
The Osteogenic Quantification and Reliability of the Heel Drop and Press up Drop

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Abstract: *Background* Jump landings have been quantified as a stimulus for bone health programs, however they may not be suitable for some populations. Currently, studies quantifying alternative types of lower body exercises are limited and no studies have quantified upper body exercises for inclusion in bone health programs. This study sought to quantify and determine the reliability of a heel drop and push up drop exercise to determine whether they achieve magnitudes and rates of force previously shown to improve bone mass among premenopausal women. *Methods* Twenty women (Mean \pm SD: 41.7 \pm 5.6 y; 68.2 \pm 10.6 kg; 165.0 \pm 7.6 cm) performed heel drops and push up drops on a Kistler force plate. *Results* The magnitude (4.9 BW's) and rate (357 BW \cdot s⁻¹) of force for the heel drop, exceeded previously determined thresholds (>3BW's and >43 BW \cdot s⁻¹) and the push up drop exceeded (147 BW \cdot s⁻¹) the rate of force threshold. The heel drop force data demonstrated moderate to good (0.45 to 0.80) reliability, and the push up drop demonstrated moderate to excellent (0.50 to 0.84) reliability. Significantly ($p < 0.001$) greater ground reaction force variables were observed in the heel drop compared to the push up drop (ES= 2.60 to 4.96). *Conclusion* The heel drop and push up drop could provide a unique osteogenic training stimulus for at risk populations and be incorporated into exercise programs to improve bone health. Longitudinal osteogenic training studies are needed to provide the dose-response relationships associated with bone remodelling and insight into the design and prescription of bone health programs.

Keywords: Bone, Impact Exercise, Biomechanics, Ground Reaction Force

1. Introduction

Osteoporosis is a disease of the skeleton, characterised by low bone density, micro-architectural deterioration, and compromised bone strength [1-3]. This disease leads to an increased risk of osteoporotic fractures, with vertebral, hip and distal forearm being the most common areas for osteoporotic fractures [4]. The operational definition of osteoporosis is based on the estimation of bone mineral density (BMD) [5]. Osteoporosis is responsible for fractures in over 50% of women and 20% of men globally [6], with approximately 52 million people with osteoporosis or osteopenia in the United States alone, with this number expected to increase to 61 million in 2020 [7]. It is evident that females are at greater risk than men for osteoporotic

fractures, more specifically post-menopausal women. This is due to women having less bone mass than adult men, and after menopause, a woman's bone mass rapidly decreases [8, 9]. The primary reason for this bone loss following menopause is due to the oestrogen deficiency. It is estimated that a 50-year-old white female has a 15-20% lifetime risk of hip fracture and a 50% risk of any osteoporotic fracture [3, 10]. Other special populations which may be at risk of osteoporosis are athletes that participate in low impact sports such as swimming and cycling [11], as well as athletes middle- and long-distance track athletes due to risk factors such as prolonged distance running, lower body mass index and fat free mass, and menstrual dysfunction [12-14].

Wolff's Law states that bone has the ability to adapt to mechanical loads under which it is placed, therefore suggesting that mechanically induced strain is a primary factor which affects bone formation. Research has investigated the threshold of strain required to achieve skeletal adaptation, with Frost hypothesising that mechanical forces exceeding this remodelling threshold would therefore stimulate bone formation, as well as increase overall bone strength and mass [15]. A previous case study, focusing on an individual that had an instrumented titanium rod implanted into his proximal femur, demonstrated that there are significant correlations between vertical ground reaction forces and internal forces at the femur for specified movements such as, the countermovement jump and drop jump [16]. Within this case study, Bassey and Colleagues [16] also stated that there was greater ground reaction force activity during jump landing movements, compared to jogging.

Researchers have demonstrated that peak vertical landing forces of 3 BW's and peak loading rates of 43 BW.s⁻¹ achieved during a countermovement jump, resulted in significant increases (2.8%) in BMD in the femur [17]. Previous studies that have been shown to increase BMD in the femoral neck among premenopausal women have utilised brief jumping protocols (10-100 jumps per day), 3-7 days per week, with studies ranging from 4-18 months duration [17-22]. These studies used loading magnitudes of between 2-6 BW's, suggesting that an effective osteogenic threshold is around this range for magnitude of strain, for jumping and hopping exercises. Within the current literature, the quantification of bilateral vertical jumps has been documented by several research groups, which all slightly varied. These groups focused on the effect of instructions given [23, 24], and different landing mechanics [24, 25].

Given that jump type exercises can be difficult to perform, especially for special populations, it is of importance to determine whether other exercises can reach these pre-determined thresholds. Recent research has shown that a simple stomping exercise can reach these pre-determined osteogenic thresholds. Ryan and colleagues [27] found that a stomping exercise could be autoregulated among pre-menopausal women using a rate of perceived exertion (RPE) scale, with stomps performed at an RPE 5 producing resultant magnitudes of 3.08 and 2.89, BW's and rates of strain 199 and 180, BW.s⁻¹ for right and left legs respectively. Stomping movements performed at higher exertions (RPE 8) were shown to significantly ($p < 0.001$) exceed both the pre-determined thresholds (4.58 and 4.42, BW's and 344 and 333, BW.s⁻¹) and the stomps performed at easy to moderate exertions (RPE 5). To the authors knowledge, this is currently the only study that has determined osteogenic thresholds for a lower body exercise that didn't involve jumping that could be performed by special populations with contraindications related to jump landings.

Another major gap within the literature is that all of the current exercises shown to improve bone health are lower body exercises. The current osteogenic thresholds refer specifically to the hip and lumbar spine. Given that the radius

is a clinically relevant site, and the distal forearm is one of the most common areas for osteoporotic fractures [4, 29], it is important to develop and quantify exercises that can stimulate bone formation in the upper body. In order to prescribe bone health programs for individuals its necessary to quantify a range of novel exercises (for upper and lower body) that can be utilised and progressively overloaded to optimise bone remodelling adaptations among special populations for the preventative treatment of osteoporosis. The current study sought to determine whether the exercises 'heel drop' and 'push up drop' reach osteogenic thresholds previously determined by Bassey and Colleagues [17], in premenopausal women. It was hypothesised that, a) the heel drop would exceed previously established magnitudes ($>3\text{BW's}$) and rates of force ($> 43 \text{ BW.s}^{-1}$) thought prerequisite for improving bone health, and b) the push up drop would exceed the previously established rate of strain ($>43 \text{ BW.s}^{-1}$) but not the magnitude of force due to participants having points of contact off the force plate and thus less mass on the force plate.

2. Methods

2.1. Approach to the Problem

Exercise has been utilised as a preventative strategy for improving bone density in premenopausal women [17-19, 21, 24, 29]. Researchers have quantified a series of jumping, hopping and stomping exercises to determine whether they exceed thresholds thought to stimulate bone ($3\times \text{BW}$ and 43 BW.s^{-1}) [17, 24, 27, 29]. The aim of this study was to quantify the heel drop and push up drop exercise utilizing a cross sectional descriptive design to determine whether they reach previously determined osteogenic thresholds shown to improve bone health in premenopausal women. Twenty healthy women performed heel drop and push up drop exercises onto a Kistler (Kistler Instruments, Victoria, Australia) force plate (length 900 mm x width 600 mm x height 100 mm). Such a design was previously used to quantify the stomp exercise [27] and bilateral vertical [24] and multidirectional jumps with reactive jump landings in premenopausal women [29].

2.2. Participants

Twenty health premenopausal women took part in this study. A summary of their descriptive characteristics is presented in Table 1. Participants were provided with a participant information sheet and completed an informed consent form. This sample size, study design and demographics are similar to previous studies [17, 21, 24, 27]. Inclusion criteria for this study was that participants must have a regular menstrual cycle, indicating premenopausal status (approximately 30-50 y). A participant was excluded if any medical problems were reported, such as injury, arthritis, osteoporosis or balance issues that impacted their ability to perform the heel drop or push up drop movement. These medical problems were identified on a pre-exercise questionnaire.

Table 1. Descriptive characteristics of subjects (mean \pm SD).

	All Participants (n = 20)
Demographics	
Age (y)	41.7 \pm 5.6
Height (cm)	165.0 \pm 7.6
Body mass (kg)	68.2 \pm 10.6
BMI	25.0 \pm 3.5
Body fat (%)	27.5 \pm 5.5
Maximal Countermovement Jump	
Vertec jump height (cm)	36.4 \pm 6.0

2.3. Procedures

Participants were required to attend a familiarisation session before they completed the testing session. During this familiarisation session, participants filled in a pre-screening questionnaire containing information about injuries or medical issues that may exclude them from the study. Height was measured using a portable stadiometer, and body mass and composition were measured using a Hologic dual-energy x-ray absorptiometry (DXA) Discovery fan beam (Marlborough, Massachusetts, USA). This machine has been shown to have excellent validity [30]. The DXA is considered the gold standard measurement for BMD [5]. A Vertec yardstick (Swift Performance Equipment, Wacol, Australia), was used to collect maximal vertical jump height for each participant. This data was taken at the end of the warm up. This data was used to determine baseline jumping and lower body power abilities [24, 27, 29, 31]. Before jump commencement, the participants reach height was determined by reaching as high as possible, allowing scapular elevation, the researcher then adjusted the Vertec height accordingly. The participant was then encouraged to jump and touch the highest vane possible on the Vertec device.

Participants were then given a demonstration of the heel drop and push up drop exercises. The participant was then asked to practice the heel drop exercise on the force plate (3 practice submaximal heel drops). All movements were performed in bare feet (see Figures 1 and 2) in order to standardise the testing between all participants. It has been suggested that the natural elastic components of the body are able to provide greater protection to loading forces in comparison to footwear [16, 24]. For the heel drop exercise, participants were instructed to come up as far as possible onto their toes, keeping their hands by their sides and to drop as quickly as possible onto their heels. After completing two heel drop trials on the force plate, the participants then followed the same protocol for the push up drop movement. Submaximal push up drops were performed in a modified push up drop position (knees on the floor). Push up drops were performed off 20 cm blocks, which was the same height previously utilised for drop jump landings among premenopausal women [24]. For the push up drop exercise, participants were instructed to stay up on their toes and get into a full press up position with their hands onto the 20 cm blocks. They were instructed to push off the blocks using their arms and adduct their arms to clear the blocks for the descent. Participants were instructed to land stiffly with arms straight and hands landing onto the force place. Prior to performing the movements

during the testing session, each participant completed a light 5-minute standardised warm-up on the Watt bike (Wattbike Trainer, Nottingham, United Kingdom), and included 10 submaximal countermovement jumps, 10 modified press ups. After participants completed the warm-up they performed the vertical jump test. Data is presented as an average of the two trials for both movements (mean + SD).



Figure 1. Lateral view of the heel drop being performed. A) Start Position; B) Top of heel drop; C) Moment before heel impact; D) Finishing position.

2.4. Data Analysis

All force-time data were filtered using a second order low-pass Butterworth filter (cut off frequency 20 Hz) with zero lag. The force-time data was calculated in Microsoft Excel 2013 and presented as peak values (i.e. N, BW and BWs^{-1}). Peak resultant forces were calculated as the square root of each axes ($X^2 + Y^2 + Z^2$) and used to calculate the rate of force development over 10 ms taken from the steepest part of the slope between the initial start of the landing force and the peak landing force [1]. A pictorial representation of the force profiles for the heel drop and press up drop utilised in this study are presented (Figure 3).

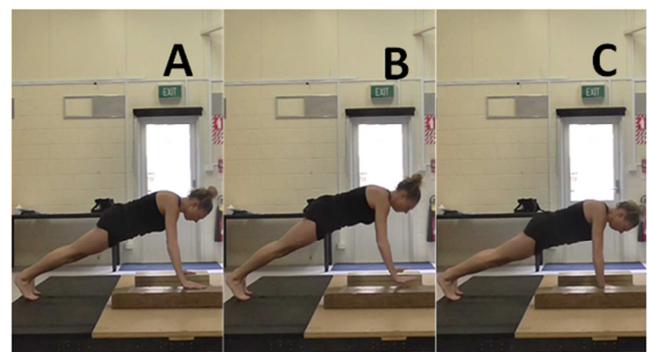


Figure 2. Lateral view of the push up drop being performed. A) Starting Position; B) Take off from blocks; C) Contact and finishing position.

2.5. Statistical Analysis

Stem and leaf plots were used to ascertain whether there were any outliers in the data for each variable. After extreme outliers were removed, descriptive statistics were calculated and reported as mean and standard deviations. Paired t-tests were

used to determine if statistical differences existed among force variables between the heel drop and the push up drop. Classifications of effect size (0.2 to 0.5, 0.51 to 0.8 and >0.8) [32] were calculated to determine the magnitude of the differences between exercises. Within session reliability was evaluated by intraclass correlation coefficient (ICC) using a two-way random effects model, absolute agreement and average measures ICC. ICCs were classified as follows: 'poor' (≤ 0.40), 'moderate' (0.41 - 0.60), 'good' (0.61 - 0.80), or 'excellent' (≥ 0.81) [33, 34]. 95% confidence intervals (95% CI) were calculated for all reliability measures. Internal consistency was assessed using Cronbach Alpha. All data analyses were conducted using SPSS 25.0 for Windows (SPSS Inc., Chicago, IL, USA). Significance was set at $p < 0.05$.

3. Results

Bassey and Colleagues [17] established osteogenic thresholds for magnitude of force ($>3\text{BW's}$) and rate of force ($43\text{ BW}\cdot\text{s}^{-1}$). Both the heel drop ($\text{BW}\cdot\text{s}^{-1}$) and push up drop ($147\text{ BW}\cdot\text{s}^{-1}$) exceeded this rate of force threshold. In regard to the magnitude of force, only the heel drop (4.9 BW's) exceeded the previously established jump-landing osteogenic threshold.

Significant ($p < 0.001$) differences were found between the heel drop and push up drop for all force variables. Large effect sizes (2.60 to 4.96) in favour of the heel drop were observed for all force variables. Ground reaction force data for the heel drop and push up drop is presented in Table 2.

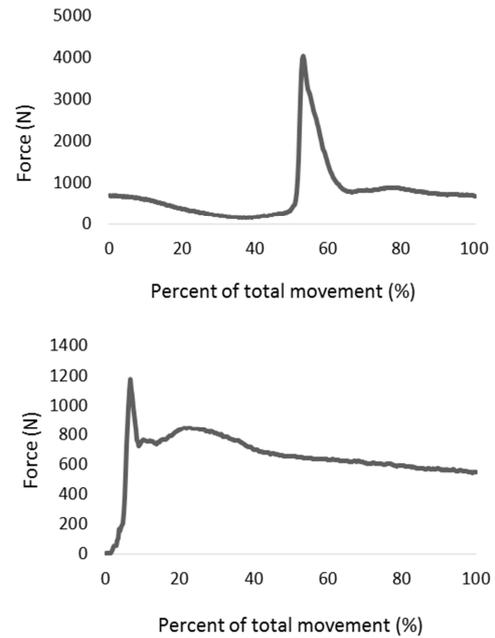


Figure 3. Resultant force profiles of the heel drop (top) and push up drop (bottom).

The within-session reliability of the heel drop and push up drop, was calculated using ICC's. The results are presented in Table 3. Moderate to good reliability was shown between trials for the heel drop and moderate to excellent reliability was shown for the push up drop.

Table 2. Ground reaction forces associated with the heel drop and push up drop.

Variables	Heel Drop	Push up Drop	Difference (%)	ES
Peak Vertical Force (N)	3243 ± 722*	1231 ± 292	62	3.97
Peak Resultant Force (N)	3185 ± 584*	1259 ± 295	60	4.38
Peak Vertical Force (BW)	4.8 ± 0.7*	1.9 ± 0.47	60	4.96
Peak Resultant Force (BW)	4.9 ± 0.72*	2.0 ± 0.48	59	4.8
Peak Rate of Force Development (N)	2321 ± 709*	969 ± 333	8	2.6
Peak Rate of Force Development ($\text{BW}\cdot\text{s}^{-1}$)	357.5 ± 99*	147 ± 51	59	2.81

*Significantly different $p < 0.001$ to the push up drop; ES effect size.

Table 3. Test-retest reliability of the heel drop and push up drop.

Test – retest reliability	ICC (SinMea)	95% CI	ICC (AvgMea)	95% CI	CA	Qualitative Inference
Heel Drop						
Peak Vertical Force (N)	0.66 ^s	0.32 to 0.85	0.80 ^s	0.49 to 0.92	0.79	Good
Peak Resultant Force (N)	0.67 ^s	0.33 to 0.85	0.80 ^s	0.49 to 0.92	0.79	Good
Peak Vertical Force (BW)	0.45 ^s	0.01 to 0.74	0.62 ^s	0.01 to 0.85	0.61	Good
Peak Resultant Force (BW)	0.45 ^s	0.01 to 0.74	0.62 ^s	0.02 to 0.85	0.61	Good
Peak Rate of Force (N)	0.42 ^s	-0.03 to 0.73	0.59 ^s	-0.06 to 0.84	0.58	Moderate
Peak Rate of Force ($\text{BW}\cdot\text{s}^{-1}$)	0.29	-0.18 to 0.65	0.45	-0.45 to 0.79	0.44	Moderate
Push up Drop						
Peak Vertical Force (N)	0.73 ^s	0.42 to 0.88	0.84 ^s	0.59 to 0.94	0.85	Excellent
Peak Resultant Force (N)	0.72 ^s	0.41 to 0.88	0.84 ^s	0.58 to 0.94	0.85	Excellent
Peak Vertical Force (BW)	0.63 ^s	0.27 to 0.84	0.77 ^s	0.43 to 0.91	0.79	Good
Peak Resultant Force (BW)	0.62 ^s	0.25 to 0.83	0.76 ^s	0.40 to 0.91	0.77	Good
Peak Rate of Force (N)	0.41 ^s	-0.05 to 0.72	0.58 ^s	-0.11 to 0.84	0.57	Moderate
Peak Rate of Force ($\text{BW}\cdot\text{s}^{-1}$)	0.33	-0.15 to 0.68	0.50	-0.35 to 0.81	0.49	Moderate

4. Discussion

Previous studies have focused on jump landings and their

effect on bone health in premenopausal women [24-25, 30]. However, there is an aspect of technical difficulty associated with jumping which may be contraindicated in some populations. Alternative lower body exercises such as the heel

drop could be more suitable. Furthermore, no studies have quantified upper body exercises to determine their potential osteogenic value. Given that the radius is a clinically relevant site it is important to quantify exercises such as the push up drop for the inclusion in bone health programs. This is the first study to quantify the GRF's associated with a heel drop and push up drop exercise in premenopausal women. The results of the study align with the initial hypothesis in that the heel drop exercise exceeded the previously established magnitudes and rates of force thought prerequisite for improving bone health and the push up drop exceeded the rate of force. Moderate to excellent reliability was shown for both the heel drop and push up drop.

In this study, the magnitude of force achieved during the heel drop was 4.9 BW's, which exceeded (1.6 x greater) the magnitude of force (> 3BW's), previously shown to improve femoral BMD gains in premenopausal women [17]. In contrast, the magnitude of force achieved during the push up drop was 1.9 BW's which was 37% lower than this threshold. The authors speculate that the magnitude of force required to stimulate the upper limbs (radius, shoulder girdle and thoracic spine), may be substantially lower due to less habitual forces being regularly translated through these bones. Bassegy and colleagues [17], used female participants, of premenopausal status and reported peak landing forces that corresponded to 3 BW's during a countermovement jump (height; 8.9 ± 5 cm). The exercise consisted of 50 vertical jumps 6 days/week, resulting in a significant increase of 2.8% in femoral BMD for the premenopausal women, after 5 months of completing the exercise. However, there was no significant change in the postmenopausal women, suggesting premenopausal status is a more desirable time to develop BMD gains. This may be due to oestrogen deficiency in postmenopausal women, as oestrogen plays a key role in the bone remodelling process [8, 36].

Ground reaction forces were measured in three axes and then used to calculate peak resultant forces for the heel drop and push up drop, the steepest 10ms was used to represent the peak rate of force development (PRFD). This method has been previously used by researchers investigating GRF's in premenopausal women [17, 24, 27, 30]. Peak rate of force development (PRFD) for the heel drop and push up drop were substantially higher than previously determined threshold ($43 \text{ BW}\cdot\text{s}^{-1}$) suggested by Bassegy and colleagues [19]. The heel drop achieved PRFD of $357 \text{ BW}\cdot\text{s}^{-1}$ (8 x greater) and the push up drop achieved PRFD of $147 \text{ BW}\cdot\text{s}^{-1}$ (3 x greater). Such values are similar to or greater than those previously reported for other lower body exercises [17, 24, 27, 30].

Clissold and colleagues [24, 30], investigated whether bilateral vertical and multidirectional jumps with reactive jump landings achieved osteogenic thresholds in premenopausal women. The magnitudes of strain for the vertical (4.59 to 5.49 BW's) and multidirectional (3.90 to 5.38 BW's) jumps were similar to those achieved during the heel drop exercise (4.9 BW's). Ryan and colleagues [27] quantified a stomping exercise at different RPE's and produced resultant magnitudes of 3.08 and 2.89, BW's (RPE 5) and 4.58 and 4.42, BW's (RPE 8), however the heel drop exercise exceeded these resultant

magnitudes (4.9 BW's). These results suggest that high magnitudes of strain achieved during jumping exercises, can also be achieved in less complex exercises that don't involve a flight phase and therefore may be more appropriate for populations where jumping exercises may be contraindicated [27].

Researchers [36] have identified that key mechanisms for providing the greatest influence for stimulating bone formation are, peak vertical force (magnitude of force) and peak rate of force development (rate of force). It has been suggested that if peak rate of force development is sufficiently high, bone adaptation may be stimulated without using high peak vertical force [24, 37, 38]. Therefore, although the push up drop didn't exceed the predetermined magnitude of force (3 BW's), it may still stimulate the bone through the high rate of force development. Interestingly, it is currently unclear what osteogenic thresholds are required to stimulate bone formation in non-weight bearing bones in the upper body. Currently studies have only focused on lower body exercises and measured changes in bone that involves regular locomotion and load bearing. Longitudinal training studies utilising upper body exercises such as the press up drop are needed to help determine osteogenic thresholds for non-weightbearing clinically relevant sites such as the radius. Such studies could also give insight into the dose response relationship associated with upper body exercises.

Reliability refers to the reproducibility of values of a test in repeated trials on the same individuals [39]. ICC's have been previously used to determine within session reliability [27, 40, 41]. Researchers have demonstrated that osteogenic exercises can be reliably progressively overloaded by individuals using an RPE scale, good to excellent within session reliability was shown for stomps performed at an RPE 5 and moderate to excellent reliability was shown for stomps performed at an RPE 8 [27]. The current study reported similar within session reliability was observed for the heel drop (ICC= 0.45 to 0.80) and push up drop exercise (ICC = 0.50 to 0.84). To the authors knowledge this is the first study to determine the reliability of a heel drop and push up drop exercise.

The results from this study demonstrate that the heel drop and push up drop exercises can be used in bone health programmes and in combination with previously quantified exercises [24, 27, 29], to create programmes targeted to premenopausal women and for individuals with contraindications for jump-landings. Current exercise prescription guidelines for the prevention and management of osteoporosis, recommends healthy adults (low to moderate risk), to perform moderate to high-impact weight bearing activities (> 2 to > 4 BW; 3-5 sets 10-20 repetitions, 1-2 minutes' rest between sets), four to seven days each week [1]. Given that bone responds to novel stresses its therefore important that an array of upper and lower body exercises are quantified for their osteogenic potential and to create progression and regression opportunities. Ultimately, it is of importance to combine different exercise types to create novel stresses that will lead to improved and sustained adaptation. Bone health programs can then be developed, and exercises can be combined and safely progressively overloaded to optimise

mechanical forces and thus the bone remodelling process.

5. Conclusion

To the authors knowledge, this is the first study to quantify and determine the reliability of the heel drop and push up drop exercises. The results show that the heel drop exceeded the predetermined osteogenic thresholds previously shown to improve bone health using jump-landings. Although the force magnitude threshold was not achieved for the push up drop, the rate of force was 3 x greater than the established threshold. The heel and press up drop exercises displayed moderate to excellent reliability between trials suggesting that they can be reliably utilised by participants to meet established thresholds. As such, they can be used in combination with other quantified osteogenic exercises to create programmes targeted to at-risk populations towards the goal of increasing BMD and preventing the onset of osteoporosis. Further research is required to determine how effective exercises such as the heel drop and push up drop are at eliciting changes to bone. In addition, the osteogenic thresholds for upper body exercises need to be investigated. Other upper body exercises could then be quantified against such thresholds to determine their suitability in bone health programs.

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References

- [1] Beck BR, Daly RM, Singh MAF, Taaffe DR. Exercise and Sports Science Australia (ESSA) position statement on exercise prescription for the prevention and management of osteoporosis. *J Sci Med Sport*. 2017; 20 (5): 438-45.
- [2] Christodoulou C, Cooper C. What is osteoporosis? *Postgrad Med J*. 2003; 79 (929): 133-8.
- [3] Black DM, Rosen CJ. Postmenopausal osteoporosis. *N Engl J Med*. 2016; 374 (3): 254-62.
- [4] Kanis JA, Melton Iii LJ, Christiansen C, Johnston CC, Khaltaev N. The diagnosis of osteoporosis. *J Bone Miner Res*. 1994; 9 (8): 1137-41.
- [5] World Health O. Assessment of fracture risk and its application to screening for postmenopausal osteoporosis: report of a WHO study group [meeting held in Rome from 22 to 25 June 1992]. 1994.
- [6] Lippuner K, Johansson H, Kanis JA, Rizzoli R. Remaining lifetime and absolute 10-year probabilities of osteoporotic fracture in Swiss men and women. *Osteoporos Int*. 2009; 20 (7): 1131-40.
- [7] Foundation IO. Osteoporosis fast facts.: International Osteoporosis Foundation 2015 [Available from: <https://www.iofbonehealth.org/facts-statistics>].
- [8] Hafeez F, Zulfiqar S, Hasan S, Khurshid R. An assessment of osteoporosis and low bone density in postmenopausal women. *Pak J Physiol*. 2009; 5 (1).
- [9] Manolagas S, O'Brien C, Almeida M. The role of estrogen and androgen receptors in bone health and disease. *Nat. Rev. Endocrinol*. 2013; 9 (12): 699.
- [10] Schott AM, Cormier C, Hans D, Favier F, Hausherr E, Dargent-Molina P, et al. How hip and whole-body bone mineral density predict hip fracture in elderly women: the EPIDOS Prospective Study. *Osteoporos Int*. 1998; 8 (3): 247-54.
- [11] Scofield K, Hecht S. Bone health in endurance athletes: runners, cyclists, and swimmers. *Curr Sports Med Rep*. 2012; 11 (6): 328-34.
- [12] Melin A, Heikura I, Tenforde A, Mountjoy M. Energy availability in athletics: health, performance, and physique. *Int J Sport Nutr Exerc Metab*. 2019; 29 (2): 152-64.
- [13] Barrack M, Fredericson M, Tenforde A, Nattiv A. Evidence of a cumulative effect for risk factors predicting low bone mass among male adolescent athletes. *Br J Sports Med*. 2017; 51 (3): 200-5.
- [14] Tenforde A, Fredericson M, Sayres L, Cutti P, Sainani K. Identifying sex-specific risk factors for low bone mineral density in adolescent runners. *Am J Sports Med*. 2015; 43 (6): 1494-504.
- [15] Frost HM. Bone's mechanostat: a 2003 update. *The Anatomical Record Part A: Discoveries in Molecular, Cellular, and Evolutionary Biology: An Official Publication of the American Association of Anatomists*. 2003; 275 (2): 1081-101.
- [16] Bassey EJ, Littlewood JJ, Taylor SJG. Relations between compressive axial forces in an instrumented massive femoral implant, ground reaction forces, and integrated electromyographs from vastus lateralis during various 'osteogenic' exercises. *J. Biomech*. 1997; 30 (3): 213-23.
- [17] Bassey EJ, Rothwell MC, Littlewood JJ, Pye DW. Pre-and postmenopausal women have different bone mineral density responses to the same high-impact exercise. *J Bone Miner Res*. 1998; 13 (12): 1805-13.
- [18] Tucker LA, Strong JE, LeCheminant JD, Bailey BW. Effect of two jumping programs on hip bone mineral density in premenopausal women: a randomized controlled trial. *Am J Health Promot*. 2015; 29 (3): 158-64.
- [19] Bassey EJ, Ramsdale SJ. Increase in femoral bone density in young women following high-impact exercise. *Osteoporos Int*. 1994; 4 (2): 72-5.
- [20] Bailey CA, Brooke-Wavell K. Optimum frequency of exercise for bone health: randomised controlled trial of a high-impact unilateral intervention. *Bone*. 2010; 46 (4): 1043-9.
- [21] Babatunde O, Forsyth J. Effects of lifestyle exercise on premenopausal bone health: a randomised controlled trial. *J. Bone Miner. Metab*. 2014; 32 (5): 563-72.
- [22] Heinonen A, Kannus P, Sievänen H, Oja P, Pasanen M, Rinne M, et al. Randomised controlled trial of effect of high-impact exercise on selected risk factors for osteoporotic fractures. *The Lancet*. 1996; 348 (9038): 1343-7.
- [23] Young WB, Pryor JF, Wilson GJ. Countermovement and Drop Jump Performance. *J Strength Cond Res*. 1995; 9 (4): 232-6.

- [24] Clissold TL, Winwood PW, Cronin JB, De Souza MJ. Do bilateral vertical jumps with reactive jump landings achieve osteogenic thresholds with and without instruction in premenopausal women? *J Appl Biomech*. 2018; 34 (2): 118-26.
- [25] Bobbert MF, Mackay M, Schinkelshoek D, Huijting PA, van Ingen Schenau GJ. Biomechanical analysis of drop and countermovement jumps. *Eur J Appl Physiol Occup Physiol*. 1986; 54 (6): 566-73.
- [26] McNitt-Gray JL. Kinetics of the lower extremities during drop landings from three heights. *J Biomech*. 1993; 26 (9): 1037-46.
- [27] Ryan C, Clissold T, Winwood P. The Quantification, Autoregulation and Reliability of the Stomp as an Osteogenic Exercise. *Sports Inj and Med*. 2021; 5 (168).
- [28] Eckstein F, Lochmüller EM, Lill CA, Kuhn V, Schneider E, Delling G, et al. Bone strength at clinically relevant sites displays substantial heterogeneity and is best predicted from site-specific bone densitometry. *J Bone Miner Res*. 2002; 17 (1): 162-71.
- [29] Clissold TL, Cronin JB, De Souza MJ, Wilson D, Winwood PW. Bilateral multidirectional jumps with reactive jump-landings achieve osteogenic thresholds with and without instruction in premenopausal women. *Clin Biomech*. 2020; 73: 1-8.
- [30] Visser M, Fuerst T, Lang T, Salamone L, Harris TB, Health FT, et al. Validity of fan-beam dual-energy X-ray absorptiometry for measuring fat-free mass and leg muscle mass. *J Appl Physiol*. 1999; 87 (4): 1513-20.
- [31] Leard JS, Cirillo MA, Katsnelson E, Kimiatek DA, Miller TW, Trebincevic K, et al. Validity of two alternative systems for measuring vertical jump height. *J. Strength Cond. Res*. 2007; 21 (4): 1296-9.
- [32] Cohen J. *Statistical power analysis for the behavioral sciences*: Routledge; 1998.
- [33] McGraw KO, Wong SP. Forming inferences about some intraclass correlation coefficients. *Psychol Methods*. 1996; 1 (1): 30.
- [34] Nunnally JC. *Psychometric theory 3E*. Tata McGraw-Hill Education; 1994.
- [35] Siddiqui JA, Partridge NC. Physiological bone remodeling: systemic regulation and growth factor involvement. *Physiology*. 2016; 31 (3): 233-45.
- [36] O'Connor JA, Lanyon LE, MacFie H. The influence of strain rate on adaptive bone remodelling. *J. Biomech*. 1982; 15 (10): 767-81.
- [37] Lanyon, L. E. (1996). Using functional loading to influence bone mass and architecture: objectives, mechanisms, and relationship with estrogen of the mechanically adaptive process in bone. *Bone*, 18 (1), S37-S43.
- [38] Turner CH, Robling AG. Designing exercise regimens to increase bone strength. *Exerc Sport Sci Rev*. 2003; 31 (1): 45-50.
- [39] Hopkins W. Measures of reliability in sports medicine and science. *Sports Med*. 2000; 30 (1): 1-15.
- [40] Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med*. 2016; 15 (2): 155-63.
- [41] Moeskops S, Oliver J, Read P, Cronin J, Myer G, Haff G, et al. Within-and between-session reliability of the isometric mid-thigh pull in young female athletes. *J Strength Cond Res*. 2018; 32 (7): 1892.