

https://dspace.org/

Skeletal sitespecific effects of jump training on bone mineral density in adults a systemic review and metaanalysis

Gabriella E Florence; Tanja Oosthuyse; A Bosch

TAYLOR & FRANCIS LTD
https://hdl.handle.net/10539/41264
WOS

Downloaded from a DSpace repository. https://dspace.org/



Journal of Sports Sciences

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/rjsp20

Skeletal site-specific effects of jump training on bone mineral density in adults: a systematic review and meta-analysis

Gabriella E Florence, Tanja Oosthuyse & Andrew N Bosch

To cite this article: Gabriella E Florence, Tanja Oosthuyse & Andrew N Bosch (2023) Skeletal site-specific effects of jump training on bone mineral density in adults: a systematic review and meta-analysis, Journal of Sports Sciences, 41:23, 2063-2076, DOI: 10.1080/02640414.2024.2312052

To link to this article: https://doi.org/10.1080/02640414.2024.2312052

View supplementary material

Published online: 02 Feb 2024.

Submit your article to this journal

Article views: 177

View related articles

View Crossmark data

Full Terms & Conditions of access and use can be found at
https://www.tandfonline.com/action/journalInformation?journalCode=rjsp20

JOURNAL OF SPORTS SCIENCES
2023, VOL. 41, NO. 23, 2063–2076
https://doi.org/10.1080/02640414.2024.2312052

Routledge
Taylor & Francis Group

PHYSICAL ACTIVITY, HEALTH AND EXERCISE

Check for updates

Skeletal site-specific effects of jump training on bone mineral density in adults: a systematic review and meta-analysis

Gabriella E Florence [a], Tanja Oosthuyse [b,c] and Andrew N Bosch [c]

[a]Institute of Sport and Exercise Medicine, Division of Orthopaedic Surgery, Faculty of Medicine and Health Sciences, Stellenbosch University, Tygerberg, South Africa; [b]School of Physiology, Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, South Africa; [c]Health through Physical Activity, Lifestyle and Sport Research Centre, Division of Physiological Sciences, Department of Human Biology, Faculty of Health Sciences, University of Cape Town, Cape Town, South Africa

ABSTRACT

Preserving or preventing declines in bone mineral density (BMD) is imperative. As jumping is a high-impact bone-loading action, this meta-analysis evaluated the efficacy of jump training to improve BMD and bone turnover relative to non-jumping controls in men and women > 18 years, following Preferred Reported Items for Systematic Reviews and Meta-Analysis guidelines. PubMed and COCHRANE Library databases were searched until February 2022. Fifteen articles (19 jumping-trials) met the predetermined search criteria. Eighteen trials were included for BMD data ($n = 666$ participants). There was a significant small-moderate effect of jumping on femoral neck BMD (%mean difference: 95%CI, +1.50%: 0.83%; 2.17%, $p < 0.0001$), that remained significant after sub-analysis by age for both younger (+1.81%: 0.98%; 2.65%) and older adults (+1.03%: 0.02%; 2.03%). BMD of total hip (+1.26%: 0.56%; 1.96% vs + 0.06%: −0.96%; 1.08%), and trochanter (+0.84%: 0.20%; 1.48% vs −0.16%: −1.08%; 0.76%) increased significantly with jump training only in younger adults and non-significantly at the lumbar spine (+0.84%: −0.02%; 1.7% vs −0.09%: −0.96%; 0.77%) only in younger but not older adults, respectively. The BMD response to jump training appears to be site-specific, with the highest sensitivity at the femoral neck. No dose-response effect suggests moderate certainty of a gain in femoral neck BMD when performing the median jump-load of 50 jumps four times weekly.

ARTICLE HISTORY
Received 21 June 2022
Accepted 19 January 2024

KEYWORDS
Adults; bone mineral density; bone turnover; jumping; osteoporosis

Introduction

Peak bone mass is attained by 30 years. Inevitably, bone loss will begin to occur thereafter, with the greatest decline in bone mass occurring after 50 years (Dasarathy & Labrador, 2018). In fact, bone mass losses of 0.3%-1.1% per year at the hips and lumbar spine have been reported in men up to 50 years and premenopausal women (Vondracek et al., 2009; Warming et al., 2002). Notably, in men older than 50 years (Kanis, 2002) and postmenopausal women (Khosla & Riggs, 2005; Marcus, 2002), the rates of bone mass loss at these axial skeletal sites can increase to 0.7%–2% per year and up to 15% over 5 years during the menopausal period (Finkelstein et al., 2008). In time, this may lead to osteoporosis, a skeletal disorder characterised by low bone mass and increased bone fragility and susceptibility to fractures (Dasarathy & Labrador, 2018). Indeed, fractures occurring due to osteoporosis are often more serious than many realise, with reports of an 8%–36% mortality rate within 1 year for osteoporotic hip fractures (Abrahamsen et al., 2009). In addition, related medical expenses may present heavy socio-economic burdens on individuals and their families (Compston, 2010).

Evidence suggests that performing sufficient weight-bearing or impact exercise can minimise a loss in bone mineral density (BMD) (Barry & Kohrt, 2008; Dasarathy & Labrador, 2018; Kohrt et al., 2004; Wolff et al., 1999), and to some extent, reverse age-related bone loss (Bolam et al., 2013; Mathis & Caputo, 2018; Wolff et al., 1999). In contrast, many endurance sports, such as cycling and swimming, are non-weight bearing and non-impact and consequently provide a poor bone loading stimulus at axial skeletal sites that are not directly stimulated by muscle contractions during the sports-specific exercise action (Dolan et al., 2006). Recently, the alert has been raised for the need to evaluate the efficacy of preventive interventions to curb or correct age-related declines in BMD (Hilkens et al., 2021; Jonvik et al., 2022; Karsenty & Khosla, 2022).

Jumping is one such example of high impact, weight-bearing exercise that is expected to produce bone strains sufficient in size to promote and maintain bone mineralisation (Al Nazer et al., 2012; Dolan et al., 2006). Most studies implementing jumping interventions designed to improve bone health have planned each session to last less than 20 min, incorporating either simple one- or two-legged jumps or a variety of jumping styles (Table 1). Importantly, jumping interventions do not appear to cause any adverse effects in premenopausal women (Bassey & Ramsdale, 1994), postmenopausal women (Hartley et al., 2020), older men (Bolam et al., 2013), osteopenic men (Hinton et al., 2015) or children (Heinonen et al., 2000; Vlachopoulos et al., 2018). As such, jumping exercise can be commended as a low cost, safe, and

CONTACT Tanja Oosthuyse oosthuyse@polka.co.za HPALS Research Centre Division of Physiological Sciences, Department of Human Biology, University of Cape Town, Sports Science Institute of South Africa, Boundary Road, Cape Town 7700, South Africa
Supplemental data for this article can be accessed online https://doi.org/10.1080/02640414.2024.2312052.
© 2024 Informa UK Limited, trading as Taylor & Francis Group

time-efficient non-pharmacological strategy that may be effective at improving bone health. Additionally, the little space and equipment required make jumping an accessible form of exercise.

According to the mechanostat theory for bone modelling, a certain minimum threshold of bone strain is required for bone maintenance (~200–1500 microstrain units), and healthy bone modelling (bone gain) occurs between ~ 1000 and 3000 microstrain units (Frost, 2003; Hughes et al., 2020). Notably, the effects of exercise on bone are specific to the area on which mechanical loading is applied, with the biggest response occurring at sites where the mechanical load is the greatest (Oosthuyse et al., 2017). Jumping has been reported to generate sufficient strain magnitudes to support bone maintenance and even bone accretion (Al Nazer et al., 2012). For example, a 2-legged vertical jump to a height of 5 cm above the ground imposes 600 microstrain units on the tibia, and the same jump to 10 cm imposes 1848 microstrain units on the tibia (Al Nazer et al., 2012). By comparison, level walking and running typically imposes 237 microstrain units and 847 microstrain units, while uphill/downhill walking and running imposes 381/414 microstrain units and 743/1226 microstrain units on the tibia, respectively (Al Nazer et al., 2012).

Both impact and non-impact exercise stimulate muscle contractions that produce strains on associated bones. However, ground reaction forces (GRFs) are only generated during impact exercise, which takes advantage of body weight to mechanically load the associated bones (Dolan et al., 2006; Groothausen et al., 1997). Typically, magnitudes of high and low bone-loading strains are defined as GRF values greater than 4 times body weight and less than 2 times body weight, respectively, with higher GRFs usually producing more favourable effects on bone accretion (Groothausen et al., 1997). Previous research using two-legged jumping has reported various landing GRF values of 2 times body weight (Bassey & Ramsdale, 1994; Heinonen et al., 1996), 3 times body weight (Arnett & Lutz, 2002; Bassey et al., 1998; McKay et al., 2005), and more than 5 times body weight (Bolam et al., 2015; Cheng et al., 2002; Fuchs et al., 2001; Heinonen et al., 1996; Kato et al., 2006; McKay et al., 2005; Vlachopoulos et al., 2015) during different jumping exercises. Each of these respective studies reported an increase in BMD or bone mineral content in at least one bone region attributed to the study's jumping intervention. These findings add support for a GRF of larger than 2 times body weight being required to support bone accretion. Unilateral jumping, or hopping, has also been utilised in bone health interventions, generating GRFs between 2- and 3-times body weight (Allison et al., 2013, 2015; Bailey & Brooke-Wavell, 2010; Hartley et al., 2020), only this time, the GRF is applied to a single leg. Although the GRF produced during a unilateral hop and bilateral jump appear to be similar, bilateral jumps may be preferential from a time and effort perspective.

A previous meta-analysis evaluated the effect of jump training on BMD in premenopausal women but was limited to 7 jump-intervention groups from 6 studies of which 2 jump-intervention groups implemented combined jump and lower-body resistance training (Zhao et al., 2014). As a result, the low certainty of effect for the improvement in BMD at the femoral neck and trochanter in that prior population-restricted meta-analysis (Zhao et al., 2014) might not be exclusively attributed to jump training alone. Therefore, a more extensive review is necessary, that is inclusive of both sexes and all adult ages and excludes for concurrent lower-body resistance training.

Given the above, we aimed to establish the mean expected percentage gain in BMD and the standardised effect size response to jump training, measured at axial skeletal sites (namely, the femoral neck, trochanter, total hip, and lumbar spine), to quantify efficacy. For this purpose, we conducted a systematic review and meta-analysis of prospective randomised controlled and non-randomised controlled intervention studies that assessed the effects of jump training on BMD and circulating bone turnover marker concentrations in adult men and women. In addition, sub-analyses for BMD were performed to investigate for differences between younger (<50 years) and older (>50 years) adults.

Materials and methods

This systematic review and meta-analysis was conducted according to the Cochrane Handbook for Systematic Reviews and Interventions (Higgins et al., 2011). All results are reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines (Moher et al., 2009).

Literature search

We searched PubMed and COCHRANE Library databases up until 28-February 2022 for the effects of jump training on measurements of bone health (see Supplementary Material S1 for the list of search terms). Electronic searches were supplemented with manual searches of references from review articles.

Selection criteria

Controlled intervention studies with pre- and post-intervention measurements comparing the effect of jump training with non-jumping groups on BMD or bone turnover markers were included. Only full-text, peer-reviewed journal articles written in English were included. We included all relevant human studies with healthy men and women older than 18 years and with no underlying illnesses or use of medication or hormone replacement therapy that may influence bone metabolism. Studies were excluded if the participants completed lower-body resistance training or high impact exercise in the six months preceding the jump intervention. Studies were included if only jumping exercises were performed for the jumping intervention group and compared with results from non-jumping controls.

Outcomes

The outcome measures were (a) mean percentage changes and its percentage standard deviation (SD) in BMD of the femoral neck, total hip, femoral trochanter and lumbar spine (L2-L4), as assessed by dual-energy x-ray absorptiometry (DXA) scans, and (b) absolute mean and SD of pre- and post-intervention circulating concentrations of bone turnover markers.

Procedures

Selection of studies

Two reviewers (GEF and TO) independently reviewed the inclusion and exclusion of articles and disagreements were discussed and resolved.

Data extraction and management

Data from included reports were independently extracted and analysed twice by the two reviewers (GEF and TO). In the absence of numerical values for outcome measurements, values were extracted from published figures. Most studies presented BMD percentage changes in bar graphs either as mean percentage change and standard error (SE) or 95% confidence interval (95%CI), which were converted to standard deviation (SD) using standard statistical equations (see Supplementary Material S2 for the data extraction method and equations).

Bone turnover markers were reported according to units specific to each marker.

Risk of bias assessment

Included studies were assessed for risk of bias by the two reviewers (GEF and TO) using the Cochrane Collaboration risk of bias tool (Higgins et al., 2011). The included studies were evaluated for low risk, high risk, or an unclear risk of selection bias, performance bias, detection bias, attrition bias and reporting bias. Any additional sources of bias were identified. The two reviewers provided justifications for the risk of bias selection. Consensus between the two reviewers was obtained for all risk of bias assessments.

Funnel plots were applied for the assessment of publication bias for BMD data. In the absence of publication bias, the funnel plot should create a symmetrical inverted funnel shape. Conversely, an asymmetrical funnel shape may indicate that some level of publication bias is present (Sterne et al., 2011). Review Manager (RevMan 5.4.1) was used to perform the risk of bias assessments and generate funnel plots.

Statistical analyses

Measures of treatment effect

Review Manager was used for primary data analyses and forest plots. The random effects model was applied to perform the meta-analysis at each BMD site and obtain the mean difference (MD) and standardised mean differences (SMD) with 95% confidence intervals for the jump-intervention relative to the control-intervention. The random effects model allows for possible variability in population effect sizes (Borenstein et al., 2010) that could occur owing to the inclusion of studies with various sample populations differing in adult ages or sex. The MD and SMD estimated the mean percentage change and effect size (ES) at each BMD site, respectively. Bone turnover marker concentrations were reported only as absolute pre- and post-intervention concentrations and for this reason were analysed separately for the jump-intervention and control-intervention to obtain SMD with 95%CI to estimate effect sizes for jump and control conditions separately. The SMD effect size scores were interpreted as: 0.0–0.2, trivial; 0.2–0.6, small; 0.6–1.2, moderate; or 1.2-2.0, large effects, respectively (Hopkins et al., 2009). A p-value <0.05 was regarded as significant.

Assessment of heterogeneity

Heterogeneity between the included studies was quantified with I-squared (I^2). I^2 values between 0% and < 50% were considered low heterogeneity; 50% to < 75% were considered moderate heterogeneity; and ≥ 75% were considered high heterogeneity. In the case of significant heterogeneity (I^2 >50% or $p > 0.10$), firstly subgroup analysis and finally sensitivity tests were applied to determine if a select study was responsible for the heterogeneity.

Sub-group analyses

Sub-analyses for age grouped as younger adults (<50 years) and older adults (>50 years) were conducted for BMD outcome variables, which concurrently stratified the studies in premenopausal women with younger adults and postmenopausal women with older adults. Differences in the mean effects between sub-groups were tested, where $p < 0.1$ was regarded as significant (Richardson et al., 2019). Sub-group study characteristics (Table 1) were compared using an unpaired t-test with significance accepted as $p < 0.05$.

Osteogenic index

We calculated the osteogenic index (OI) per week for each jump-intervention group (Table 1) using the method described by Turner and Robling (2003). The OI integrates the jumps per session and weekly jump frequency to generate a composite bone stimulus index (see Supplementary Material S3 for a description of OI and the equations applied).

Grading of the evidence

The GRADE approach (grading of recommendations, assessment, development, and evaluation) was used to assess the certainty of the effect estimate outcomes (see Supplementary Material S4 for the list of standard grading criteria).

Results

Search results

Figure 1 shows the systematic search and selection of included articles. Of the 1092 articles identified from searches, 1035 were excluded based on their titles and abstracts. Thirty articles were reviewed in full, and an additional 15 articles were excluded based on eligibility criteria. One study included upper body resistance training with the jumping exercise intervention and the results pertaining to changes in bone turnover markers were excluded from this meta-analysis (Bolam et al., 2015). The meta-analysis was conducted on 14 randomised controlled trials (where participants were randomly assigned to the intervention or control group) and 1 non-randomised controlled trial (where participants self-selected to participate in either the intervention or control group), including a total of 760 participants. Fifteen articles that included a total of 19 intervention groups met the predetermined search criteria.

Table 1. General characteristics of included studies.

Authors	Participants	Sample size (n)	Age (mean±SD)	Jump intervention duration (months)	Jump intervention details vs. Control	Jump frequency (days/ week)	Total jumps per week	Jump Osteogenic Index per week (OI/ wk)	Measured BMD sites; Bone turnover markers
YOUNGER ADULTS (<50 years)									
Bailey and Brooke-Wavell (2010)	Premenopausal women	J2: 16 J4: 13 J7: 16 C: 20	34 ± 11	6	50 1-leg hops vs. con leg	2 4 7	100 200 350	24 47 83	Femoral neck, total hip, trochanter
Bassey et al. (1998)	Premenopausal women	J: 30 C: 25	37 ± 8	5	50 2-leg jumps vs. con	6	300	70	Femoral neck, lumbar spine, trochanter; OC, NTx
Heinonen et al. (1996)	Premenopausal women	J: 39 C: 45	39 ± 3	18	100–200 2-leg jumps vs. con	3	450	48	Femoral neck, trochanter
Kato et al. (2006)	Premenopausal women	J: 18 C: 18	20 ± 1	6	10 2-leg jumps vs. con	3	30	22	Femoral neck, lumbar spine, trochanter; DPD
Shibata et al. (2003)	Premenopausal women	J: 11 C: 17	37 ± 6	12	10 2-leg jumps & 10 000 steps vs. 10 000 steps con	7	70	50	Femoral neck
Sugiyama et al. (2002)	Premenopausal women	J: 14 C: 16	48 ± 4	6	100 2-leg jumps vs. con	2	200	32	Femoral neck, lumbar spine, total hip
Tucker et al. (2015)	Premenopausal women	J10: 23 J20: 14 C: 23	40 ± 5	4	J10: 10 2-leg jump 2×/day J20: 20 2-leg jump 2×/day vs. con	6 6	120 240	75 95	Total hip
Vainionpää et al. (2005)	Premenopausal women	J: 39 C: 41	38 ± 2	12	†40 min high-impact jump vs. con	3	800	66	Femoral neck, trochanter
YOUNGER ADULTS (<50 years)									
Median			37	6	50	4	200	50	
Mean			36	8	69	4	260	56	
(Range)			(20–48)*	(4–18)	(10–167)	(2–7)	(30–800)	(22–95)	
OLDER ADULTS (>50 years)									
Allison et al. (2013)	Older men	J: 35 C: 35	70 ± 4	12	50 1-leg hops vs. con leg	7	350	83	Femoral neck, trochanter
Bassey et al. (1998)	Postmenopausal women	J: 45 C: 32	55 ± 4	12	50 2-leg jumps vs. con	6	300	70 70	Femoral neck, lumbar spine, trochanter; OC, NTx
Bolam et al. (2015)	Older men	J40: 15 J80: 13 C: 13	60 ± 7	9	J40: 40 2-leg jumps J80: 80 2-leg jumps vs. con	4 4	160 320	45 53	Femoral neck, lumbar spine, total hip, trochanter
Hartley et al. (2020)	Postmenopausal women	J: 35 C: 35	62 ± 4	6	50 1-leg hops vs. con leg	7	350	83	Femoral neck
Sen et al. (2020)	Postmenopausal women	J: 16 C: 18	54 ± 5	6	60 2-leg jumps vs. con	3	180	37	Femoral neck, lumbar spine, total hip; OC, CTx
Sugiyama et al. (2002)	Postmenopausal women	J: 13 C: 13	53 ± 4	6	100 2-leg jumps vs. con	2	200	32	Femoral neck, lumbar spine, total hip
OLDER ADULTS (>50 years)									
Median			59	9	50	4	300	53	
Mean			59	9	60	5	266	58	
(Range)			(53–70)*	(6–12)	(40–87)	(2–7)	(160–350)	(32–83)	

(*Continued*)

Table 1. (Continued).

Authors	Participants	Sample size (n)	Age (mean±SD)	Jump intervention duration (months)	Jump intervention details vs. Control	Jump frequency (days/ week)	Total jumps per week	Jump Osteogenic Index per week (OI/ wk)	Measured BMD sites; Bone turnover markers
ALL BMD STUDIES									
Median			41	6	50	4	200	52	
Mean			45	8	65	5	252	56	
(Range)			(20–70)	(4–18)	(10–267)	(2–7)	(30–800)	(22–95)	
ADDITIONAL BONE TURNOVER MARKER STUDIES									
Hinton et al. (2015)	Osteopenic men	J: 19 RT: 19	44 ± 2	12	120 2-leg jumps vs. RT con	3	360	48	OC, CTx
Rantalainen et al. (2011)	Older men	J: 9 C: 9	72 ± 4	3	7×10 s 2-leg jumps vs. con	3	210	28	PICP, CTx
Vainionpää et al. (2009)	Premenopausal women	J: 37 C: 39	38 ± 2	12	50 2-leg jumps vs. con	6	300	71	P1NP, TRAP5b
ALL BONE TURNOVER MARKER STUDIES									
Median			44	6	50	3	300	48	
Mean			46	8	59	4	240	49	
(Range)			(20–72)	(3–12)	(10–120)	(3–6)	(30–360)	(22–71)	

BMD: bone mineral density; C: non-exercising control group; PICP: C-terminal collagen propeptide; con: non-exercising control; CTx: C-terminal telopeptide of type I collagen; DPD: deoxypyridinoline; J: jump intervention group; J2: jump 2 days/week; J4: jump 4 days/week; J7: jump 7 days/week; J10: 10 jumps 2×/day; J20: 20 jumps 2×/day; J40: 40 jumps/session; J80: 80 jumps/session; NTx: N-terminal telopeptides of type I collagen; OC: osteocalcin; P1NP: N-terminal propeptide of type I procollagen; RT: resistance training; TRAP5b: tartrate resistant acid phosphatase; †denotes that the exact number of jumps/session is unknown for this study and an estimate is applied based on time; *denotes a significant difference in the age of the participants in the younger (<50 years) and older (>50 years) studies, $p < 0.0001$.

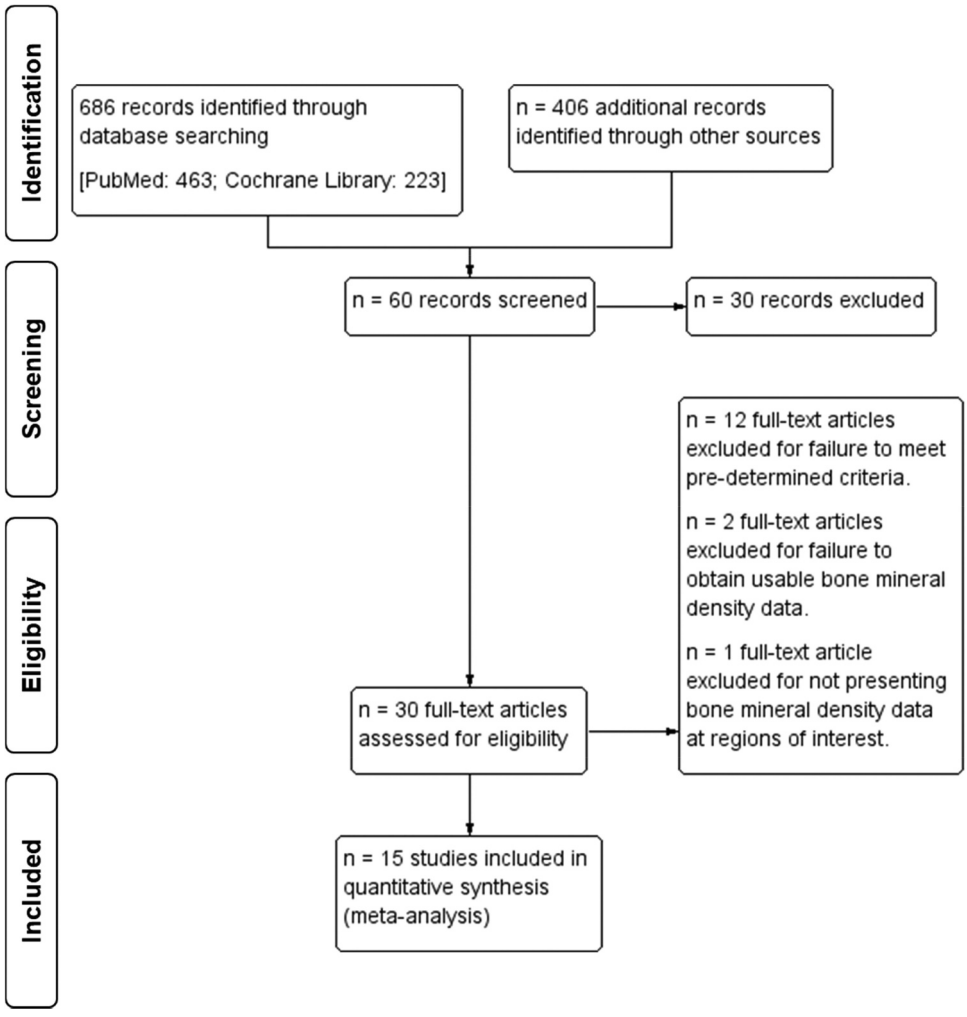


Figure 1. Flow diagram for the selection of studies.

Description of studies

The general descriptions of the included studies are presented in Table 1. Studies were conducted in premenopausal women, postmenopausal women or older men, in addition to one single study in young osteopenic men that was included only for the change in bone turnover markers.

Five studies included more than one jump exercise group. Studies incorporating more than one jump intervention group differed in the weekly frequency (Bailey & Brooke-Wavell, 2010) or intensity of the jump training (Bolam et al., 2015; Tucker et al., 2015) or age of participant groups, and in this latter case included separate age-matched control groups (Bassey et al., 1998; Sugiyama et al., 2002). Each jump group was analysed separately and compared with the non-jumping control group.

Four studies were conducted in the United Kingdom (Allison et al., 2013; Bailey & Brooke-Wavell, 2010; Bassey et al., 1998; Hartley et al., 2020), one in Australia (Bolam et al., 2015), four in Finland (Heinonen et al., 1996; Rantalainen et al., 2011; Vainionpää et al., 2005, 2009), three in Japan (Kato et al., 2006; Shibata et al., 2003; Sugiyama et al., 2002), two in the United States of America (Hinton et al., 2015; Tucker et al., 2015), and one in Istanbul (Sen et al., 2020).

Types of jumping interventions

All the studies compared the effectiveness of a jump training intervention with a non-jumping control group. Three studies designed a unilateral jump intervention and their non-jumping control group corresponds to the non-jumping contralateral leg (Allison et al., 2013; Bailey & Brooke-Wavell, 2010; Hartley et al., 2020).

Most of the included studies' durations ranged from 6 to 12 months (Table 1). There was no significant difference in study duration between sub-groups stratified by age ($p = 0.6554$). The weekly frequency of jump training varied from twice per week to daily, with a median frequency of 4 jump training sessions per week and a median of 50 jumps per training session (Table 1). The median total number of jumps completed per week for studies reporting BMD was 200 jumps/week where nine intervention groups performed ≤ 200 jumps per week and nine intervention groups performed > 200 jumps per week. There was no significant difference between the studies stratified by age as younger (<50 years) and older (>50 years) adults for the number of jumps per session ($p = 0.7702$), total number of jumps per week ($p = 0.9486$), the jump frequency per week ($p = 0.7887$) or the osteogenic index per week ($p = 0.8647$) (Table 1). In addition, there was no significant difference in

the vertical ground reaction force (GRF) relative to body weight of the jump routines in the studies in younger (mean ± SD: 3.7 ± 0.6, measured in 7 of the 11 intervention groups) and older adults (4.0 ± 1.3, measured in 5 of the 7 intervention groups) ($p = 0.5865$). However, as expected the age of participants differed significantly between the younger (<50 years) and older (>50 years) adult studies ($p < 0.0001$) (Table 1).

Risk of bias assessment

Most studies were marked as having either low or unclear risk of bias for all categories (see Supplementary Material S5 for the risk of bias figure summary and justification for each study's characterisation per category).

Funnel plots

Symmetrical funnel plots were obtained for femoral neck, trochanter and lumbar spine BMD. A small degree of asymmetry was observed for total hip BMD, likely owing to the few studies available for this BMD site (see Supplementary Material S6 to view the funnel plots).

Meta-analysis of the effect of jumping on bone mineral density

Twelve included studies presented BMD data from a total of 418 premenopausal women, 172 postmenopausal women, and 76 older men across 18 jump training groups.

Femoral neck

Changes in femoral neck BMD were reported in 11 studies and included 16 jumping intervention groups from a total of 601 participants. There was a significant overall percentage gain in BMD at the femoral neck from pre- to post-jump training relative to non-jumping controls of moderate effect size (Figure 2), however, with significant heterogeneity ($I^2 = 70\%$, $p < 0.0001$). Sub-analysis by age revealed a gain in femoral neck BMD relative to non-jumping controls of moderate effect size in younger premenopausal women (<50 years) and small effect size in older adults (>50 years), where significance was retained for both sub-groups, and with no significant difference between sub-groups (Figure 2).

Total hip

Changes in total hip BMD were reported in 4 studies and included a total of 7 jumping intervention groups from 209 participants. Overall jump training resulted in a small effect improvement in total hip BMD from pre- to post-intervention relative to non-jumping controls that was not significant (Figure 3), with low heterogeneity. However, sub-analysis by age revealed a significant moderate gain in total hip BMD relative to non-jumping controls only in younger adults and no significant effect in older adults (Figure 3). This difference between sub-groups was significant (Figure 3).

Trochanter

Seven studies reported changes in trochanter BMD and included a total of 11 jumping intervention groups from 441 participants. Overall, there was a trivial effect of the jumping interventions on

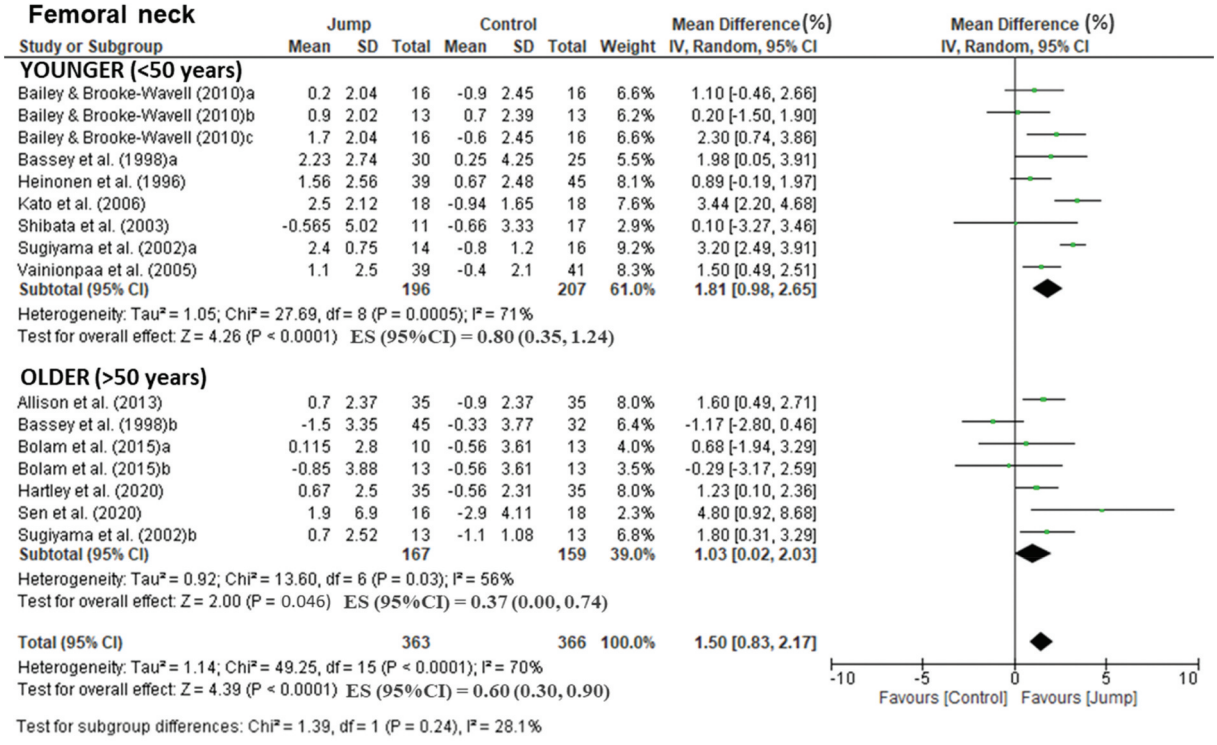


Figure 2. Forest plots presented as percentage mean difference (%) for changes in bone mineral density at the femoral neck with jump training for younger (<50 years) and older (>50 years) adults, relative to non-jumping controls. The *diamond* denotes the sub-group and overall treatment outcomes with 95% confidence intervals (95%CI) and ES denotes effect size.

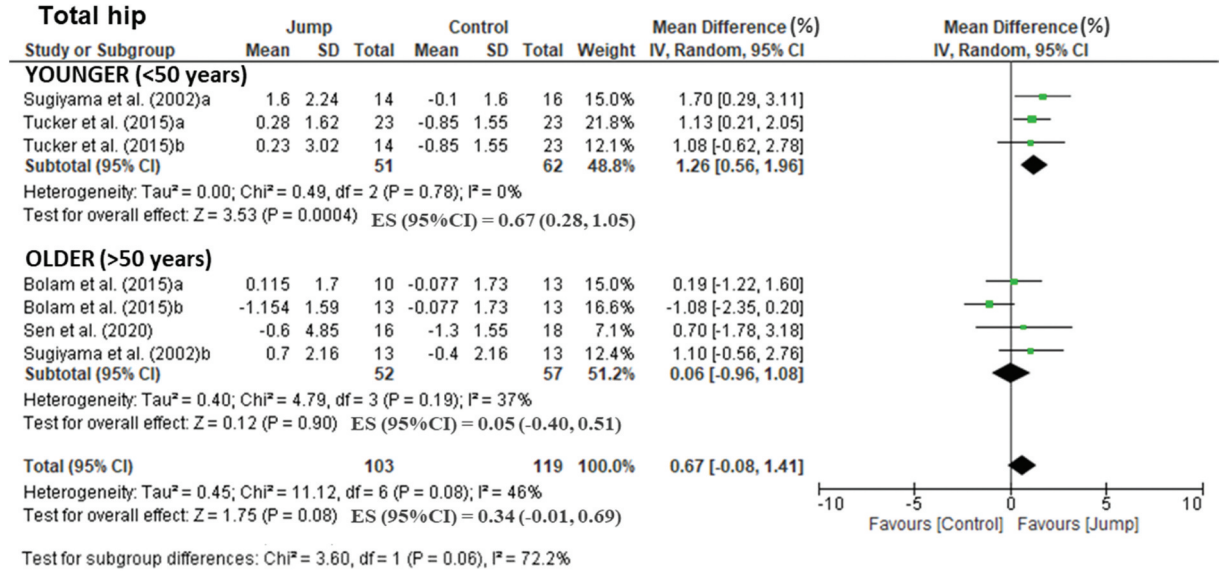


Figure 3. Forest plots presented as percentage mean difference (%) for changes in bone mineral density at the total hip with jump training for younger (<50 years) and older (>50 years) adults, relative to non-jumping controls. The *diamond* denotes the sub-group and overall treatment outcomes with 95% confidence intervals (95%CI) and ES denotes effect size.

the trochanter BMD from pre- to post-intervention relative to non-jumping controls (Figure 4), with low heterogeneity. However, sub-analysis by age revealed a significant small gain in trochanter BMD relative to non-jumping controls only in younger, but not in older adults (Figure 4). The difference between sub-groups was significant (Figure 4).

Lumbar spine

Seven studies that included a total of 10 jumping intervention groups reported change in the L2-L4 lumbar spine from a total of 406 participants. Overall jump training had a trivial, non-significant effect on lumbar spine BMD from pre to post intervention relative to non-jumping controls, (Figure 5), with low heterogeneity. Sub-analysis by age revealed a small effect on L2-L4 lumbar spine BMD relative to non-jumping controls in younger adults that was not significant, and no effect in older adults, with no significant difference between sub-groups (Figure 5).

Sensitivity analysis at the femoral neck

The significant heterogeneity in the effect outcome at the femoral neck could not be explained by sub-analyses for age, and therefore sensitivity testing was performed to identify

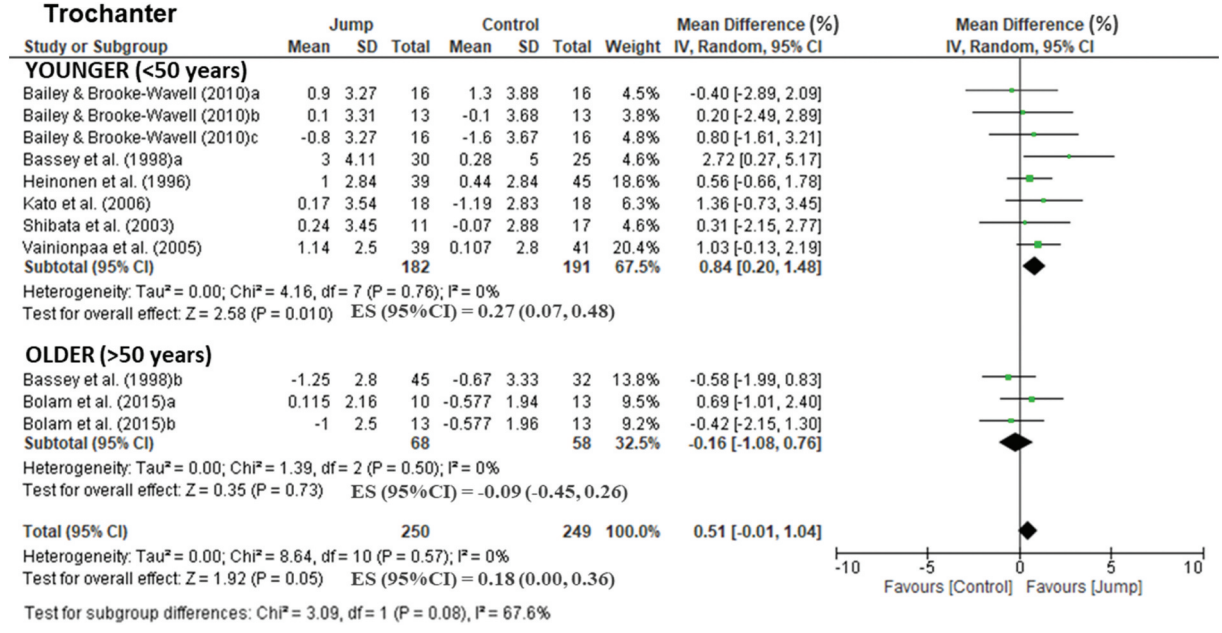


Figure 4. Forest plots presented as percentage mean difference (%) for changes in bone mineral density at the trochanter with jump training for younger (<50 years) and older (>50 years) adults, relative to non-jumping controls. The *diamond* denotes the sub-group and overall treatment outcomes with 95% confidence intervals (95%CI) and ES denotes effect size.

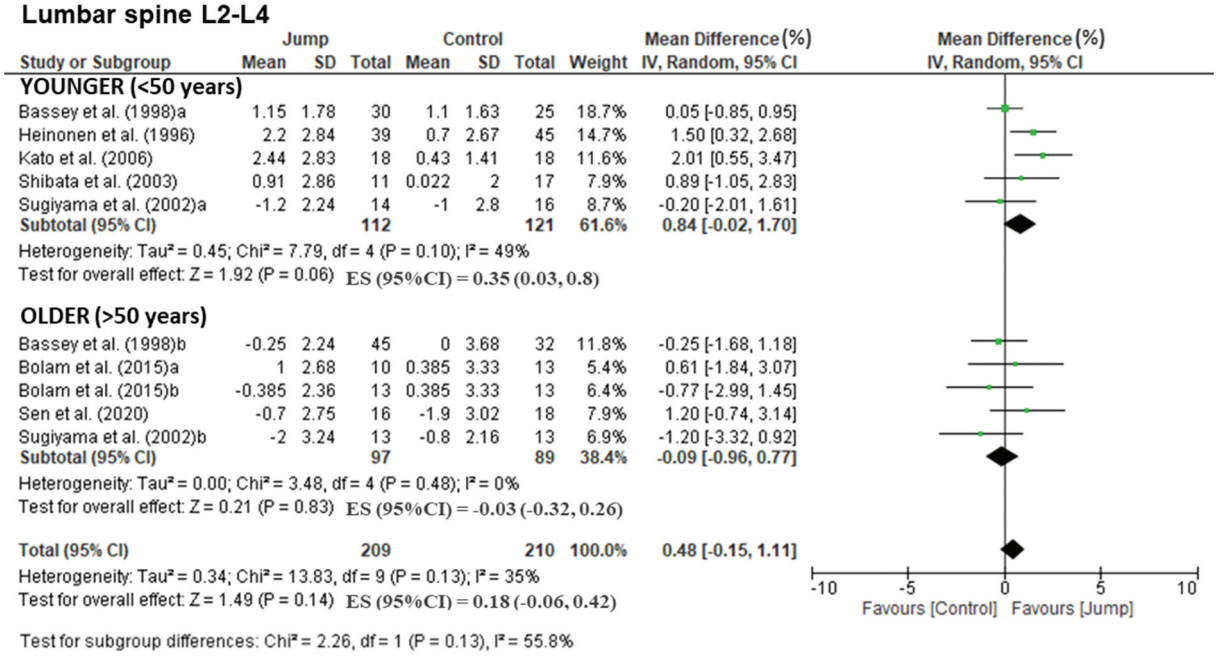


Figure 5. Forest plots presented as percentage mean difference (%) for changes in bone mineral density at the L2-L4 lumbar spine with jump training for younger (<50 years) and older (>50 years) adults, relative to non-jumping controls. The *diamond* denotes the sub-group and overall treatment outcomes with 95% confidence intervals (95%CI) and ES denotes effect size.

whether one or more study group was responsible for the notable heterogeneity. Markedly, two premenopausal study groups from two separate studies presenting large effect responses (Kato et al., 2006; Sugiyama et al., 2002) appeared to be mainly responsible for the significant heterogeneity at the femoral neck. When these two study groups were excluded, the level of heterogeneity was reduced and no longer significant ($I^2 = 39\%$, $p = 0.07$) with the outcome having a small significant effect (ES = 0.41 (95%CI: 0.21 to 0.62)); and %MD of 1.16% (95% CI: 0.65% to 1.67%) ($p < 0.0001$). When a third study with post-menopausal women presenting a negative trivial response was excluded (Bassey et al., 1998), the level of heterogeneity at the femoral neck was reduced further to zero ($I^2 = 0\%$, $p = 0.60$) and the outcome remains as a small effect (ES = 0.50 (95%CI: 0.34 to 0.67)) with %MD of 1.34% (95%CI: 0.92% to 1.76%) ($p < 0.0001$).

Dose-response analysis

Eleven studies with a total of 16 jumping intervention groups and 601 participants were included in a dose-response linear regression analysis for BMD changes relative to non-jumping controls at the femoral neck with the number of weekly jumps or weekly OI. The linear regression plots showed no significant correlation between the percentage mean difference (%MD) at the femoral neck and total number of jumps per week ($r = -0.1741$, $p = 0.5349$) (Figure 6(a)), or OI per week ($r = -0.2822$, $p = 0.2895$) (Figure 6(b)) for the jumping loads used in the included studies.

Meta-analyses of the effect of jumping on bone turnover markers

Changes in circulating bone formation marker concentrations from pre- to post-intervention were reported in 5 studies with a total of 126 jumpers and 98 non-jumping controls. Three studies measured changes in osteocalcin (OC) (ng/ml) (Bassey et al., 1998; Hinton et al., 2015; Sen et al., 2020), one study measured C-terminal propeptide of type I procollagen (PICP) (ng/ml) (Rantalainen et al., 2011), and one study measured N-terminal propeptide of type I procollagen (P1NP) (ng/ml) (Vainionpää et al., 2009). There was a trivial effect in both the jumpers (ES (95%CI): 0.12 (−0.13 to 0.37), Z = 0.93, $p = 0.35$) and non-jumping controls (ES (95%CI): 0.14 (−0.15 to 0.42), Z = 0.94, $p = 0.35$) for the change in bone formation marker concentrations, with low heterogeneity for the jumpers ($I^2 = 0\%$, $p = 0.42$) and non-jumping controls ($I^2 = 0\%$, $p = 0.54$).

Six studies reported changes in circulating bone resorption marker concentrations from a total of 136 jumpers and 108 non-jumping controls. Measured bone resorption markers included C-terminal telopeptide of type I collagen (CTx) (ng/ml) in three studies (Hinton et al., 2015; Rantalainen et al., 2011; Sen et al., 2020), N-terminal telopeptides of type I collagen (NTx) in one study (nmol BCEs/mmol Cr) (Bassey et al., 1998), deoxypyridinoline (DPD) (nmol/mmol Cr) in one study (Kato et al., 2006), and tartrate resistant acid phosphatase (TRAP5b) (U/L) in one study (Vainionpää et al., 2009). There was a trivial effect in both the jumpers (ES (95%CI): 0.02 (−0.22 to 0.25), Z = 0.13, $p = 0.90$) and non-jumping controls (ES (95%CI): 0.06 (−0.21 to 0.33), Z = 0.44, $p = 0.66$) for the change in bone resorption marker concentrations, with low heterogeneity for the jumpers ($I^2 = 0\%$, $p = 0.45$) and non-jumping controls ($I^2 = 0\%$, $p = 0.89$) (see Supplementary Material S7 for bone turnover marker forest plots).

GRADE assessment

All outcomes were downgraded for possible publication bias because published studies only exist for premenopausal and

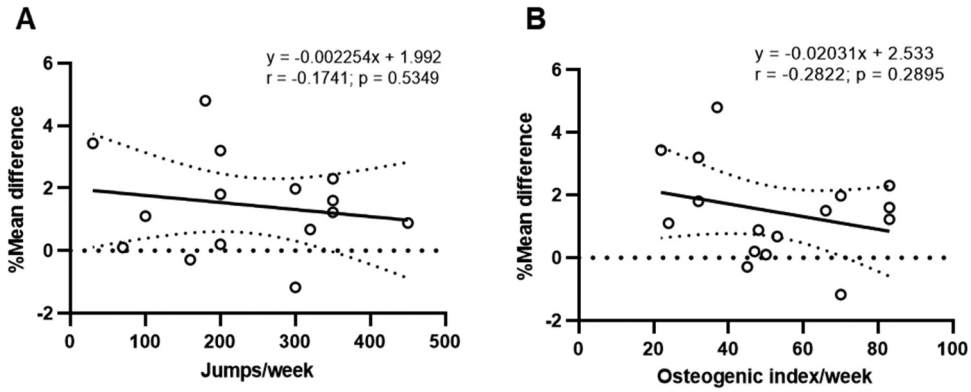


Figure 6. Dose-response showing best-fit line and 95%CI for the correlation between percentage mean difference in bone mineral density at the femoral neck and total number of jumps completed per week (a) or osteogenic index per week (b), for the jumping loads applied. One study was excluded from the regression analysis for weekly jumps as an outlier with 800 jumps/week (Vainionpää et al., 2005).

postmenopausal women and older men, with only one study in younger men. Femoral neck BMD was initially downgraded for inconsistency according to notable heterogeneity but following sensitivity testing that identified the two outlier studies that caused majority of the heterogeneity, the inconsistency was removed. Total hip BMD and bone turnover marker outcomes were downgraded for imprecision due to the small sample size of studies and wide confidence intervals. No upgrades were warranted. As a result, the certainty in the evidence is moderate for femoral neck, trochanter and lumbar spine BMD and low for total hip BMD and bone turnover markers (see Supplementary Material S8 for a Table showing the detailed GRADE assessment results).

Discussion

The primary purpose of this systematic review and meta-analysis was to quantify the effect of jump training on changes in BMD relative to non-jumping controls at the femoral neck, total hip, femoral trochanter, and lumbar spine. Additionally, bone turnover markers, as a secondary bone health outcome, were measured to evaluate for changes in bone formation and bone resorption activity. Most notably, the current meta-analysis found that jump training induces a positive effect on BMD at the femoral neck, both in younger premenopausal women (<50 years) and in older men and postmenopausal women (>50 years). Jump training is also effective at increasing BMD at total hip and trochanter, only in younger premenopausal women (<50 years), but not older men and postmenopausal women (>50 years). No dose-response relation is evident in the number of weekly jumps or weekly OI and the percentage gain in BMD at the femoral neck. In addition, there were only trivial effects of jump training on markers of bone formation and bone resorption activity.

Effect of jumping on BMD

Despite the moderate and small effect size outcomes for femoral neck BMD relative to non-jumping controls in younger and older adults, respectively, the mean percentage gain in BMD at the femoral neck from pre- to post-intervention was not significantly different between sub-groups. However, sensitivity analysis was used to identify the source of heterogeneity in the BMD outcome at the femoral neck and supports a disparate effect of age on BMD responsiveness to jumping exercises. The significant heterogeneity in the BMD outcome at the femoral neck is mostly accounted for by 2 studies in premenopausal women that produced an exaggerated large effect (Kato et al., 2006; Sugiyama et al., 2002). Moreover, when accounting for a third study with postmenopausal women reporting a trivial negative effect at the femoral neck (Bassey et al., 1998), the heterogeneity was eliminated at the femoral neck. However, 8% of the postmenopausal women in the latter study were smokers (Bassey et al., 1998), and this may have further caused a notably smaller effect of jumping on femoral neck BMD in this study, contributing to heterogeneity in the overall effect.

Interestingly, jump training was also effective in increasing BMD from pre- to post-intervention relative to non-jumping controls at all the other measured bone sites only in younger but not in older adults. These results suggest that jumping may have a larger effect in adults younger than 50 years and a lesser effect in individuals older than 50 years, despite a similar jump load, frequency and intensity (measured by vertical GRF). However, the rate of force produced was mostly not reported and whether jump rate differed between studies in younger and older adults cannot be known. Nevertheless, the apparent similar jump load and intensity between studies in younger and older adults suggests that the noted age-related differences in the BMD response to jump training is possibly due to age-related variations in mechanosensation. This may be owing to the age-associated decline in androgens (Chen et al., 2004; Žofková, 2008) and oestrogen (Geoghegan et al., 2019) that has been shown to reduce new bone formation (Demontiero et al., 2012; Ott, 2018), and the increase in sympathetic nervous system tone with ageing that promotes bone resorption dominance (Karsenty & Khosla, 2022). The high inflammatory status associated with ageing in both men and women and with oestrogen-deficiency in postmenopausal women negatively impact osteocyte mechanosensory perception and signalling in response to mechanical loading (Geoghegan et al., 2019; Metzger & Narayanan, 2019). Specifically, osteocyte integrin receptor integrity has been shown to be compromised in older individuals (Metzger & Narayanan, 2019) and in postmenopausal women

(Geoghegan et al., 2019). These integrin receptors are essential in sensing fluid sheer stress in the lacuno-canalicular network that is induced by mechanical loading and that initiates osteocyte signalling in favour of bone formation (Galea et al., 2017); thus, further explaining why older adults may be less responsive to bone-loading exercise than younger adults.

The bigger or more consistent significant effect of jump training on BMD at the femoral neck compared with a smaller significant effect in younger adults or lack of effect in older adults at the other bone sites, could possibly be explained by the loading of a jump action. Performing a normal jump subjects the femoral neck to both bending and compressive forces (Niu et al., 2010), of which both types of forces may attenuate by the time they have been transmitted to the hip and trochanter regions. Therefore, the jumping exercises may have generated sufficient bone strains to be perceived by nearby osteocytes only at the femoral neck, particularly in older adults.

Although the current meta-analysis shows a moderate significant effect only in younger and no significant change in older adults in BMD at the total hip, it has been speculated that changes in femoral neck may better predict hip fractures than total hip BMD alone. Specifically, a decrease in femoral neck BMD of 1 SD may increase the fracture risk at the hip by 2.6 times in postmenopausal women (Cummings et al., 1993). Therefore, the larger increase in femoral neck BMD compared with the small increases in total hip and trochanter BMD may still yield clinical importance in reducing the risk of hip fractures. Furthermore, during a normal jump, the bone strains generated at the hip and femoral neck are higher than that received at the lumbar spine and is likely owing to the attenuation of the mechanical stimuli by the time it is transmitted to the lumbar spine region (Coventry et al., 2006). Therefore, it is unsurprising that the lumbar spine BMD did not respond in the same manner as the BMD of the hip and femoral neck, producing only a nonsignificant small effect in younger adults and no effect in older adults. These results suggest that the effect of jump training causes greater bone adaptations where the impact is highest and less noticeable effects at more distal bone regions (Vainionpää et al., 2005, 2007).

In addition, the dose-response regression plots in the current meta-analysis revealed no significant correlations between BMD effect (relative to non-jumping controls) at the femoral neck and the number of weekly jumps applied in the included studies; with a median of 50 jumps per training session, performed with a median frequency of 4 times weekly. However, the effectiveness of jump training to improve bone health may depend on the provision of short breaks interspersed between jumping sets. Previous research has demonstrated that providing rest periods between repeated sets of load-bearing exercises is vital for enhancing bone accretion (Robling et al., 2000; Rubin & Lanyon, 1984; Srinivasan et al., 2002) where such repeated on-off loading cycles maximise fluid flow near osteocytes (Donahue et al., 2001; Lanyon, 1987). Without rest periods, the continued loading will cause osteocytes to habituate and stop responding to the mechanical stimuli (Robling et al., 2000; Turner, 1998). Accordingly, within a single jump session, 10–20 s of rest has been suggested between each set of 10 jumps to limit mechanosensory habituation (Boudenot et al., 2021; Srinivasan et al., 2002).

Similarly, training frequency may be an important consideration for bone responsiveness, where splitting a fixed-weekly training volume over more days per week has been shown to be better than completing all in one or 2 days per week (Turner & Robling, 2003). Moreover, two shorter training sessions per day (given a minimum recovery of 6–8 h) have been shown to be more effective than a single longer daily session (Turner & Robling, 2003). Accordingly, Turner and Robling (2003) developed a composite OI that takes into consideration the number of jumps per session, the weekly jump-session frequency, and the recovery time between jump sessions. Their model suggests that 24 h is needed for complete restoration of osteocyte mechanosensation and if repeated exercise sessions are performed within a single day, then the subsequent sessions will not afford full osteogenic loading benefits (Turner & Robling, 2003). Notably, when the jump routines of the studies included in the current meta-analysis were ranked according to the calculated OI per week, no dose-response was noted for magnitude of change in BMD at the femoral neck and OI scores varying between 22 and 83 per week (with a median OI of 52 per week), implying an equal gain across that range.

Effect of jumping on bone turnover markers

The overall effect of jumping on bone turnover markers appeared to be trivial and non-significant in this meta-analysis in both the jumpers and non-jumping controls. Bone turnover markers obtained from serum or urine samples are not site-specific but rather reflect whole body bone metabolism (Banfi et al., 2010; Lanyon, 1987) and, therefore, may not be sufficiently sensitive to identify changes in bone turnover that may occur only at one or selected skeletal sites. Therefore, the trivial effect of jumping exercise on bone turnover obtained in this meta-analysis indicates no notable change in whole body bone metabolism, despite the meaningful BMD changes that occurred possibly only at a selected skeletal site, for example, in this case, only at the femoral neck in older adults.

The lack of effect in bone turnover markers may also be a consequence of only comparing pre- to post-intervention values following a long intervention period. The findings by Sen et al. (2020) and Rantalainen et al. (2011) add support for smaller changes being detected over a longer duration (6 months) compared with shorter durations of approximately 3 months. It may be that once the initial bone modelling is accomplished, the bone turnover response reverts to normal bone maintenance at this new established gain in bone mass without any further accrual to the now accustomed bone-loading routine. As a result, serum bone marker concentrations measured at this later post-intervention period again reflect pre-intervention levels.

In addition, certain bone markers depict bone enzyme activities that may represent delayed responses or may represent increased metabolic demands, such as OC (Kanazawa, 2015; Wei & Karsenty, 2015). For that reason, OC may not be a suitable bone formation marker on its own when assessing the effects of an exercise intervention on bone turnover. Rather, changes in circulating concentrations of P1NP and CTx are indicative of current bone turnover status because they are peptide fragments cleaved from bone procollagen precursor

or matrix collagen during formation or resorption activity, respectively (Banfi et al., 2010) and are the current recommended markers in bone health research (Hu et al., 2013; Jenkins et al., 2013). However, only one study reported changes in P1NP (Vainionpää et al., 2009) and only three reported changes in CTx (Hinton et al., 2015; Rantalainen et al., 2011; Sen et al., 2020). Further investigation is warranted to determine the effect of jumping on changes in P1NP and CTx concentrations following the early weeks of the training program.

Limitations

It should be noted that BMD is only one representative measure of bone strength and does not identify microstructure, geometric factors, or torsional strength indices (Fonseca et al., 2014; Manske et al., 2010). The sparsity of jump training studies in male participants is noted and of these, most included elderly men (50–80 years) with only one study in younger men (Hinton et al., 2015). Future studies should investigate for a sex effect of jump training on BMD and bone turnover markers. Notably, three studies included some participants who were smokers (Bassey et al., 1998; Vainionpää et al., 2005, 2009), and it is well-accepted that smoking can negatively impact bone health (Al-Bashaireh et al., 2018). Future research should investigate for differences between smokers and non-smokers in bone indices' responses to jump training.

Conclusions

Bone mineral density responses to jump training appear to be site-specific, with the highest sensitivity at the femoral neck. The overall finding of 1.50% improvement in femoral neck BMD after a median of 6 months of jump training relative to non-jumping controls in the current meta-analysis is graded as moderate certainty and may be clinically relevant in reducing the risk and severity of hip fractures. Notably, lack of a dose-response relation within the range of weekly jumps tested implies moderate certainty of achieving a small-moderate effect size gain in femoral neck BMD when performing the median jump-load of 50 jumps four times weekly. Furthermore, jump training has a small-moderate positive significant effect on BMD relative to non-jumping controls at total hip, trochanter and a small nonsignificant effect at the lumbar spine only in young premenopausal women but not in older men and postmenopausal women with these findings graded as low, moderate and moderate certainty, respectively. Thus, sedentary individuals should begin jump training at an early age to avoid progressive bone loss at these axial skeletal sites.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The author(s) reported there is no funding associated with the work featured in this article.

ORCID

Gabriella E Florence http://orcid.org/0000-0002-6203-405X
Tanja Oosthuyse http://orcid.org/0000-0002-4065-4506
Andrew N Bosch http://orcid.org/0000-0002-9543-9408

References

Abrahamsen, B., van Staa, T., Ariely, R., Olson, M., & Cooper, C. (2009). Excess mortality following hip fracture: A systematic epidemiological review. *Osteoporosis International*, *20*(10), 1633–1650. https://doi.org/10.1007/s00198-009-0920-3

Al-Bashaireh, A. M., Haddad, L. G., Weaver, M., Chengguo, X., Kelly, D. L., & Yoon, S. (2018). The effect of tobacco smoking on bone mass: An overview of pathophysiologic mechanisms. *Journal of Osteoporosis*, *2018*, 1206235. https://doi.org/10.1155/2018/1206235

Allison, S. J., Folland, J. P., Rennie, W. J., Summers, G. D., & Brooke-Wavell, K. (2013). High impact exercise increased femoral neck bone mineral density in older men: A randomised unilateral intervention. *Bone*, *53*(2), 321–328. https://doi.org/10.1016/j.bone.2012.12.045

Allison, S. J., Poole, K. E., Treece, G. M., Gee, A. H., Tonkin, C., Rennie, W. J., Folland, J. P., Summers, G. D., & Brooke-Wavell, K. (2015). The influence of high impact exercise on cortical and trabecular bone mineral content and 3D distribution across the proximal femur in older men: A randomised controlled unilateral intervention. *Journal of Bone and Mineral Research*, *30*(9), 1709–1716. https://doi.org/10.1002/jbmr.2499

Al Nazer, R., Lanovaz, J., Kawalilak, C., Johnston, J. D., & Kontulainen, S. (2012). Direct in vivo strain measurements in human bone-a systematic literature review. *Journal of Biomechanics*, *45*(1), 27–40. https://doi.org/10.1016/j.jbiomech.2011.08.004

Arnett, M. G., & Lutz, B. (2002). Effects of rope-jump training on the os calcis stiffness index of postpubescent girls. *Medicine and Science in Sports and Exercise*, *34*(12), 1913–1919. https://doi.org/10.1097/00005768-200212000-00009

Bailey, C. A., & Brooke-Wavell, K. (2010). Optimum frequency of exercise for bone health: Randomised controlled trial of a high-impact unilateral intervention. *Bone*, *46*(4), 1043–1049. https://doi.org/10.1016/j.bone.2009.12.001

Banfi, G., Lombardi, G., Colombini, A., & Lippi, G. (2010). Bone metabolism markers in sports medicine. *Sports Medicine*, *40*(8), 697–714. https://doi.org/10.2165/11533090-000000000-00000

Barry, D. W., & Kohrt, W. M. (2008). Exercise and the preservation of bone health. *Journal of Cardiopulmonary Rehabilitation and Prevention*, *28*(3), 153–162. https://doi.org/10.1097/01.HCR.0000320065.50976.7c

Bassey, E. J., & Ramsdale, S. J. (1994). Increase in femoral bone density in young women following high-impact exercise. *Osteoporosis International*, *4*(2), 72–75. https://doi.org/10.1007/BF01623226

Bassey, E. J., Rothwell, M. C., Littlewood, J. J., & Pye, D. W. (1998). Pre- and postmenopausal women have different bone mineral density responses to the same high-impact exercise. *Journal of Bone and Mineral Research*, *13*(12), 1805–1813. https://doi.org/10.1359/jbmr.1998.13.12.1805

Bolam, K. A., Skinner, T. L., Jenkins, D. G., Galvão, D. A., & Taaffe, D. R. (2015). The osteogenic effect of impact-loading and resistance exercise on bone mineral density in middle-aged and older men: A Pilot study. *Gerontology*, *62*(1), 22–32. https://doi.org/10.1159/000435837

Bolam, K. A., van Uffelen, J. G., & Taaffe, D. R. (2013). The effect of physical exercise on bone density in middle-aged and older men: A systematic review. *Osteoporosis International*, *24*(11), 2749–2762. https://doi.org/10.1007/s00198-013-2346-1

Borenstein, M., Hedges, L. V., Higgins, J. P., & Rothstein, H. R. (2010). A basic introduction to fixed-effect and random-effects models for meta-analysis. *Research Synthesis Methods*, *1*(2), 97–111. https://doi.org/10.1002/jrsm.12

Boudenot, A., Pallu, S., Uzbekov, R., Dolleans, E., Toumi, H., & Lespessailles, E. (2021). Free-fall landing and interval running have different effects on trabecular bone mass and microarchitecture, serum osteocalcin, biomechanical properties, *SOST* expression and on osteocyte-related

characteristics. *Applied Physiology, Nutrition, and Metabolism*, *46*(12), 1525–1534. https://doi.org/10.1139/apnm-2020-0683

Cheng, S., Sipilä, S., Taaffe, D. R., Puolakka, J., & Suominen, H. (2002). Change in bone mass distribution induced by hormone replacement therapy and high-impact physical exercise in post-menopausal women. *Bone*, *31* (1), 126–135. https://doi.org/10.1016/s8756-3282(02)00794-9

Chen, Q., Kaji, H., Kanatani, M., Sugimoto, T., & Chihara, K. (2004). Testosterone increases osteoprotegerin mRNA expression in mouse osteoblast cells. *Hormone and Metabolic Research*, *36*(10), 674–678. https://doi.org/10.1055/s-2004-826013

Compston, J. (2010). Osteoporosis: social and economic impact. *Radiologic Clinics of North America*, *48*(3), 477–482. https://doi.org/10.1016/j.rcl.2010.02.010

Coventry, E., O'Connor, K. M., Hart, B. A., Earl, J. E., & Ebersole, K. T. (2006). The effect of lower extremity fatigue on shock attenuation during single-leg landing. *Clinical Biomechanics*, *21*(10), 1090–1097. https://doi.org/10.1016/j.clinbiomech.2006.07.004

Cummings, S. R., Black, D. M., Nevitt, M. C., Ensrud, W., Palermo, J., Browner, K., Genant, H. K., Cauley, L., Vogt, J., Scott, T. M., & Vogt, T. M. (1993). Bone density at various sites for prediction of hip fractures The study of Osteoporotic fractures research group. *Lancet*, *341*(8837), 72–75. https://doi.org/10.1016/0140-6736(93)92555-8

Dasarathy, J., & Labrador, H. (2018). Bone health in women. *Primary Care*, *45* (4), 643–657. https://doi.org/10.1016/j.pop.2018.07.011

Demontiero, O., Vidal, C., & Duque, G. (2012). Aging and bone loss: New insights for the clinician. *Therapeutic Advances in Musculoskeletal Disease*, *4*(2), 61–76. https://doi.org/10.1177/1759720X11430858

Dolan, S. H., Williams, D. P., Ainsworth, B. E., & Shaw, J. M. (2006). Development and reproducibility of the bone loading history questionnaire. *Medicine and Science in Sports and Exercise*, *38*(6), 1121–1131. https://doi.org/10.1249/01.mss.0000222841.96885.a8

Donahue, S. W., Jacobs, C. R., & Donahue, H. J. (2001). Flow-induced calcium oscillations in rat osteoblasts are age, loading frequency, and shear stress dependent. *American Journal of Physiology Cell Physiology*, *281* (5), C1635–C1641. https://doi.org/10.1152/ajpcell.2001.281.5.C1635

Finkelstein, J. S., Brockwell, S. E., Mehta, V., Greendale, G. A., Sowers, M. R., Ettinger, B., Lo, J. C., Johnston, J. M., Cauley, J. A., Danielson, M. E., & Neer, R. M. (2008). Bone mineral density changes during the menopause transition in a multiethnic cohort of women. *The Journal of Clinical Endocrinology and Metabolism*, *93*(3), 861–868. https://doi.org/10.1210/jc.2007-1876

Fonseca, H., Moreira-Gonçalves, D., Coriolano, H. J., & Duarte, J. A. (2014). Bone quality: The determinants of bone strength and fragility. *Sports Medicine*, *44*(1), 37–53. https://doi.org/10.1007/s40279-013-0100-7

Frost, H. M. (2003). Bone's mechanostat: A 2003 update. *the anatomical record. Part A, discoveries in molecular. Cellular, and Evolutionary Biology*, *275*(2), 1081–1101. https://doi.org/10.1002/ar.a.10119

Fuchs, R. K., Bauer, J. J., & Snow, C. M. (2001). Jumping improves hip and lumbar spine bone mass in prepubescent children: A randomized controlled trial. *Journal of Bone and Mineral Research*, *16*(1), 148–156. https://doi.org/10.1359/jbmr.2001.16.1.148

Galea, G. L., Lanyon, L. E., & Price, J. S. (2017). Sclerostin's role in bone's adaptive response to mechanical loading. *Bone*, *96*, 38–44. https://doi.org/10.1016/j.bone.2016.10.008

Geoghegan, I. P., Hoey, D. A., & McNamara, L. M. (2019). Estrogen deficiency impairs integrin $\alpha_v\beta_3$-mediated mechanosensation by osteocytes and alters osteoclastogenic paracrine signalling. *Scientific Reports*, *9*(1), 4654. https://doi.org/10.1038/s41598-019-41095-3

Groothausen, J., Siemer, H., Kemper, H. C. G., Twisk, J., & Welten, D. C. (1997). Influence of peak strain on lumbar bone mineral density: An analysis of 15-year physical activity in young males and females. *Pediatric Exercise Science*, *9*(2), 159–173. https://doi.org/10.1123/pes.9.2.159

Hartley, C., Folland, J. P., Kerslake, R., & Brooke-Wavell, K. (2020). High-impact exercise increased femoral neck bone density with no adverse effects on imaging markers of knee osteoarthritis in postmenopausal women. *Journal of Bone and Mineral Research*, *35*(1), 53–63. https://doi.org/10.1002/jbmr.3867

Heinonen, A., Kannus, P., Sievänen, H., Oja, P., Pasanen, M., Rinne, M., Uusi-Rasi, K., & Vuori, I. (1996). Randomised controlled trial of effect of high-impact exercise on selected risk factors for osteoporotic fractures. *The Lancet*, *348*(9038), 1343–1347. https://doi.org/10.1016/S0140-6736(96)04214-6

Heinonen, A., Sievänen, H., Kannus, P., Oja, P., Pasanen, M., & Vuori, I. (2000). High-impact exercise and bones of growing girls: A 9-month controlled trial. *Osteoporosis International*, *11*(12), 1010–1017. https://doi.org/10.1007/s001980070021

Higgins, J. P., Altman, D. G., Gøtzsche, P. C., Jüni, P., Moher, D., Oxman, A. D., Savovic, J., Schulz, K. F., Weeks, L., & Sterne, J. A. Cochrane Bias Methods Group, & Cochrane Statistical Methods Group. (2011). The Cochrane Collaboration's tool for assessing risk of bias in randomised trials. *BMJ (Clinical Research Ed)*, *343*(2), d5928. https://doi.org/10.1136/bmj.d5928

Hilkens, L., Knuiman, P., Heijboer, M., Kempers, R., Jeukendrup, A. E., van Loon, L., & van Dijk, J. W. (2021). Fragile bones of elite cyclists: To treat or not to treat? *Journal of Applied Physiology*, *131*(1), 26–28. https://doi.org/10.1152/japplphysiol.01034.2020

Hinton, P. S., Nigh, P., & Thyfault, J. (2015). Effectiveness of resistance training or jumping-exercise to increase bone mineral density in men with low bone mass: A 12-month randomized, clinical trial. *Bone*, *79*, 203–212. https://doi.org/10.1016/j.bone.2015.06.008

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41*(1), 3–13. https://doi.org/10.1249/MSS.0b013e31818cb278

Hughes, J. M., Castellani, C. M., Popp, K. L., Guerriere, K. I., Matheny, R. W., Jr., Nindl, B. C., & Bouxsein, M. L. (2020). The central role of osteocytes in the four adaptive pathways of bone's mechanostat. *Exercise and Sport Sciences Reviews*, *48*(3), 140–148. https://doi.org/10.1249/JES.0000000000000225

Hu, W. W., Zhang, Z., He, J. W., Fu, W. Z., Wang, C., Zhang, H., Yue, H., Gu, J. M., & Zhang, Z. L. (2013). Establishing reference intervals for bone turnover markers in the healthy shanghai population and the relationship with bone mineral density in postmenopausal women. *International Journal of Endocrinology*, *2013*, 513925. https://doi.org/10.1155/2013/513925

Jenkins, N., Black, M., Paul, E., Pasco, J. A., Kotowicz, M. A., & Schneider, H. G. (2013). Age-related reference intervals for bone turnover markers from an Australian reference population. *Bone*, *55*(2), 271–276. https://doi.org/10.1016/j.bone.2013.04.003

Jonvik, K. L., Torstveit, M. K., Sundgot-Borgen, J., & Mathisen, T. F. (2022). Do we need to change the guideline values for determining low bone mineral density in athletes? *Journal of Applied Physiology*, *132*(5), 1320–1322. https://doi.org/10.1152/japplphysiol.00851.2021

Kanazawa, I. (2015). Osteocalcin as a hormone regulating glucose metabolism. *World Journal of Diabetes*, *6*(18), 1345–1354. https://doi.org/10.4239/wjd.v6.i18.1345

Kanis, J. A. (2002). Diagnosis of osteoporosis and assessment of fracture risk. *The Lancet*, *359*(9321), 1929–1936. https://doi.org/10.1016/S0140-6736(02)08761-5

Karsenty, G., & Khosla, S. (2022). The crosstalk between bone remodeling and energy metabolism: A translational perspective. *Cell Metabolism*, *34* (6), 805–817. https://doi.org/10.1016/j.cmet.2022.04.010

Kato, T., Terashima, T., Yamashita, T., Hatanaka, Y., Honda, A., & Umemura, Y. (2006). Effect of low-repetition jump training on bone mineral density in young women. *Journal of Applied Physiology*, *100*(3), 839–843. https://doi.org/10.1152/japplphysiol.00666.2005

Khosla, S., & Riggs, B. L. (2005). Pathophysiology of age-related bone loss and osteoporosis. *Endocrinology and Metabolism Clinics of North America*, *34*(4), 1015–xi. https://doi.org/10.1016/j.ecl.2005.07.009

Kohrt, W. M., Bloomfield, S. A., Little, K. D., Nelson, M. E., Yingling, V. R., & American College of Sports Medicine. (2004). American college of sports medicine position stand: Physical activity and bone health. *Medicine and Science in Sports and Exercise*, *36*(11), 1985–1996.

Lanyon, L. E. (1987). Functional strain in bone tissue as an objective, and controlling stimulus for adaptive bone remodelling. *Journal of Biomechanics*, *20*(11–12), 1083–1093. https://doi.org/10.1016/0021-9290(87)90026-1

Manske, S., Macdonald, H., Nishiyama, K., Boyd, S., & McKay, H. (2010). Clinical tools to evaluate bone strength. *Clinical Reviews in Bone and Mineral Metabolism*, *8*(3), 122–134. https://doi.org/10.1007/s12018-009-9066-2

Marcus, R. (2002). Post-menopausal osteoporosis. *Best Practice & Research Clinical Obstetrics & Gynaecology*, *16*(3), 309–327. https://doi.org/10.1053/beog.2002.0284

Mathis, S. L., & Caputo, J. L. (2018). Resistance training is associated with higher lumbar spine and hip bone mineral density in competitive male cyclists. *Journal of Strength and Conditioning Research*, *32*(1), 274–279. https://doi.org/10.1519/JSC.0000000000002209

McKay, H. A., MacLean, L., Petit, M., MacKelvie O'Brien, K., Janssen, P., Beck, T., & Khan, K. M. (2005). "Bounce at the bell": A novel program of short bouts of exercise improves proximal femur bone mass in early pubertal children. *British Journal of Sports Medicine*, *39*(8), 521–526. https://doi.org/10.1136/bjsm.2004.014266

Metzger, C. E., & Narayanan, S. A. (2019). The role of osteocytes in inflammatory bone loss. *Frontiers in Endocrinology*, *10*, 285. https://doi.org/10.3389/fendo.2019.00285

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & PRISMA Group. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Medicine*, *6*(7), e1000097.

Niu, K., Ahola, R., Guo, H., Korpelainen, R., Uchimaru, J., Vainionpää, A., Sato, K., Sakai, A., Salo, S., Kishimoto, K., Itoi, E., Komatsu, S., Jämsä, T., & Nagatomi, R. (2010). Effect of office-based brief high-impact exercise on bone mineral density in healthy premenopausal women: The sendai bone health concept study. *Journal of Bone and Mineral Metabolism*, *28*(5), 568–577. https://doi.org/10.1007/s00774-010-0163-6

Oosthuyse, T., McVeigh, J. A., Micklesfield, L. K., & Meiring, R. M. (2017). Radial and tibial bone indices in athletes participating in different endurance sports: a pQCT study. *European Journal of Sport Science*, *17*(2), 231–240. https://doi.org/10.1080/17461391.2016.1219770

Ott, S. M. (2018). Cortical or trabecular bone: What's the difference? *American Journal of Nephrology*, *47*(6), 373–375. https://doi.org/10.1159/000489672

Rantalainen, T., Hoffrén, M., Linnamo, V., Heinonen, A., Komi, P. V., Avela, J., & Nindl, B. C. (2011). Three-month bilateral hopping intervention is ineffective in initiating bone biomarker response in healthy elderly men. *European Journal of Applied Physiology*, *111*(9), 2155–2162. https://doi.org/10.1007/s00421-011-1849-8

Richardson, M., Garner, P., & Donegan, S. (2019). Interpretation of subgroup analyses in systematic reviews: A tutorial. *Clinical Epidemiology and Global Health*, *7*(2), 192–198. https://doi.org/10.1016/j.cegh.2018.05.005

Robling, A. G., Burr, D. B., & Turner, C. H. (2000). Partitioning a daily mechanical stimulus into discrete loading bouts improves the osteogenic response to loading. *Journal of Bone and Mineral Research*, *15*(8), 1596–1602. https://doi.org/10.1359/jbmr.2000.15.8.1596

Rubin, C. T., & Lanyon, L. E. (1984). Regulation of bone formation by applied dynamic loads. *Journal of Bone and Joint Surgery*, *66*(3), 397–402. https://doi.org/10.2106/00004623-198466030-00012

Sen, E. I., Esmaeilzadeh, S., & Eskiyurt, N. (2020). Effects of whole-body vibration and high impact exercises on the bone metabolism and functional mobility in postmenopausal women. *Journal of Bone and Mineral Metabolism*, *38*(3), 392–404. https://doi.org/10.1007/s00774-019-01072-2

Shibata, Y., Ohsawa, I., Watanabe, T., Miura, T., & Sato, Y. (2003). Effects of physical training on bone mineral density and bone metabolism. *Journal of Physiological Anthropology and Applied Human Science*, *22*(4), 203–208. https://doi.org/10.2114/jpa.22.203

Srinivasan, S., Weimer, D. A., Agans, S. C., Bain, S. D., & Gross, T. S. (2002). Low-magnitude mechanical loading becomes osteogenic when rest is inserted between each load cycle. *Journal of Bone and Mineral Research*, *17*(9), 1613–1620. https://doi.org/10.1359/jbmr.2002.17.9.1613

Sterne, J. A., Sutton, A. J., Ioannidis, J. P., Terrin, N., Jones, D. R., Lau, J., Carpenter, J., Rücker, G., Harbord, R. M., Schmid, C. H., Tetzlaff, J., Deeks, J. J., Peters, J., Macaskill, P., Schwarzer, G., Duval, S., Altman, D. G., Moher, D., & Higgins, J. P. (2011). Recommendations for examining and interpreting funnel plot asymmetry in meta-analyses of randomised controlled trials. *BMJ*, *343*(1), d4002. https://doi.org/10.1136/bmj.d4002

Sugiyama, T., Yamaguchi, A., & Kawai, S. (2002). Effects of skeletal loading on bone mass and compensation mechanism in bone: A new insight into the "mechanostat" theory. *Journal of Bone and Mineral Metabolism*, *20*(4), 196–200. https://doi.org/10.1007/s007740200028

Tucker, L. A., Strong, J. E., LeCheminant, J. D., & Bailey, B. W. (2015). Effect of two jumping programs on hip bone mineral density in premenopausal women: A randomized controlled trial. *American Journal of Health Promotion*, *29*(3), 158–164. https://doi.org/10.4278/ajhp.130430-QUAN-200

Turner, C. H. (1998). Three rules for bone adaptation to mechanical stimuli. *Bone*, *23*(5), 399–407. https://doi.org/10.1016/s8756-3282(98)00118-5

Turner, C. H., & Robling, A. G. (2003). Designing exercise regimens to increase bone strength. *Exercise and Sport Sciences Reviews*, *31*(1), 45–50. https://doi.org/10.1097/00003677-200301000-00009

Vainionpää, A., Korpelainen, R., Leppäluoto, J., & Jämsä, T. (2005). Effects of high-impact exercise on bone mineral density: A randomized controlled trial in premenopausal women. *Osteoporosis International*, *16*(2), 191–197. https://doi.org/10.1007/s00198-004-1659-5

Vainionpää, A., Korpelainen, R., Sievänen, H., Vihriälä, E., Leppäluoto, J., & Jämsä, T. (2007). Effect of impact exercise and its intensity on bone geometry at weight-bearing tibia and femur. *Bone*, *40*(3), 604–611. https://doi.org/10.1016/j.bone.2006.10.005

Vainionpää, A., Korpelainen, R., Väänänen, H. K., Haapalahti, J., Jämsä, T., & Leppäluoto, J. (2009). Effect of impact exercise on bone metabolism. *Osteoporosis International*, *20*(10), 1725–1733. https://doi.org/10.1007/s00198-009-0881-6

Vlachopoulos, D., Barker, A. R., Ubago-Guisado, E., Williams, C. A., & Gracia-Marco, L. (2018). The effect of a high-impact jumping intervention on bone mass, bone stiffness and fitness parameters in adolescent athletes. *Archives of Osteoporosis*, *13*(1), 128. https://doi.org/10.1007/s11657-018-0543-4

Vlachopoulos, D., Barker, A. R., Williams, C. A., Knapp, K. M., Metcalf, B. S., & Gracia-Marco, L. (2015). Effect of a program of short bouts of exercise on bone health in adolescents involved in different sports: The PRO-BONE study protocol. *BMC Public Health*, *15*(1), 361. https://doi.org/10.1186/s12889-015-1633-5

Vondracek, S. F., Hansen, L. B., & McDermott, M. T. (2009). Osteoporosis risk in premenopausal women. *Pharmacotherapy: The Journal of Human Pharmacology and Drug Therapy*, *29*(3), 305–317. https://doi.org/10.1592/phco.29.3.305

Warming, L., Hassager, C., & Christiansen, C. (2002). Changes in bone mineral density with age in men and women: A longitudinal study. *Osteoporosis International*, *13*(2), 105–112. https://doi.org/10.1007/s001980200001

Wei, J., & Karsenty, G. (2015). An overview of the metabolic functions of osteocalcin. *Reviews in Endocrine & Metabolic Disorders*, *16*(2), 93–98. https://doi.org/10.1007/s11154-014-9307-7

Wolff, I., van Croonenborg, J. J., Kemper, H. C., Kostense, P. J., & Twisk, J. W. (1999). The effect of exercise training programs on bone mass: A meta-analysis of published controlled trials in pre- and postmenopausal women. *Osteoporosis International*, *9*(1), 1–12. https://doi.org/10.1007/s001980050109

Zhao, R., Zhao, M., & Zhang, L. (2014). Efficiency of jumping exercise in improving bone mineral density among premenopausal women: A meta-analysis. *Sports Medicine*, *44*(10), 1393–1402. https://doi.org/10.1007/s40279-014-0220-8

Žofková, I. (2008). Hormonal aspects of the muscle-bone unit. *Physiological Research*, *57*(1), S159–S169. https://doi.org/10.33549/physiolres.931501