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Review Article

Jump-landings that supersede bone health threshold requirements for premenopausal women

Tracey Clissold[1]*, Cronin JB[2,3], De Souza MJ[4] and Winwood PW[1,2]

[1]Department of Sport and Fitness, Faculty of Health, Education and Environment, Toi Ohomai Institute of Technology / Te Pukenga, Tauranga, New Zealand

[2]AUT University, Sports Performance Research Institute New Zealand (SPRINZ), AUT University, Auckland, New Zealand

[3]School of Exercise, Biomedical and Health Sciences, Edith Cowan University, Perth, Australia

[4]Department of Kinesiology, Pennsylvania State University, Pennsylvania, United States

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***Corresponding author:** Dr. Tracey Clissold, Researcher, Department of Sport and Fitness, Faculty of Health, Education and Environment, Toi Ohomai Institute of Technology / Te Pukenga, Private Bag 12001, Tauranga 3143, New Zealand, Tel: 07 557 8681; E-mail: tracey.clissold@toiohomai.ac.nz

ORCID: https://orcid.org/0000-0002-4647-6069

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Introduction

Osteoporosis is a disease characterized by a reduction in the density and quality of bone leading to a weakness of the skeleton and associated increased risk of fracture [1]. The most common type of osteoporosis is termed primary osteoporosis and includes both postmenopausal and age-related osteoporosis, which involves the structural deterioration of bone and increased porosity leading to increased fragility [2] (Figure 1). This disease is recognized as a major public health issue in New Zealand and globally, affecting more than half of women and one-third of men over the age of 60 years [3,4]. Osteoporosis is largely preventable, with specific types of exercise being widely recognized as the leading green prescription. Exercise has been shown to reduce risk factors for lifestyle-related diseases such as obesity, cardiovascular and metabolic disease [5,6] however, not all exercise provides the stimulus required to be osteogenic [7,8].

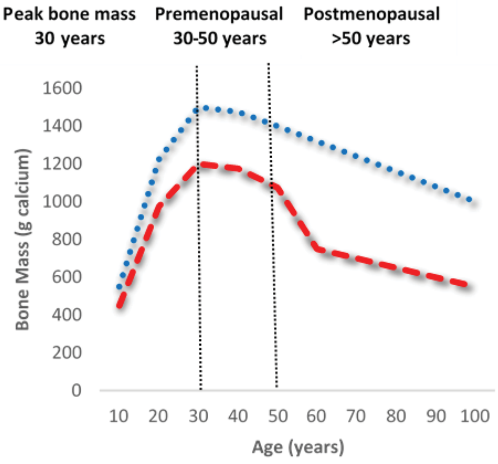

Figure 1: A typical pattern depicting age-related changes in bone mass in males and females.

It has been suggested that jumping can produce an osteogenic response using low repetition, rapid-onset, high-intensity protocols [9,10], as researchers using animals studies have shown the relationship between impact forces and the influence of this type of loading on bone strength, mass, and geometry [11]. Although the optimal dose of exercise is yet to be determined for premenopausal women, researchers have established several criteria deemed necessary to stimulate the bone in this population, including a force magnitude of greater than 3-body weights (BW); a rate of force development exceeding 43-body weights per second ($BW \cdot s^{-1}$); and, an unfamiliar or diverse direction of force application [8,12-17].

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However, an in-depth understanding of the magnitude and rate of these impact forces in relation to various jump types is unknown. In addition, information about the osteogenic potential and bone-loading forces of different types of exercise would be beneficial to the development of exercise regimes to promote bone formation in premenopausal women. Therefore, the purpose of this literature review is to: determine those jumps and conditions that meet osteogenic threshold requirements for premenopausal women; identify the limitations in the research thus far; and, detail future research directions in this area for this specific population.

Literature search methods

The aim of the search strategy was to find articles that quantified the magnitude and rate of loading from jump-landing GRFs in premenopausal women. The databases searched were Academic Search Premier, SPORT Discus, PubMed, MEDLINE, and CINAHL. Literature searches were undertaken using several keywords including; 'osteogenic exercise', 'strength and 'conditioning', 'resistance training', 'premenopausal', 'impact exercise', 'jumping', 'jump-landing', 'ground reaction forces', 'osteogenic threshold', 'bone mineral density', 'bone geometry', 'jumping technique', 'jump-landing technique, hard-landing', soft-landing', 'ballistic jump', 'reactive jump', 'plyometrics', and 'bone health'. Only English-language articles published in peer-reviewed journals were considered. Relevant literature was also sourced from searches of related articles and books arising from the reference list of those obtained from the database searches. Eight studies (Table 1) were found that met the inclusion criteria which included; being female; between 30-51 years; the measurement of GRFs for jump-landings using force plate technology (magnitude and rate), a bone health focus, and mean data presented for a sample size of at least 10 participants.

Summary of the research

Participants

A total of 226 participants were involved in the studies outlined in Table 1. All five studies used healthy adult female participants classified as premenopausal, with an average age of 39.2 years. The premenopausal stage is defined as representing the time after the attainment of peak bone mass (around 30 years) and before the onset of hormonal changes associated with menopause (around 51 years) [18].

Table 1: Quantification studies for ground reaction forces for jump-landings for premenopausal women.

Authors	Participants	Type of Jump Arm Swing	GRF Magnitude	GRF Rate	Jump Height (cm) and Direction
[19]	*n* = 14 females, 32.0 ± 1.2yr	Submaximal CMJ Continuous Arm Swing	> 3 BW	> 43 BW·s⁻¹	8 cm Vertical only
[12]	*n* = 20 females, 38.4 ± 7.4yr	Submaximal CMJ Continuous Arm Swing	> 3 BW	> 43 BW·s⁻¹	8 cm Vertical only
[20]	*n* = 45 females 32.9 ± 2.4yr	Submaximal Hops Continuous No Arm Swing	2.5 - 2.8 BW	Not stated	10 – 12 cm Multidirectional
[21]	*n* = 47 females 39.2 ± 6yr	Low CMJ High CMJ Box jump Continuous No Arm Swing	2.4 BW 3.0 BW 3.4 BW	50 BW·s⁻¹ 100 BW·s⁻¹ 175 BW·s⁻¹	< 5 cm > 5 cm 20 cm Vertical only
[22]	*n* = 37 females 41.1 ± 4.4yr	Maximal CMJ Singular Arm Swing	3.8 - 4.1 BW	217 - 243 BW·s⁻¹	38 cm Vertical only
[15]	*n* = 21 females 43.3 ± 5.9yr	Maximal CMJ & DJ Reactive Jump Rest Integrated Arm Swing	4.6 - 5.5 BW	264 - 359 BW·s⁻¹	20cm box (DJ) Vertical only
[13]	*n* = 21 females 43.3 ± 5.9	Maximal SJ & SD Reactive Jump Rest Integrated Arm Swing	3.9 - 5.3 BW	192 - 329 BW·s⁻¹	Not Stated Multidirectional
[14]	*n* = 21 females 43.3 ± 5.9	Maximal Multiplanar Hops Rest Integrated Arm Swing	4.2 - 5.1 BW	239 - 334 BW·s⁻¹	Not Stated Multidirectional

Key: GRF: Ground Reaction Force; BW: Body Weight; BW s⁻¹: Body Weights per Second; CMJ: Countermovement Jump; DJ: Drop Jump; SJ: Star Jump; Stride Jump

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Discussion

It is well accepted that bone responds optimally to the net effect of different loading activity variables (including; strain magnitude, strain rate, and strain direction), and these loading variables collectively contribute to the overall osteogenic effect of mechanical loading and are as such interlinked and interdependent [23]. Therefore, the jump-landing strategy utilized and a variety of other factors including; type of jump-landing instruction, use of arms, and type of footwear, can have a significant effect on landing forces, and therefore need to be considered for determining appropriate exercise which can benefit bone. A discussion of the factors identified in this review to be considered when selecting exercises, and the instructions provided for jump-landings, with the potential to optimally stimulate an adaptive bone response are presented. Please note that findings from the studies reviewed were combined with relevant longitudinal research where appropriate, which has investigated osteogenic loading in premenopausal women.

Load magnitude

From Wolff's Law, we understand that bone has the ability to adapt to mechanical loading, suggesting that mechanically-induced strain is a key factor that affects bone formation. A graded dose-response relationship exists for load magnitude and change in bone mass, with an upper 'minimum effective strain' threshold described where damage to bone can occur with excessive loading [24]. Studies using rat tibia and ulnar determined a linear relationship between the magnitude of an externally applied load and bone strain magnitude [25]. This has justified the measurement of GRF, represented as Body Weight (BW) to be used to estimate the influence of this loading on bone. Bassey and colleagues [12], previously defined a vertical osteogenic threshold for GRF magnitude (> 3 BW) which they developed after they achieved significant gains in femoral BMD using a bilateral jump-landing intervention with premenopausal women [12]. However, GRFs of 2 - 6 BW have been previously shown to stimulate bone and result in bone formation [12,26,27]. A variety of jumps were quantified in this review, however most of the studies (80%) used a vertical or Countermovement Jump (CMJ). Although these studies utilised the same type of jump, the GRF magnitudes ranged from 2.4 to 5.5 BW, which may reflect the different CMJ techniques utilised in the different studies. For example, one research group reported GRFs for vertical hops performed maximally which did not achieve (2.5 - 2.8 BW) the accepted osteogenic threshold, however they speculated 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 exceeded the bone stimulation threshold for GRF magnitude.

Effect of jump-landing Instruction

As can be observed from studies in this review, there is a great deal of variability (2.4 – 5.5 BW) associated with the measurement of peak vertical GRF during jump-landings, highlighting the need to identify the factors that affect this variability. Lees [28] reported significant variation in the magnitude of peak GRFs occurring during the first 150 - 200 ms of landing, which was described as the 'impact absorption phase' [28]. In the absence of specific jump-landing instruction, some subjects will bend their knees considerably after landing, whereas others will make only a small downward movement and land "stiffly" [29]. Lees [28], described a jump with increased knee flexion as a "soft" landing as the absorption of impact energy by the leg musculature over a longer time resulted in reduced peak GRFs.

Four of the studies in this review used submaximal continuous jumps (either set of 10 or 20) and reported peak landing vertical forces which corresponded to 3 BWs, with instructions provided for participants to land with flexion of the ankles, knees, and hips, followed by a heel strike [12,19,21]. One study utilized the same landing instructions, however, the subjects performed a single maximal jump and rested for 30 seconds between repetitions, and reported greater peak landing forces of 3.8 to 4 BW [22]. In addition, three studies (from the same research group), that provided instructions for a flat-footed "stiff" landing whilst utilising a "reactive" or double-landing reported even higher peak landing forces (3.9 to 5.5 BW) [13-15]. It would seem from these results that the instruction provided for landing ("soft" or "stiff") affects the landing GRFs, and therefore needs to be considered carefully in programming for osteogenesis.

Effect of arms

Researchers attempting to determine the influence of arm swing during jumping have reported that an inconsistent arm swing whilst jumping increased variability between trials and have suggested that efficient use of arm swing can increase jump height by 10% - 20% [30,31]. Bassey and colleagues [12], stated that jump heights for their premenopausal participants were only 8.9 ± 5 cm (3 BW) using a countermovement arm swing, whereas the Tucker, et al. [22] study cued a vigorous arm swing but also instructed participants to jump as high as they could, which resulted in baseline vertical jump heights of 34 ± 11 cm (4 BW). Interestingly, the osteogenic threshold for GRF magnitude (> 3BW) was achieved for jump-landings for both studies, despite the large variability in jump heights (i.e. 8 cm *vs*. 34 cm). Three things are apparent from these findings: 1) what a subject does in the landing phase would seem more important than the propulsive phase in terms of stimulating bone; 2) if all else was equal in terms of instruction regarding landing, then the GRFs of those who jump higher would be greater; and, 3) since arm action can increase jump height substantially then there is the potential to also increase landing forces and therefore the osteogenic stimulus substantially.

Effect of footwear

All eight studies stated that the jumps were performed barefooted. Bassey, et al. [12], instructed participants to remain in working clothes to perform the 10-minute jumping routine (inclusive of gentle warm-up and mobilization exercises) and stated that all jumps were in barefooted condition. Early research by Bassey and Ramsdale [19] compared jumping activities with subjects 'wearing' and 'not wearing shoes' to

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determine the effect on GRFs. They concluded that the natural elastic components of the body provided a greater protective effect than artificial footwear against excessive load during voluntary exercise. In addition, consideration is needed for the attenuation of forces that can be attributed to the cushioning influence of shoes. Thus, footwear is a factor to be considered and clarified when: assessing the magnitude of forces generated in bone; prescribing jump-landing programs; and, informing future research in this area.

Load rate

Although GRF magnitude is considered an important factor in bone adaptation, the load rate (rate of force development) is considered equally important [8,24,32]. Lanyon [11] modified the original 'minimum effective strain' theory to include other osteogenic factors such as the rate of strain (minimum effective strain-stimulus theory), proposing that the rate a bone was exposed to load was more important than the magnitude of the load on influencing the adaptive response [8,16]. This concept suggested that the mechanisms identified for providing the greatest influence for stimulating bone formation are a function of both peak GRF and peak rate of force production [33], implying if peak rate of force production is sufficiently high, then bone adaptation can be stimulated without using high force magnitudes [8,24,33]. Thus, both peak magnitude and loading rate are considered appropriate ways to represent osteogenic thresholds. Bassey and colleagues [12], previously defined a vertical osteogenic threshold for load rate (> 43 $BW \cdot s^{-1}$) which they developed using a bilateral jump-landings intervention that achieved significant femoral BMD gains in premenopausal women [12]. As can be observed from the studies reviewed in Table 1, there is a great deal of variability (43 - 243 $BW \cdot s^{-1}$) associated with the measurement of the peak rate of force development during jump-landings, highlighting the need to identify the factors that affect variability.

Effect of jump-landing Instruction

The rate of force development values reported in this review ranged from 43 - 359 $BW \cdot s^{-1}$ for vertical and CMJ. Tucker and colleagues [22] described an average rate of strain for vertical jump-landings of 243 $BW \cdot s^{-1}$, which far exceeded the previously defined osteogenic threshold (43 $BW \cdot s^{-1}$), and the load rates reported by the other studies in this review (43 - 100 $BW \cdot s^{-1}$). The rate of force development landing forces was 400%-600% greater for the participants in the Clissold studies than those reported by the other studies in the review, interestingly this 400%-600% increase is similar to the greater jump heights observed in the participants in this study. Although the big difference in the participant's jump heights did not seem to influence GRF magnitude, as described previously, it appears to have affected the GRF rate dramatically. Another factor to be considered is the instructions given regarding continuous versus discontinuous jumping. Clissold and Colleagues [13-15] and Tucker and colleagues [22], were the only researchers who cued their participants to jump maximally, rest (30 seconds), and then jump again, whereas all of the other studies in the review utilized submaximal sets of ten jumps or hops, with rest interspersed between each set. Thus, it could be hypothesized that maximal jumps performed singularly may have a greater effect on landing load rate than load magnitude, however, this requires further investigation.

Researchers have indicated that repeated jump-landings had the potential to heighten bone stimulation [28-30,34]. Repeated jumps, were shown to be more ballistic in nature and prevented subjects from "softening" the landing due to the short time period available between jumps [35]. With repeated jumps (i.e. jump immediately after the initial jump-landing), participants were instructed to push off quickly after landing and potentially utilize the elastic energy absorbed during the brief landing during the subsequent take-off [35]. It is therefore of interest for future research to investigate the effect of utilizing a reactive or repeated (but not continuous) jump landing, as utilised by Clissold and colleagues [13-15], whilst cueing for maximal jump height to gain a better understanding of how the repeated jump technique can influence GRF's with respect to the rate of force development. Furthermore, the measurement of GRF's for jump-landings with instructions provided for the jump-landing phase (cueing participants to land 'stiffly' and to utilise a flat-footed ground contact), as well as the propulsive jumping phase (utilise a vigorous arm swing and jump maximally), to compare with osteogenic thresholds previously shown to increase bone mass in premenopausal women is warranted.

Effect of arms

The studies in this review provided a variety of different instructions for arm position during jumping or no specific cueing about the use of arms. Six studies out of eight, stated the use of an arm swing during jumping, whereas the remaining two studies either provided no instructions or placed no restrictions on arm movement throughout the jumping activities. Although Bassey and colleagues [12,19], used a countermovement arm swing for the CMJ, they stated that the jumps were submaximal and could not be described as athletic. Tucker, et al. [22], on the other hand, described the countermovement swing they utilized as vigorous to complement a maximal CMJ. Interestingly, the landing load rate range for participants employing a vigorous arm swing was 200% - 250% greater than for the study which reported CMJ's (> 15 cm), performed without using an arm swing. Therefore, arm swing may be a factor to be considered in future research, with the potential to influence the rate of force development for jump-landings in premenopausal women.

Effect of footwear

All of the studies in this review performed the jump-landings without shoes, whilst utilizing a firm surface. As a wide range of values for GRF loading rates were reported across the eight studies, further research is needed to understand the influence of footwear on the resulting landing GRFs when performing jumps.

Load direction

All studies in this review involved jumping in the vertical plane, however, three studies used bilateral or unilateral

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multiplanar jumps [10,13,14]. Researchers have stated that bone adaptation is blunted by habitual patterns of loading (e.g. walking and running), so novel or diverse loading patterns are required to stimulate an adaptive bone response [8,11]. Thus, exercises such as jumping and hopping, which are considered to provide 'unusual' or 'unfamiliar' patterns of loading have been shown to have a greater osteogenic effect than landing force magnitude alone, with bone adaptation being observed at much lower GRF when these non-habitual strains are applied [8,24]. Furthermore the 'error strain distribution hypothesis' suggests that unusual or novel directions of force application may have a greater osteogenic effect than the magnitude and is therefore vital to osteogenesis [11,24]. Although three studies in this review included multidirectional jump-landings, it should be highlighted that only two of the studies reported multiplanar GRF's [13,14]. As osteogenic thresholds, and most available GRF jump-landing data are represented in the vertical direction only, research is required for quantifying multiplanar jump-landings (i.e. star jumps, stride jumps, multi-directional hops), across all planes of motion (i.e. anterior-posterior, medio-lateral and resultant). In addition, research to determine the contribution of each GRF vector to the overall osteogenic stimulus for bone is warranted.

Effect of jump-landing instruction

As only three studies in the review has included multiplanar jump-landings performed by premenopausal women, there is clearly a need for further research in this area. Although Bailey and Brooke-Wavell [10], instructed their participants to precede the hop with slight knee flexion (countermovement), they provided no specific instruction for jump-landings. However, the jump-landing technique involving a quick "stiff" landing and incorporating a "reactive jump", was a central focus for Clissold and colleagues (2018, 2019, 2022) [13-15], who reported substantially higher peak ground reaction force magnitudes and rates. Thus, future research is required to explore the effect of cueing participants to land 'stiffly' and to utilize a flat-footed ground contact for multidirectional jump-landings. In addition, the ability to interpret unilateral and multiplanar jump-landing forces with respect to osteogenic thresholds (magnitude and rate) previously established using bilateral vertical jump-landings is needed.

Effect of arms

It may be speculated that aggressive arm movements in the anterior-posterior direction would increase jump distance and landing forces in this plane of motion, similar to the effects of upward arm movement on vertical GRF. However, no description or standardization for use of arms was provided for the study utilizing multiplanar jump-landings. In contrast, the studies by Clissold and colleagues (2018, 2019, 2022) [13-15], instructed a vigorous arm swing in a countermovement style, and reported peak landing forces 2 times greater for their hop landings. Thus, further research is needed to understand the influence of arm swing on the resulting landing GRFs when performing multidirectional jumps.

Effect of footwear

Although only three studies in this review investigated multiplanar jump landings, the participants performed the jump landings in unshod conditions. Thus, further research is needed to understand the influence of footwear on the resulting landing GRFs when premenopausal women perform multiplanar jumps.

Conclusion

Although the authors of the studies in this review stated that to confer the greatest benefit to bone you need to subject the skeleton to large magnitude forces at rapid loading rates, only one research group provided the instructions or specific cueing for the jump-landing phase to optimize bone stimulation for premenopausal women. Therefore, further research is warranted to investigate the effect of specific cueing (i.e. think of the ground as a hot plate and try to land 'stiffly') on jump-landing GRFs in premenopausal women. In addition, the effects of repeated or reactive jump-landing need to be investigated, as it appears that this technique has the potential to influence impact and force absorption, and therefore the osteogenic effectiveness of selected jumps. Furthermore, factors such as jump effort, arm swing, and footwear also require additional research focus to be able to clarify the influence of these variables on jump-landing GRF's.

Currently GRF data is limited for different jumping movements and has been predominantly presented in the vertical plane only. Thus, future studies are needed to quantify landing forces for a variety of jumps (i.e. star and stride jumps) using premenopausal women. In addition, jump-landing GRF's need to be quantified across all planes of motion to gain a better understanding of the contribution of each GRF vector to the overall osteogenic stimulus for bone. Enhanced knowledge about these factors has the potential to influence the osteogenic effectiveness, standardisation and repeatability of jump-landings in this population. Such information could be used to identify what jumps could be best utilised and matched in the development of osteogenic exercise programmes for premenopausal women, to help optimise and create a novel impact stimulus required to promote bone formation.

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