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Multidirectional Hop Landings Exceed Osteogenic Thresholds with and with Instruction Withdrawn in Premenopausal Women

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Abstract: The purpose of this study was to quantify ground reaction forces across all planes of motion and determine the influence of instruction associated with vertical, forward and lateral hop landings in premenopausal women. Bilateral jump-landings have previously been the focus in this population with forces quantified primarily in the vertical direction. There is a need to understand and quantify the landing forces for different types of exercises to determine their osteogenic potential as a stimulus for bone development across the life stages, in addition to identifying at risk populations. Such exercises could help to build a better skeleton, and maintenance of that would decrease the susceptibility to fractures and osteoporosis in later years. Twenty-one women [Mean (SD): 43.3 (5.9) yr; 69.4 (9.6) kg; 167 (5.5) cm; 27.5 (8.7) % body fat] performed a testing session 'with instruction' followed by a testing session performed one week later with 'instruction withdrawn'. The resultant magnitudes (4.02 to 4.93 body weights, BW's) and rates of strain (237 to 319, body weights per second, BW/s), exceeded previously determined jump-landings thresholds (>3BW's and >43BW/s, respectively) that have achieved bone gains in this population. Jump-type effects were observed, with larger peak vertical and resultant forces (↑10% to ↑14%; $p \leq .001$, BW) produced for the vertical hop. Significant differences ($p \leq .001$) were detected for hop landing ground reaction force's across all planes of motion (19% to 93%) suggesting that each landing type provides a different type of force distribution as required to optimize bone stimulation. These multidirectional hop-landings represent a unique training stimulus for premenopausal women and exceed osteogenic thresholds thought pre-requisite for bone growth.

Keywords: Bone, Impact Exercise, Jump-landings, Unilateral, Ground Reaction Forces

1. Introduction

Osteoporosis is a disease characterised by a reduction in the density and quality of bone leading to a weakness of the skeleton and associated increased risk of fracture [1]. This disease is recognised as a major public health issue in the developed world affecting more than half of women and one third of men over the age of 60 years. A study in 2005 estimated the direct costs of osteoporosis treatment in the United States exceeded $19 billion annually, and predicted this would reach $25.3 billion in 2025 [2]. Osteoporosis is largely preventable, with specific types of exercise being widely recognised as the leading green prescription.

Although regular exercise has been shown to reduce risk factors for lifestyle-related diseases such as obesity, cardiovascular and metabolic disease [3, 4], not all exercise provides the stimulus required to be osteogenic [5, 6]. Although the optimal dose of exercise is yet to be determined, researchers have established several criteria deemed necessary to stimulate bone including; a force magnitude of greater than 3-body weights (BW), a rate of force development exceeding 43-body weights per second (BW/s) and an unfamiliar or diverse direction of force application [5, 7, 8]. Evidence from cross-sectional studies describe athletes in weight-bearing sports (i.e. gymnastics, tennis, and volleyball) which involve high magnitude and rates of loading and novel or diverse loading patterns, as having greater bone mass at loaded skeletal sites compared to non-athletes or athletes in non-weight-bearing or lower-impact sports [9-11]. Therefore, there is a need to understand and quantify the landing forces for different types of exercises to determine their osteogenic potential as a stimulus for bone development across the life stages, in addition to identifying at risk populations. Such exercises could help to build a better skeleton, and maintenance of that would decrease the susceptibility to fractures and osteoporosis in later years.

2. Literature Review

Jumping and hopping exercises are of special interest as have been shown to increase peak bone mass in young people and minimize age-related bone loss in females [7, 12-17]. From different meta-analyses [18, 19] it can be concluded that brief jumping protocols (10 - 100 jumps/day, 3 - 7 days/week), of 4 - 18 months duration, and loading magnitudes (between 2 - 6 BW) and rates (> 43 BW/s), can produce significant gains in femoral neck bone mineral density (BMD) of 0.5 - 3% in premenopausal women. These evidence-based values suggest that a safe and effective osteogenic threshold exists around this range of load magnitude and rate for jumping and hopping exercises, however the primary focus has been on bilateral jump-landings. Research conducted by Bailey and Brooke-Wavell (2010) investigated whether hopping (unilateral jump-landings) would have greater osteogenic potential than jumping (bilateral jump-landings) due to total body weight-bearing on one leg only, and providing a greater 'novelty factor' for premenopausal women. A strength of their study was the paired design they utilized, which provided a direct comparison between the trained and controlled limb for each participant, during the 6-month exercise intervention, and they reported almost 2% gain in BMD at the femoral neck of the trained limb. However, although this study acknowledged the importance of utilizing a selection of hops due to their multidirectional landing qualities, ground reaction force (GRF) magnitudes and rates of loading were presented in the vertical direction only. It is therefore of interest to investigate the forces across all planes of motion associated with multidirectional jump-landings, as understanding such kinetics would assist other practitioners in program design for osteogenesis.

Jump-landing technique was also of interest to the current study as previous research has described how landing mechanics can affect the magnitude and rate of impact forces, and providing specific cues to land 'stiffly' can prevent participants from 'softening' the landing and influence its osteogenic effectiveness [20-23]. Thus, instruction was deemed important to both quantify the magnitude of GRF's with specific jump-landing instructions provided, and to determine whether similar or greater GRF's could be achieved after instruction was withdrawn. This would have implications for the hops to be performed in the home setting, once proficient, with the knowledge that the appropriate GRF's and subsequent osteogenic thresholds would be met. It is therefore important that jump-landing technique is clarified and standardized (with respect to factors such as; instructions provided, arm swing and landing technique), in order to maximize the opportunity for premenopausal women to consistently achieve the rates and magnitudes of GRF's [7], which have achieved gains in bone strength and mineralization in other studies [7, 24-27].

Although jump impact forces have been quantified by several research groups, the focus has been primarily on bilateral jumps in this population [12, 24, 28], and thus the estimation of landing forces associated with unilateral jumps or hops has been limited [29]. In addition, these studies have presented GRF's in the vertical direction only, therefore neglecting the contribution of landing forces across all planes of motion. Given the limitations identified, this study sought to; a) determine whether GRF's for unilateral multidirectional jump-landings, [forward hop, (FH), lateral hop, (LH) and vertical hop, (VH)] could achieve osteogenic thresholds previously presented for bilateral vertical jumps, which improved bone mass among premenopausal women; b) determine if differences in landing forces exist for the different types of hops to satisfy the bones directional loading requirement (in addition to magnitude and rate of strain); and, c) determine if differences exist in landing forces between the different hops 'with instruction' and then performed one week later with 'instruction withdrawn'. Due to the scope of the study, several hypotheses were generated; i) Vertical and resultant GRF's for all hop-landings would achieve and exceed previously defined vertical only, osteogenic thresholds for magnitude and rate (>3BW's and >43BW/s, respectively); ii) superior vertical GRF's (magnitude and rate), would be observed for the VH landings, greater medio-lateral landing forces would be associated with the LH landings, and greater anterio-posterior landing forces would be associated with the FH landings, representing the multidirectional qualities required to stimulate bone remodelling; and, iii) greater magnitudes and rates of strain would occur for hop-landings performed with 'instruction withdrawn' due to learning and practice effects;

3. Methods

3.1. Participants

Twenty-one healthy premenopausal women (31 - 50 yr), volunteered to participate in this study. It was calculated using G*Power, that a target sample size of 21 participants will allow for the detection of changes in jump performance (α= 0.05, 1-β= 0.80) between jumps with and without instruction. A summary of the participant characteristics are presented in Table 1. All participants were considered healthy as determined by a Physical Activity Readiness Questionnaire (PAR-Q) and a Pre-exercise questionnaire, and inclusion criteria required participants to be between 30 and 50 years of age, in conjunction with the participants reporting a regular menstrual cycle to determine premenopausal status. Participants were excluded if any medical problems were reported that compromised their participation or performance in this study, including; having a recent or current musculoskeletal injury, osteoarthritis and any condition of impaired balance or coordination. The methods and procedures used in this study were approved by the Institutional Review Board Committee (R14/17).

Table 1. *Baseline characteristics of the participants (mean ± SD).*

	All Participants (n = 21)
Demographics	
Age (yr)	43.3 ± 5.9
Height (cm)	167 ± 5.5
Body mass (kg)	69.4 ± 9.6
BMI ($kg{\cdot}m^{-2}$)	24.9 ± 3.4
Body fat (%)	27.5 ± 8.7
Maximal Countermovement Jump	
Jump height (cm)	35.5 ± 9.3

3.2. Experimental Approach to the Problem

A cross-sectional descriptive design was utilized for this study. Data was collected for each participant over two testing sessions separated by one week, with a familiarization session scheduled at least 3 - days prior to the first testing session (Figure 1). In the familiarization and first testing session participants were given detailed instruction on how to perform the hops and in the second testing session participants were just asked to perform the hops with instructions withdrawn. All participants refrained from performing any of the hops between testing sessions and commencement of normal daily activity was undertaken as determined by activity diaries. The study design utilized in this study was previously used to quantify a series of vertical bilateral jump-landings in the same population [28, 30].

3.3. Testing Protocol

3.3.1. Familiarization (Session 1)

Participants were required to complete pre-screening questionnaires and had their height and body mass recorded, and their body composition measured using a bioelectrical impedance machine (InBody230, Biospace, Seoul, Korea). The Vertec Yardstick (Swift Performance Equipment, Australia) was used to measure vertical jump height and baseline jumping ability, which was used as a surrogate measure for lower body explosive power [31, 32]. Before jump commencement the participants reach height was determined. They were then encouraged to jump and touch the highest vane of the Vertec device. The authors thought it important to determine maximal baseline vertical jump ability to allow for comparison with previous studies who have utilized this subject demographic. Participants were then given a demonstration of the hops (VH, FH and LH), followed by two to three practice hops (on each leg) on the force plate. They were taught to bend their knees and hips slightly (during the eccentric phase) to perform a maximal jump for height (during the concentric phase) and to land stiffly, with the foot flat on the ground. All hops in this study were performed barefooted as researchers have suggested the natural elastic components of the body provide a greater protective effect than artificial footwear against excessive load during voluntary exercise [12, 13].

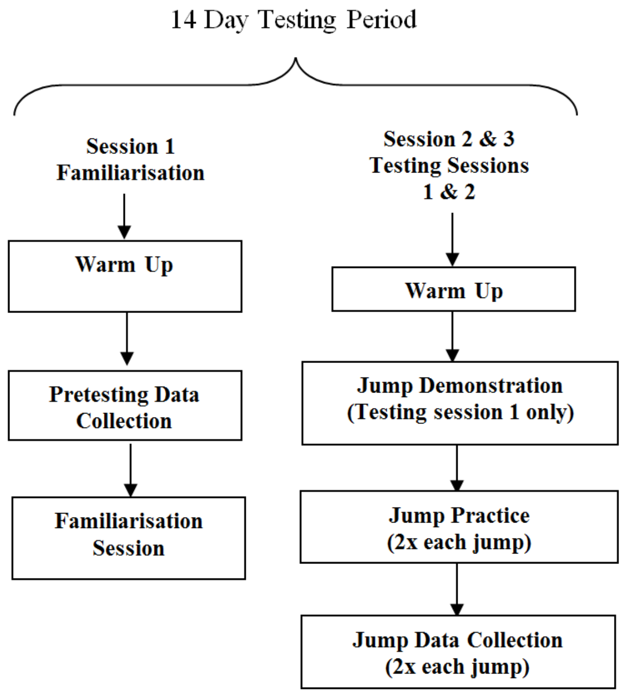

Figure 1. *Experimental design of the 14-day testing period.*

3.3.2. Testing Protocol (Sessions 2 & 3)

For the first testing session, participants performed a ten-minute standardized warm- up prior to testing that consisted of easy cycling on a stationary Wattbike (Wattbike Trainer, Nottingham, United Kingdom) followed by dynamic stretching and bodyweight mobilization exercises. Testing commenced five minutes after the warm-up. Prior to testing, the hops were demonstrated using proper technique, with all instructions standardized for every participant, and provided before every hop. For the VH, participants were instructed to stand on the force plate with feet shoulder-width apart with their arms by their side. Participants were then instructed to start with arms above their head, then flex the knees and hips (during the eccentric phase) and quickly jump upwards (during the concentric phase) with arms 'swinging' in a countermovement style, to land stiffly on one leg. For the FH and LH participants stood on one side of the force plate with feet shoulder-width apart before leaping forward or sideways, and landing stiffly onto the other side of the force plate on one foot. Participants were cued to land with minimal flexion of the hip and knee, and to utilize a flat footed ground contact. A pictorial representation of the phases of the hops presented in this study are depicted in Figure 2.

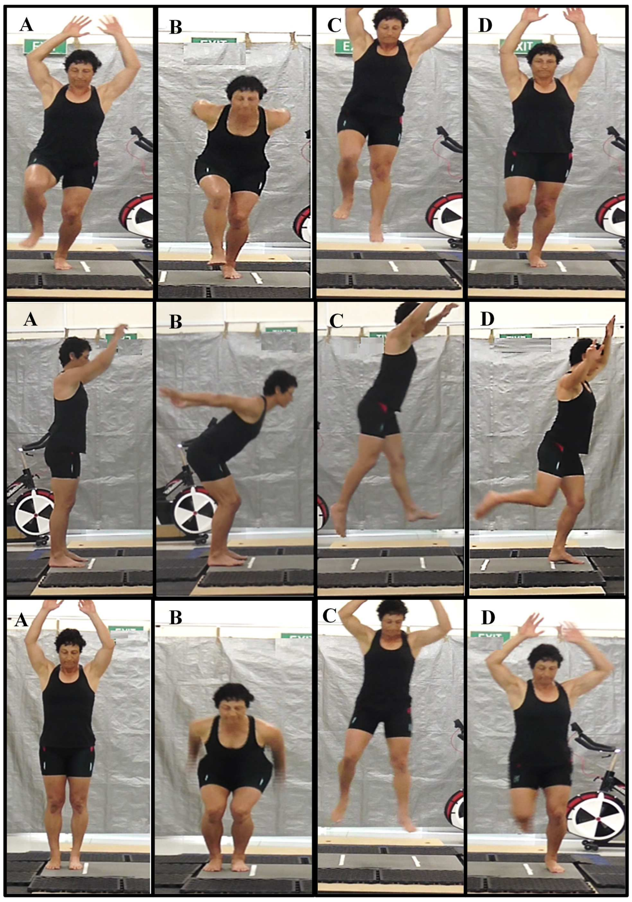

Figure 2. *Pictorial representation of the phases of the VH (top), FH (middle) and LH (below), as described in this study: A) Start of eccentric phase; B) Start of concentric phase; C) Flight phase; D) Landing phase.*

Peak jump-landing forces were collected for the hop-landings 'with instruction' and with 'instruction withdrawn' at 400 Hz using a portable AMTI (Advanced Mechanical Technology Inc., Watertown, Massachusetts) Accupower (ACP) force plate (length 101.6 cm x width 76.2 cm x height 12.4 cm). Participants remained stationary on the force plate for five seconds after landing and each hop was separated by a 30 - second rest interval. The participants performed two practice hops (on each leg), followed by two hops (on each leg) where they were cued to jump maximally in the vertical direction for each hop type, and force plate data was collected using AMTI version 1.5 software (Athletic Republic, Fargo, North Dakota). Hops were performed in a randomized order which was replicated in the second testing session. Data was analysed as an average of the two hops (for each leg).

For the second testing session the same protocol was followed, however, no instruction or cueing was given (instruction withdrawn) for how the participant was to perform the hops. All testing for this study was undertaken at a similar time of day with participants instructed to maintain their normal dietary intake before and after each testing session. Participants completed activity diaries to monitor physical activity to ensure that inter-session physiological status was similar. We did not control for nutrition, or hydration levels but participants were told not to make any changes in the above during the testing period. All jump testing was performed indoors in a temperature-controlled Sports Science testing facility.

3.4. Data Analysis

The force-time data was calculated in Microsoft Excel 2013 (v 15.0.5179.1000, Microsoft, California, USA) and presented as peak values. Forces in the x and y axis were calculated as medial (positive) and lateral (negative), and anterior (propulsive) and posterior (braking), respectively. Peak GRF magnitude was presented in respect to body weight (BW), and was calculated as peak GRF, (N)/ body mass, (N). Peak resultant forces were calculated as $\sqrt{x^2 + y^2 + z^2}$ and used to determine the rate of force development ($N{\cdot}s^{-1}$ * 100/ body mass, N; body weight per second, BW/s) over 10 ms taken from the steepest part of the slope between the end of the flight phase and the peak landing force [12]. All force-time data were filtered using a second order low-pass Butterworth filter (cut off frequency 20 Hz) with zero lag. A pictorial representation of the force profile of the hops utilized in this study are presented in Figure 3.

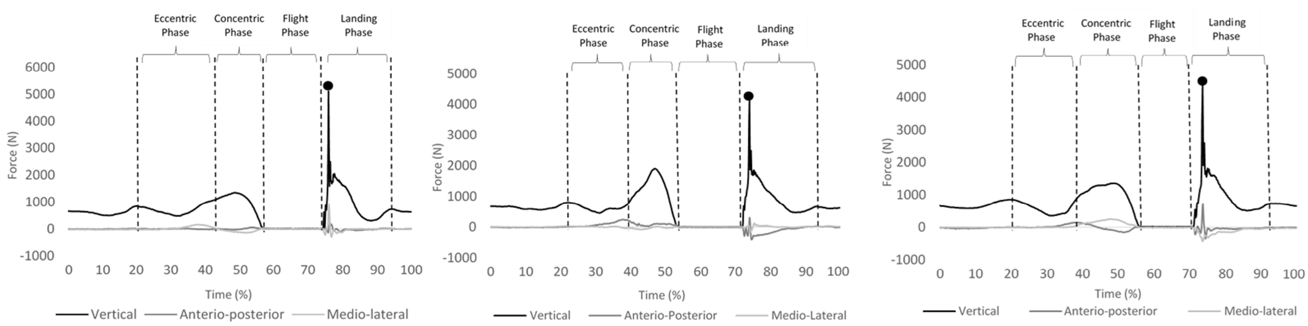

Figure 3. *A typical vertical force profile of the Vertical hop (left), Forward hop (middle) and Lateral hop (right). Dashed lines represent the various phases of the hops. The circles indicate peak landing forces.*

3.5. Statistics

Stem and leaf plots were used to ascertain whether there were any outliers in the data for each variable. All values three or more box lengths from upper or lower edges of box were considered extreme outliers and were investigated carefully before being considered extreme outliers and were removed [33]. After extreme outliers were removed descriptive statistics were calculated and reported as mean and standard deviations. A 2-way (jump type x instruction type) ANOVA with Bonferroni's post hoc tests was used to determine if significant differences existed between the jump type and whether instruction was provided. A Shapiro-Wilk's test was used to show all data was normally distributed and met the assumptions associated with the 2-way ANOVA. Significance was accepted at the $p \leq .01$ level. All statistical analyses were carried out using Data Desk 6.01 for Windows (Data Description Inc., Ithaca, NY, USA). Effect sizes (ES = mean change/standard deviation of the sample scores) were calculated to quantify the magnitude of the effects associated with landings 'with instruction withdrawn'. Cohen (1998) applied qualitative descriptors were used for the effect sizes with ratios of 0.2, 0.5 and 0.8 indicating small, moderate and large changes, respectively [34].

4. Results

The range of peak magnitudes (4.17 to 5.12 BW's) and peak rates of strain (239 to 334 BW/s) for vertical and resultant forces for the unilateral jump-landings in this study exceeded previously defined osteogenic thresholds (>3 BW's and 43 BW/s) [7] (Table 2).

No significant interactions were observed between jump type and instruction type (Table 3). Jump type was found to have a significant main effect ($p \leq .01$), with the vertical hop producing consistently higher GRF than the forward and lateral hop at all axes (except posterior) (↑10% to ↑92%; N and BW, respectively). Significantly higher ($p \leq .001$) posterior forces were observed for the FH and LH when compared to the VH (↑71% and ↑69%, respectively). In addition, lateral GRF's were significantly larger ($p \leq .0001$) for the LH and VH, when compared to the FH (↑35% and ↑42%, respectively). Peak rate of force development (↑2% to ↑20%; $p \leq .0001$) also showed a significant effect ($p \leq .01$) for jump type with the VH producing higher rates of strain than the LH and FH (↑2% to ↑20%; N and BW, respectively).

No significant main effects for 'Instruction' were observed. Decreases in force for all axes (except medial) were observed for the vertical hop (ES = -0.04 to -0.79), and the forward hop (ES = -0.06 to 0.59), with instruction withdrawn. Although trivial and small decreases in GRF's were found for the lateral hop in the vertical, posterior and medial direction (ES = 0.02 to -0.42), small to large increases were observed in the anterior (ES = -0.79 and -0.78) and lateral (ES = 0.32 and 0.37) directions (N and BW, respectively).

Table 2. *Ground reaction forces associated with unilateral vertical forward and lateral hop landings with and without instruction.*

Peak Force Parameters	Vertical Hop			Forward Hop			Lateral Hop		
	WI	WO	ES	WI	WO	ES	WI	WO	ES
Vertical									
PVF (N)	3386 ± 947	3183 ± 762	0.24	3085 ± 775	2705 ± 755	0.50	2809 ± 680	2794 ± 919	0.02
PVF (BW)	5.07 ± 1.55	4.76 ± 1.19	0.23	4.62 ± 1.30	3.83 ± 1.40	0.59	4.19 ± 1.09	4.17 ± 1.46	0.02
Anterior									
PAF (N)	176 ± 91	170 ± 97	0.07	209 ± 150	156 ± 90	0.44	7 ± 4	12 ± 9	-0.79
PAF (BW)	0.26 ± 0.14	0.26 ± 0.15	0.05	0.32 ± 0.24	0.24 ± 0.15	0.44	0.01 ± 0.01	0.02 ± 0.01	-0.78
Posterior									
PPF (N)	-84 ± 31	-76 ± 26	-0.28	-301 ± 59	-275 ± 79	-0.38	-274 ± 76	-249 ± 71	-0.33
PPF (BW)	-0.12 ± 0.04	-0.11 ± 0.04	-0.23	-0.44 ± 0.07	-0.41 ± 0.12	-0.28	-0.40 ± 0.10	-0.36 ± 0.10	-0.42
Medial									
PMF (N)	485 ± 220	497 ± 203	-0.06	86 ± 34	91 ± 41	-0.15	396 ± 177	391 ± 234	0.02
PMF (BW)	0.73 ± 0.34	0.74 ± 0.30	-0.04	0.12 ± 0.06	0.12 ± 0.09	-0.06	0.60 ± 0.29	0.60 ± 0.40	0.02
Lateral									
PLF (N)	-239 ± 68	-195 ± 43	-0.79	-139 ± 66	-114 ± 61	-0.39	-186 ± 25	-202 ± 82	0.32
PLF (BW)	-0.36 ± 0.11	-0.30 ± 0.08	-0.63	-0.21 ± 0.12	-0.17 ± 0.10	-0.39	-0.27 ± 0.04	-0.30 ± 0.13	0.37
Resultant									
PRF (N)	3417 ± 959	3213 ± 774	0.23	3091 ± 779	2711 ± 757	0.49	2839 ± 690	2822 ± 938	0.02
PRF (BW)	5.12 ± 1.57	4.80 ± 1.21	0.23	4.63 ± 1.30	3.84 ± 1.41	0.58	4.24 ± 1.11	4.22 ± 1.49	0.02
RFD									
PRFD ($kN.s^{-1}$)	2152± 869	1940 ± 830	0.25	2211 ± 1075	1861 ± 1054	0.33	1572 ± 732	1641 ± 958	-0.08
PRFD ($BW.s^{-1}$)	319.4 ± 131.0	287.28 ± 122.68	0.25	333.7 ± 169.0	277.9 ± 160.9	0.34	238.7 ± 122.3	245.0 ± 149.1	-0.05

Key: Data expressed as mean ± SD

WI With Instruction; WO Without instruction; ES Effect size; N Newtons; BW Body weight; $kN.s^{-1}$ kilo Newtons per second; $BW.s^{-1}$ Body weight per second; RFD Rate of Force Development.

Table 3. *Results of the analysis of variance main effects of jump type on force variables for the different hops.*

Peak Force Variables	Mean values VH	Mean values FH	Mean values LH	df	F-ratio	*p*-value
Vertical force (N)	3285	2950†	2832†	(2,99)	9.69	≤.001
Vertical force (BW)	4.82	4.35	4.17	(2,93)	10.3	≤.001
Anterior force (N)	174.6	182.6‡	13.93†	(2,97)	56.5	≤.001
Anterior force (BW)	0.26	0.27‡	0.02†	(2,96)	51.7	≤.001
Posterior force (N)	-80.93	-287.7†	-266.2†	(2,93)	217.3	≤.001
Posterior force (BW)	-0.12	-0.42†	-0.39†	(2,93)	190.5	≤.001
Medial force (N)	491.2‡	109.9†	400.3§	(2,95)	77.6	≤.001
Medial force (BW)	0.75§	0.17‡	0.58†	(2,94)	89.0	≤.001
Lateral force (N)	-216.8§	-126.7	-198.5§	(2,97)	31.4	≤.001
Lateral force (BW)	-0.33§	-0.19‡	-0.29	(2,98)	30.3	≤.001
Resultant force (N)	3315	2956†	2862†	(2,99)	9.87	≤.001
Resultant force (BW)	4.86	4.36†	4.21†	(2,93)	10.5	≤.001
RFD ($kN.s^{-1}$)	2094	2036‡	1692†	(2,97)	6.07	.003
RFD ($BW.s^{-1}$)	310.6	294.5	248.7†	(2,95)	6.63	.002

Key: † significantly different to VH; ‡ significantly different to LH; § significantly different to FH.
RFD Rate of Force Development. VH Vertical hop; FH Forward hop; LH Lateral hop.

5. Discussion

This is the first study to quantify the multiplanar GRF's associated with multidirectional hop-landings in premenopausal women 'with instruction' and 'instruction withdrawn'. The main findings of the current study with respect to the proposed hypotheses were: i) Vertical osteogenic thresholds for GRF magnitude and rate previously shown to improve bone mass at clinically relevant sites for premenopausal women were achieved and exceeded for vertical and multidirectional hop landings; ii) The hypothesis that vertical landing forces would be greater ($p \leq .01$) for the vertical hop was supported, with significantly ($p \leq .01$) different medio-lateral and anterio-posterior GRF's observed for the multidirectional hops; and, iii) In contrast to the original hypothesis, smaller ($p = .015$) magnitudes and rates of GRF occurred for hops performed with 'instruction withdrawn'.

The current study presents a range of GRF magnitudes (4.02 to 4.93 BW's) and rates of strain (237 to 319 BW/s) for vertical and resultant hop-landing forces, which easily exceeds previously defined vertical osteogenic thresholds (>3 BW's and 43 BW/s) [7] developed using bilateral jump-landings with premenopausal women. Interestingly, although Bailey and Brooke-Wavell (2010) reported GRF's for vertical hops performed maximally which do not achieve the stated osteogenic thresholds (2.5 and 2.8 BW) they reported femoral BMD gains of nearly 2% for the female participants [34.6 (7.9)yr]. They speculated however that the single-leg landing forces may be equivalent to a total landing force of 5 - 6 BW's due to forces being transmitted through one leg only, and therefore easily exceeding the bone stimulation threshold.

The variability that exists when quantifying peak vertical landing forces (2 to 6 times body weights) for vertical jumps (bilateral and unilateral) in different studies [7, 17, 24, 28, 35], highlights the need to explore different aspects of jump technique and the way instruction can influence jump-landing GRFs. The Bailey and Brooke-Wavell study (2010) reported utilizing a 'countermovement' style of jumping, however they were referring to knee flexion prior to jumping and provided no instructions for arm swing or landing mechanics. We believe cueing our participants to use a vigorous arm swing in a 'countermovement' style enhanced jump height and may have contributed to the substantially greater impact forces we observed for our participants [36]. In addition, we cued our participants to 'land stiffly', with minimal knee flexion, which potentially enhanced the osteogenic potential of the hops [22, 28].

Interestingly, although no significant main effects were observed for instruction, we demonstrated that in contrast to the original hypothesis, smaller ($p = .015$; ES = 0.02 to -0.79) magnitudes and rates of GRF occurred in jump-landings performed one week later, with 'instruction withdrawn'. Instruction was of interest to this study to determine whether similar or greater GRF's could be achieved when instruction was withdrawn, as this could influence programing considerations. Although the current study reported reduced GRF's at most axes for the non-instucted session, the landing forces for the hops (with instruction and with instruction 'withdrawn'), exceeded magnitudes and rates of strain previously shown to improve femoral BMD in premenopausal women.

In spite of the small decreases in peak force production observed across all axes (except medial) for the forward hop (↑ 6% and no change) and the vertical hop (↑ 3% and ↑1%) with instruction withdrawn, small to large increases were observed for the lateral hop in the anterior (↑71% and ↑100%; ES = -0.79 and -0.78) and lateral (↑9% and ↑11%; ES = 0.32 and 0.37) direction (N and BW, respectively). These results may indicate that participants are more likely to improve their jump-landing ability hops in more unusual or unaccustomed directions (medial and lateral) when practiced over time due to initial unfamiliarity. This proposition was evident in the recent 'Hip-Hop' study which reported baseline GRF's of 2.7 BW for hops performed by older men (70 (4) yr), which increased to 3 BW after 6 months of performing the hop programme [37]. In addition to participants developing adaptations to both generate and tolerate increased landing forces over time, multidirectional hopping interventions have reported improvements in factors relevant to falls prevention, such as muscle strength and balance, in addition to enhanced BMD for premenopausal women at clinically relevant sites for osteoporosis prevention [15, 38].

Our study demonstrated that jump type had a significant effect, with greater forces observed in the vertical hop for all force variables measured (except posterior). Jump type was found to have a significant main effect ($p \leq .01$), with the vertical hop producing consistently higher GRF than the forward and lateral hop at all axes (except posterior) (↑10% to ↑92%; N and BW, respectively). Significantly higher ($p \leq .001$) posterior forces were observed for the FH and LH when compared to the VH (↑71% and ↑69%, respectively). In addition, lateral GRF's were significantly larger ($p \leq .0001$) for the LH and VH, when compared to the FH (↑35% and ↑42%, respectively). Peak rate of force development (↑2% to ↑20%; $p \leq .0001$) also showed a significant effect ($p \leq .01$) for jump type with the VH producing higher rates of strain than the LH and FH (↑2% to ↑20%; N and BW, respectively). A paucity of research exists in the area of quantifying landing forces associated with hop exercises, with an exclusive presentation of the vertical hop and vertical GRF's only [14, 17, 35, 39]. Therefore, a limitation exists for the interpretation of multiplanar force data and the contribution of each vector to the overall osteogenic stimulus for bone. However, it is well accepted that unusual or unfamiliar directions of force application, as provided by multidirectional hops, may further enhance the overall osteogenic potential of mechanical loading and warrant further investigation.

Wolff's Law, is well described in terms of bones ability to adapt to mechanical loads, leading to bone formation, and Frost (1987) explored the forces to achieve skeletal adaptation in the development of his 'minimum effective strain', or 'mechanostat' theory, hypothesizing that mechanical forces exceeding this remodelling threshold would therefore stimulate bone formation and increase bone mass and bone strength [40-42]. Furthermore the 'error strain distribution hypothesis' suggests that unusual or novel directions of force application may have a greater osteogenic effect than magnitude and therefore vital to osteogenesis [43, 44]. Thus the intention of quantifying multidirectional single leg landings in the current study was to provide unique and variably distributed forces to the skeleton, and specifically the femoral neck, and to provide opportunity for exercise progressions (i.e. variation and progressive overload) with respect to osteogenic program design.

6. Conclusion

In conclusion, our results show that the multidirectional hop-landings, once cued to land 'stiffly', and to utilize a flat footed ground contact, easily exceeded osteogenic thresholds previously shown to increase bone mass in premenopausal women. This has implications for multidirectional hops, as part of a wider osteogenic program, to be performed effectively in the home-setting, after only one instructed session. As research has predominantly focussed on minimizing postmenopausal BMD losses and risk factors associated with falling, exercise regimes for improving bone mass in adults are generic and lack specific recommendations for the premenopausal age group. Thus jump-landing exercises, including hopping and jumping, which have been quantified using premenopausal women could be utilized to develop a periodized jump-landing program specifically relevant to this population. However, multidirectional hops, such as those described in the current study, may require pre-conditioning exercise, and the performance of bilateral jump-landings first, as part of a program designed to safely optimize the impact stimulus required to promote bone formation in premenopausal women.

Declaration of Interest Statement

The authors have no conflicts of interest to disclose.

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