using inverse dynamics and were normalized to each participant's body height (m) and mass (kg)[31]. Internal moments are used to represent internal muscle forces produced to counteract the external moments created by landing (i.e., ground reaction) forces. Exemplar graphs of vertical ground reaction force, loading rate, knee angle and moments during landing are presented in Figure 1 and an image of the 3D model during the landing at the point of peak knee flexion in Figure 2.

Statistical Analysis

To assess the effects of vibration over time, data were assessed at four time points: pre-vibration, immediate post vibration, and 10 and 20 minutes post vibration. To assess changes between pre- and post-WBV exposure, as well as differences between sexes, separate 2 x 4 (sex x time) Repeated Measures Analyses of Variance (RM-ANOVA) contrasts were performed on GRF, loading rate, knee valgus/varus angle, valgus knee moment and jump height. Follow-up pairwise comparisons were performed were appropriate. Sphericity was assessed, and if violated, Huhyn-Feldt corrections were used for data comparisons. For all comparisons the experiment-wise alpha level was set at $p \leq 0.05$[34,35].

Results

General Findings

All 19 participants completed the study safely with no reported discomfort. Summary data for all dependent measures across all testing periods are presented in Table 1. After processing the individualized frequency of all participants, the mean frequency was 33.68±7.42 Hz with a range from 20-50 Hz and the mode frequency was 30 Hz (11 participants had this individualized frequency). For all measures, significance mean and standard deviation data is reported in Table 1.

Ground Reaction Forces and Loading Rate

For the measures of peak GRF as well as loading rate across the pre, post, 10 and 20 minute post assessments,

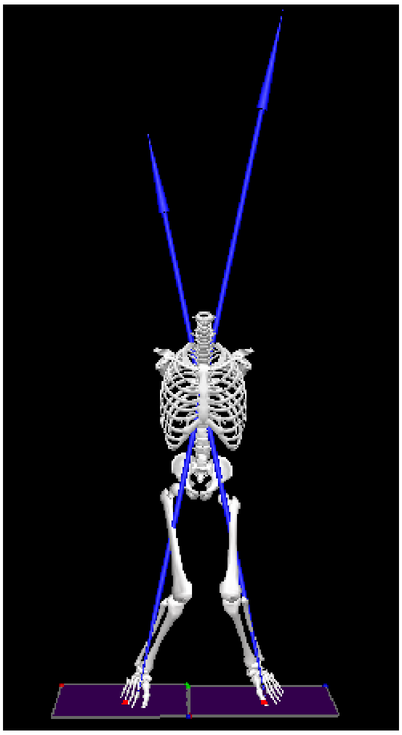

Figure 2: Sample drop landing at the point of maximum knee flexion. Resultant ground reaction force vectors arrows originating from each force platform represent the magnitude and direction of the force vector.

Table 1: Summary data across sexes and WBV exposure timing

Variable	Gender	Pre-Vibration (mean±SD)	Post Vibration (mean±SD)	10 Min. Post Vibration (mean±SD)	20 Min Post Vibration (mean±SD)	P Values		
						Time	Sex	Time x Sex
GRF (BW)	Male	2.78±0.63	2.64±0.54	2.63±0.57	2.61±0.69	0.158	0.408	0.623
	Female	2.92±0.49	2.94±0.56	2.87±0.52	2.82±0.70			
Loading Rate (BW/s)	Male	215.63±79.40	207.27±66.80	204.86±57.54	190.82±53.77	0.155	0.565	0.153
	Female	217.67±81.59	231.07±82.35	226.31±74.47	220.40±80.06			
Knee Valgus Angle (degrees)	Male	-6.79±6.87	-7.27±6.63	-7.46±6.23	-7.69±6.87	0.011[a]	0.091	0.647
	Female	-11.56±5.93	-12.79±5.66	-12.84±6.14	-13.03±5.69			
Knee Valgus Moment (Nm/kg)	Male	-0.31±0.26	-0.31±0.22	-0.309±0.22	-0.35±0.23	0.859	0.038[a]	0.756
	Female	-0.80±0.49	-0.78±0.64	-0.77±0.51	-0.77±0.52			
Jump Height (m)	Male	0.41±0.047	0.41±0.04	0.40±0.03	0.41±0.03	0.657	<0.001[a]	0.465
	Female	0.29±0.071	0.28±0.71	0.28±0.06	0.28±0.05			

[a] Indicates significant difference based on comparison, BW=bodyweight, Nm/kg=Newton meters per kilogram.

there were no significant differences for the main effects of time, sex, or for the higher order interaction of time by sex ($p > 0.05$).

Knee Valgus Angle

Assessing the measure of valgus knee angle revealed a significant main effect for time ($F_{(2.30,\ 36.89)} = 4.78$, $p = 0.01$). Further pairwise comparisons revealed that valgus knee angle increased significantly during the immediately post vibration ($p = 0.008$), 10 minutes post vibration ($p = 0.03$) and 20 minute post vibration ($p = 0.02$) compared to baseline (Table 1). These findings indicate that following WBV, when collapsed across sex, participants landed with significantly greater knee valgus angle. The effects for sex and the interaction between sex and time were not significant (Table 1).

Jump Comparison

Jump height was assessed to determine if vibration improved jump height as referenced in previous studies. Jump height was not significantly ($p=0.68$) affected at any of the three-time intervals following WBV or for the higher order interaction of time by sex ($p=0.47$). However, sex comparisons revealed that the males jumped significantly higher than females ($F_{(1,16)} = 21.71$, $p < 0.001$).

Knee Moment

The valgus knee moment did not significantly change ($p = 0.90$) across the three-time intervals following WBV or for the higher order interaction of time by sex ($p = 0.76$). Females did, however, show significantly ($F_{(1,16)} = 29.42$, $p = 0.04$) greater valgus knee moment when compared with males.

Discussion

The purpose of this study was to explore the acute effects of an individualized WBV training protocol on ground reaction forces, loading rate, valgus knee mechanics and differences between sexes on drop jump performance. Similar to previous research[21] we hypothesized that WBV would decrease peak GRF during a drop jump. While the previous study assessed single-leg drop jumps, the current study using a two-legged landing did not show a significant change in peak GRF following WBV. In contrast, other research revealed that WBV was able to acutely reduce peak impact and loading rate during a two-legged drop jump[22]. During that study the researchers used a total volume of 30 seconds of vibration and included a rest break before performing drop landings of 0.3-0.5 meters. Whereas the current study utilized a total of 10 minutes of vibration[3] and tested drop landings from a height of 0.6 meters[26] immediately following WBV and also assessed the influence of up to 20 minutes of rest[36]. Use of a rest period has been shown previously to improve performance when implemented following WBV[37]. While the population in the current study were considered active, their current and past experience with jumping and landing was not assessed. Consequently the drop height of 0.6 meters could have exceeded their maximal jump height and served as a supra-maximal height to control during landing, which could have ultimately resulted in potential slipping of muscle cross-bridges[38] or an inability to effectively control the momentum and rebound immediately.

While no significant change in ground reaction forces was observed following WBV, significant increases in knee valgus angle occurred immediately post, and persisted through 10 and 20 minutes post vibration rest intervals. While improvements in squat jump performance following WBV have been shown to persist up to 15-minutes[39] the current study suggests that a potential deleterious effect from WBV may occur upwards of 20-minutes post vibration. These findings are in contrast to other research indicating improvements in knee stability during single-leg drop jumps[21]. In the single-leg drop study, decreases in GRFs were measured following vibration, as well as increases in sagittal knee angular displacement[22]. The authors described this as a potential mechanism for reducing GRF, however changes in knee valgus angle were not reported.

Risks associated with landing have been shown to be greater in females than males in numerous studies. We did not have any reason to believe that the WBV exposure would impact males and females differently and the results supported this. Conversely it was expected that there would be sex differences for jump height and knee valgus angle and loading during landing. During the landing maneuver females exhibited smaller jump heights and greater knee valgus moments, but despite more than a five degree greater peak valgus knee angle the difference did not reach the level of statistical significance. When designed the purpose of this study was to assess landing mechanics following WBV using a common drop height of 0.6 m. Ultimately this height was considerably greater than the mean maximum jump heights for either sex and likely influenced their ability control the descent during the drop landings. It is unknown if this drop height was reduced to a more manageable level if this would have elicited additional differences between the two groups.

Potential limitations for this study include participants assuming a stance position during vibration that required toes to be pointed straight ahead and feet shoulder width apart while in a semi-squat position[29]. Although not specifically assessed, this shoulder width stance produced an observable valgus knee angle during WBV exposure. Consequently, it is possible that the stance used during vibration may have contributed to the increase in knee valgus angle. Alternatively, a different study utilized a stance where the participants outwardly rotated their feet approximately five degrees, and participants displayed improved knee stability following a WBV protocol[40]. Although not reported, the figures included in the article suggest that the participants may have been in a hip width stance rather than the shoulder width stance, as used in this study. In addition to foot placement, the height of drop for the landing may have affected the jump height of the subsequent jump as well as the ability to control the overall descent. It has been suggested that a drop height as low as 0.4m may limit the ability to produce greater countermovement jump heights when compared to squat jumps[41]. This may in part explain why a significant increase in jump height was not observed in the current study. An additional limitation was that a control group was not analyzed limiting the comparison to a group that just performed drop jumps without the vibration intervention. It is important to note however that all participants performed practice drop-jump trials during the initial testing day to help familiarize them to the protocol and help reduce the potential learning effects.

In conclusion the results of the current study suggest that while WBV may increase knee angular displacement in the sagittal plane, knee valgus angles may also increase. Given that valgus knee angles during landings are a potential risk factor for ACL injury[17-19], further research is needed to determine if this increase has the potential to put individuals at a greater risk for ACL injury and if a greater rest period following vibration may help to attenuate this effect.

Practical Applications

Whole body vibration utilizing an individualized frequency resulted in an increased valgus knee angle for up to 20 minutes following a vibration training protocol. These data show that WBV may play a contributing factor to increased valgus knee angles in non-sedentary individuals. Strength training professionals should exercise caution when supplementing plyometric training programs with WBV and ensure all athletes have appropriate landings mechanics. This study warrants future investigation to more clearly define the effect of WBV on neuromuscular control of the lower extremities during landing tasks.

Author Contributions

Conceptualization, R.P.H. and D.C.D.; methodology, R.P.H., D.C.D, H.W., P.N.; formal analysis, R.P.H., D.C.D., J.M.A., R.W.; investigation, R.P.H.; writing—original draft preparation, R.P.H., D.C.D., P.N., and H.W.; writing—review and editing, R.P.H., D.C.D., J.M.A., and R.W. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

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