Title: High Impact Exercise Increased Femoral Neck Bone Mineral Density in Older Men: A Randomised Unilateral Intervention

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Highlights:

- We examined the influence of a 12 month high impact, unilateral exercise programme on bone density.

- Participants were 50 healthy, community dwelling men aged 65-80 years.

- The brief daily exercises increased to 50 multidirectional hops, on one randomly selected leg.

- Femoral neck BMD, BMC and geometry increased significantly in the exercise leg compared to the control leg.

- Carefully targeted high impact exercises may reduce risk of hip fracture in healthy older men.

Abstract:

Introduction*:* There is little evidence as to whether exercise can increase BMD in older men with no investigation of high impact exercise. Lifestyle changes and individual variability may confound exercise trials but can be minimised using a within-subject unilateral design (exercise leg [EL] vs. control leg [CL]) that has high statistical power. **Purpose:** This study investigated the influence of a 12 month high impact unilateral exercise intervention on femoral neck BMD in older men. **Methods:** Fifty, healthy, community-dwelling older men commenced a 12 month high impact unilateral exercise intervention which increased to 50 multidirectional hops, 7 days a week on one randomly allocated leg. BMD of both femurs was measured using dual energy X-ray absorptiometry (DXA) before and after 12 months of exercise, by an observer blind to the leg allocation. Repeated measures ANOVA with post hoc tests was used to detect significant effects of time, leg and interaction. **Results:** Thirty-five men (mean ± SD, age 69.9 ± 4.0 yrs) exercised for 12 months and intervention adherence was 90.5 ± 9.1% (304 ± 31 sessions completed out of 336 prescribed sessions). Fourteen men did not complete the 12 month exercise intervention due to: health problems or injuries unrelated to the intervention (n=9), time commitments (n=2), or discomfort during exercise (n=3), whilst BMD data were missing for one man. Femoral neck BMD, BMC and cross-sectional area all increased in the EL (+0.7, +0.9 and +1.2 % respectively) compared to the CL (-0.9, -0.4 and -1.2%); interaction effect *P*<0.05. Although the interaction term was not significant (P > 0.05), there were significant main effects of time for section modulus (*P* =0.044) and minimum neck width (*P* =0.006). Section modulus increased significantly in the EL (P=0.016) but not the CL (*P* =0.465); mean change +2.3% and +0.7% respectively, whereas minimum neck width increased significantly in the CL (*P* =0.004) but not in the EL (*P* =0.166); mean changes being +0.7% and +0.3% respectively. **Conclusion:** A 12 month high impact unilateral exercise intervention was feasible and effective for improving femoral neck BMD, BMC and geometry in older men. Carefully targeted high impact exercises may be suitable for incorporation into exercise interventions aimed at preventing fractures in healthy community-dwelling older men.

1. Introduction

Osteoporotic fractures are a major public health problem among older adults. One in two women and one in five men aged fifty and over in the UK will suffer a fracture in their lifetime [1]. Osteoporotic fractures commonly occur at the hip, spine, and wrist and of these hip fractures have the highest short-term mortality, morbidity and associated socio-economic impact [2-4]. Regular exercise is widely recommended as the most effective non-pharmacological method for improving and maintaining BMD [5] and can also reduce the risk of falling. As such, exercise has an important role in reducing the predisposition to osteoporotic hip fracture.

Although older people are the population at most immediate risk of osteoporosis, it has been suggested that exercise may be less effective in older, than younger, people [6-7]. This may be related to the type and intensity of the exercise interventions studied, as lower neuromuscular function [8] or greater injury risk may limit exercise intensity in older people. Meta analysis of exercise intervention studies suggests that mixed loading interventions including low to moderate impact exercises in the form of jogging, walking and stair climbing, together with resistance training, can maintain BMD at the femoral neck in postmenopausal women [9]. However, evidence from animal experiments suggests that the optimal loading regimens are high in magnitude, high in strain rate and provide novel stress on the bone [10-13]. In children and young adults, high impact jumping exercises that exert a high magnitude of loading at the hip have produced the greatest increases in femoral neck BMD [6]. Therefore, interventions that incorporate brief but regular high impact exercise could potentially increase femoral neck BMD (rather than just preventing bone loss) in older adults.

Few studies have investigated the effects of interventions consisting only of high impact loading in the form of vertical jumping on femoral neck BMD in older people [14-15]. These studies found no change in femoral neck BMD following the intervention but these findings pertain to postmenopausal women, whose adaptive response to mechanical loading is thought to be impaired by estrogen deficiency and reduced estrogen receptor number [16-17].

Older men are at risk of osteoporotic fractures, and hip fracture related morbidity and mortality are higher for men than women [18]. However, there is little information

concerning the effects of long-term exercise interventions on BMD in this population [19-20]. One exercise intervention including high impact exercises (single and double foot landings, bench stepping, and jumping off 15- and 30-cm benches) increased femoral neck BMD in middle aged and older men (50-79 yrs) [21, 22]. However, the high impact exercises in this intervention formed only a very small component of a progressive resistance training programme, requiring over 3 hours of exercise per week. High impact exercise alone may be more feasible, as exercises are less time-consuming and can be performed at home, without requiring any special equipment. Brief, high impact exercises performed at home can increase BMD in premenopausal women [23], but the effectiveness of high impact exercise alone on femoral neck BMD in older men is unknown.

Individual differences and lifestyle modifications such as genotype, physical activity, diet and age-related change may confound longitudinal exercise intervention trials in older people [24]. The effect of these confounders can be minimised by using a within-subjects unilateral design (exercise leg [EL] vs. control leg [CL]) that has greater statistical power than studies comparing changes between individuals. Recently, it was demonstrated that high impact unilateral exercise increases femoral neck BMD in premenopausal women [25]. Therefore, the aim of this study was to investigate the influence of a 12 month high impact unilateral exercise intervention on femoral neck BMD in healthy community dwelling older men, using a within-subjects unilateral design.

2. Methods

2.1 Experimental overview

The study was conducted as a longitudinal, randomised trial of a high impact exercise intervention in older men. The men were prescribed a 12 month, high impact unilateral exercise intervention which increased to 5 sets of 10 multidirectional hops, 7 days a week on one randomly allocated exercise leg, with the contralateral leg being untrained to provide a control leg. Randomisation was performed using the minimisation method so that half of participants exercised on the left leg and half on the right leg. All men were requested to maintain their habitual lifestyle, with no unaccustomed exercise or diet during the intervention period. Participants completed a familiarisation session 3 to 4 days before pre-exercise measurements. Follow-up measurements were completed after 6 and 12 months of exercise. During the familiarisation visit participants completed health, lifestyle and habitual physical activity questionnaires and were requested to complete a 7 day weighed food diary.

They were also familiarised with performing a set of 10 exercise hops on a force plate. At the first measurement session (pre-exercise) anthropometry, bone mass, bone geometry and the ground reaction forces (GRF) generated during a set of 10 exercise hops were recorded. After pre-exercise measurements were complete, the hopping exercises were demonstrated and completed under supervision. After 6 months of exercise, measurements of anthropometry and GRF generated during set of 10 exercise hops were repeated. After 12 months of exercise (post-exercise), measurements of anthropometry, bone mass and bone geometry were repeated.

2.2 Participants

Older men were recruited from the local area by email, advertising and organised visits to local community groups. To be eligible to take part in the study, all participants had to be healthy, community-dwelling men of white European origin, between the ages of 65-80 years, have no impairment in mental or physical function that may affect ability to exercise or follow instructions and have no recent (previous 12 months) involvement in strength, power or weight-bearing endurance exercise for more than 1hr/wk. Exclusion criteria were: BMI >30 kg/m^2; history of strength training or moderate intensity physical activity (weight-bearing or high impact); previous or existing injuries to the lower limbs or back that could be exacerbated by undertaking high impact exercise; recent (previous 12 months) medical or surgical problems likely to affect bone metabolism or neuromuscular function and any history of diagnosed or symptomatic diseases likely to influence bone, neuromuscular function or ability to perform high impact exercises (including osteomalacia, impaired liver/renal function, hypertension and locomotor disease). Written informed consent was obtained from all eligible participants and consent was given to notify their local general practitioner of their involvement in the study. The study was approved by the National Research Ethics Service and the Loughborough University Ethical Advisory Committee. The involvement of participants at each stage of the study is demonstrated in the consort flow diagram (Figure 1).

[Figure 1]

2.3 Exercise intervention

2.3.1 Home-based exercise intervention

Participants commenced a high impact unilateral exercise programme that involved performing brief hopping exercise sessions on their EL at home over a 12 month period (Figure 2). The exercises were demonstrated at the pre-exercise measurement session, once measurements were complete. Each exercise session consisted of several minutes of mobilisation exercises before participants performed the exercise routine which increased progressively to 5 sets of 10 multi-directional hops 7 days per week (Table 1). Each set of hops were interspersed with a 15 s rest period which consisted of gentle on the spot walking. In total the hopping exercises lasted between 2 to 3 minutes and the total duration of each exercise session was typically ~15 minutes. Multi-directional hops were introduced in the ninth week of the programme and involved 1 set of each of anterior-posterior, medio-lateral, rotational hops as well as 2 sets of vertical hops.

[Figure 2]

If necessary, participants were advised to hold onto a secure support (i.e. the back of a chair or kitchen bench) to assist with stability in the first three weeks of the training. We highlighted that the support was to assist stability, rather than to assist propulsion. The height of the hops increased from gentle hop attempts in the first week through to the maximum height that could be sustained for 10 consecutive hops in week five. Thus, exercise intensity increased by encouraging participants to continue to hop as high and as fast as they could. The typical progression of exercise is summarised in Table 1, although this was individualised by only progressing once participants were confident with the existing exercises, and reducing intensity (hop height) and or frequency in any participant that reported discomfort during or after exercise. To monitor the exercise progression and safety, participants were requested to attend supervised exercise sessions in groups of five to six. These took place each week for the first month of the training and one supervised exercise session every 3 months thereafter. Attendance at each of supervised sessions was recorded and they involved performing the exercise routine as a group under the supervision of an observer with feedback on technique and verbal encouragement. All hopping exercises were recorded in a log book and participants were asked to record the occurrence and extent of any adverse events or injuries associated with the exercises. Log books were checked during each supervised session.

[Table 1]

2.4 Health, physical activity, dietary and anthropometric measurements

Health and lifestyle questionnaires documented information regarding medical history, past and current medications, fracture history, tobacco use and alcohol consumption. Habitual physical activity was measured using a validated questionnaire [26] that separated activity into work (referred to household activities if participant were in retirement), leisure and sports. Dietary intakes (including supplement use [type and dosage]) were assessed using a 7 day weighed food diary. Participants were provided with a set of electronic kitchen scales (Model 1004, Salter Housewares, London, UK) and requested to weigh and record all food and drink consumed during seven consecutive days that were typical of usual diet. Analysis was conducted using CompEat dietary analysis software (version 1, Nutrition Systems, Banbury, UK) which yielded estimates of energy, carbohydrate, fat, protein, calcium and vitamin D intake over the 7 day period. Height was measured to the nearest 0.001 m using a portable stadiometer (Holtain Ltd, Pembrokeshire, UK) and body mass was recorded to the nearest 0.1 kg using a beam balance scale (Herbet and Sons Ltd, London UK) while participants wore shorts and a T-shirt.

2.5 Dual energy X-ray absorptiometry measurements

Scans of the whole body and both proximal femurs were taken on a GE-Lunar Prodigy dual energy X-ray absorptiometry (DXA) scanner (GE Healthcare, Madison, WI, USA) that was maintained according to the manufacturer's recommendations, including the performance of daily calibration and phantom scan for quality control. Participant positioning for each scan type followed the standardised positioning protocol outlined in the manufactures guidelines. Fat and lean tissue masses of the whole body and BMD and BMC at both proximal femurs were used for further analysis. The Lunar Advanced Hip Analysis (AHA) algorithms (version 10.10, encore 2006 software) were used to calculate femoral neck bone geometry (minimum neck width, cross-sectional area [CSA]) and strength (cross-sectional moment of inertia [CSMI], section modulus). All scans and subsequent analysis was performed by the same operator, who was blind to the exercise leg allocation.

2.6 Ground reaction forces during the hop exercise

To assess musculoskeletal loading during the intervention period, vertical ground reaction force (GRF) was sampled at 2000 Hz with a calibrated force plate (9286AA, Kistler Instruments Ltd, London, UK). Briefly the summed vertical forces from the four vertical

channels were interfaced with an analogue to digital converter (CED micro 1401, CED, Cambridge, UK) and recorded with a computer utilising Spike 2 software (version 7.02a; CED, Cambridge, UK). Participants stood barefoot in the centre of the force plate and were instructed to stand upright and still with their shoulders back and arms by their sides for ≥ 5 s. From stationary standing, participants performed 10 consecutive vertical hops on their EL that were typical of their routine hopping exercises. The 10 hops were repeated if the participant did not take off or land successfully in the centre of the force plate. A stable 1 s period of vertical GRF during quiet standing was used to calculate body mass. Force recordings were analysed to yield the absolute and relative (to body weight) peak GRF during take-off and landing averaged over 10 hops.

2.7 Statistical analysis

An a priori sample size calculation yielded n = 30 in order to detect a similar differential response between legs for femoral neck BMD as a previous study (equivalent to a 2.0% difference with a statistical power of 80% and $P < 0.05$) [25]. Coefficients of variation (CVs) for DXA-derived variables were based on repeat measurements taken on the same day during post exercise scans in 11 older men from this study [27]. CVs for GRF variables were based on repeat measurements taken on separate days (~6 months apart) in a control group of 17 older men previously tested in our laboratory. Differences between legs (EL vs. CL) pre-exercise were determined using paired t-tests. Repeated measures multivariate analysis of variance (RM-MANOVA) was used to find out whether exercise effects differed according to hip site over time (leg x time x site [upper neck, lower neck, trochanter] interactions). Two-way repeated measures analysis of variance (ANOVA) examined the influence of the 12 month high impact unilateral exercise intervention over time (pre vs. post); between legs (exercise leg [EL] vs. control leg [CL]) and detect any leg x time interactions. When any significant main or interaction effects were identified, paired t-tests were then used to determine which means differed. Paired t-tests were also performed to examine differences pre-exercise and after 6 months of exercise for peak GRF during take-off and landing averaged over 10 hops. Descriptive data are presented as mean ± SD and inferential data are presented as mean ± SEM. Statistical analysis was conducted using PASW Statistics software (PASW 18.0, SPSS Inc., Chicago, Illinois) with the significance level set at $P < 0.05$.

3. Results

3.1 Reproducibility

CVs for percentage total body fat and lean soft tissue were 1.2% and 0.5%. CVs for femoral neck BMD, BMC, CSMI, section modulus and minimum neck width were 1.0%, 1.0%, 4.7%, 3.4% and 1.4% respectively. CVs for absolute peak and mean GRF during take-off and during landing were 6.4%, 5.9%, 8.5% and 7.0%.

3.2 Intervention adherence and adverse events

Of the fifty men that took part in the study, thirty-five men exercised for 12 months. Fourteen (28%) of the 50 men withdrew from the study, while BMD data were missing for one man. Three men withdrew from the study due to musculoskeletal discomfort (knee pain [n=2]), sciatic pain [n=1]) which appeared to be related to the exercise intervention. Of the thirty-five men that exercised for 12 months, three men reported minor discomfort (aggravated lower back ache [n=2] and toe pain [n=1]) but over a short period of time and were happy to continue with the exercises. Five men reported discomfort (aching hip [n=1], knee pain [n=2], ankle and knee pain [n=1], aggravated lower back ache [n=1]) that required 2-14 days rest before being reintroduced to the exercises. All participants had progressed to performing 5 sets of 10 multi-directional hops 7 days per week within 3 months since commencing the intervention. The intervention adherence (home-based and supervised sessions) was $90.5 \pm 9.1\%$ (304 ± 31 sessions completed out of 336 prescribed sessions).

3.3 Physical characteristics

Physical characteristics of the thirty five men are presented in Table 2. One man out of thirty five smoked, specifically one cigar per week. Thirty three men were retired and two men were semi-retired (office work, 2 days per week [n = 1], boatyard operator 3 days per week [n = 1]). Sixteen men did not take part in any physical activity (45.7%), twelve men (34.3%) currently took part in low intensity activity (e.g. golf, average energy expenditure 0.76 MJ/h) for 3.8 ± 1.8 hrs/wk and seven men (20.0%) took part in moderate intensity activity (e.g. cycling, average energy expenditure 1.26 MJ/h) for 2.4 ± 1.7 hrs/wk. The men had an average dietary calcium intake of 1068 mg/d which is higher than the UK recommended dietary intake (RDI) of 700 mg/d but their average vitamin D intake (3.3 µg/d) was lower than the UK RDI (10-15 µg/day) for older men (50-70+ yrs) [28].

[Table 2]

3.4 Body composition and ground reaction forces

Body mass did not change following 12 months of exercise (-0.2 ± 2.1 kg, P = 0.543) but increased significantly following 6 months of exercise (+0.8 ± 1.7 kg, P = 0.000). Similarly, BMI did not change following 12 months of high impact exercise (-0.03 ± 0.70 kg/m^2, P = 0.827) but increased significantly following 6 months of exercise (+0.27 ± 0.52 kg/m2, P = 0.004). After 12 months of exercise there were no significant changes in total body fat (21.9 ± 5.4 vs. 21.8 ± 4.9 kg, P = 0.658) or total lean soft tissue mass (55.7 ± 5.6 vs. 55.6 ± 5.6 kg, P = 0.649).

During the high impact exercise absolute peak GRF during landing and take-off had both increased following 6 months of the intervention (Table 3). Peak GRF during landing, expressed in relative terms, increased from 2.7 times body weight to 3.0 time body weight, representing a 12% increase following 6 months of high impact exercise but relative peak GRF during take-off remained unchanged (Table 3).

[Table 3]

3.5 Bone mineral density, bone mineral content and geometry

The EL and CL did not differ significantly pre-exercise for any BMD (0.391<P<0.942), BMC (0.234<P<0.997) or geometry parameters (0.325<P<0.682). Mean femoral neck BMD increased (by 0.7%) in the EL and decreased (by 0.9%) in the CL (Table 4; Figure 3), representing a 1.6% net gain in BMD. This difference in response between legs was statistically significant (P for leg x time interaction in ANOVA = 0.003). Femoral neck BMC showed similar changes (Table 4), increasing in the exercise leg relative to the control leg (+.0.9% vs. -0.4%; Figure 3) (net gain of 1.3%) as did CSA (+1.2% vs. -1.2%).

When femoral neck BMD changes were compared between sites (upper neck, lower neck, trochanter) by RM-MANOVA, an overall exercise effect was evident (significant leg x time interaction, P = 0.007) which differed significantly according to site (leg x time x site interaction significant; P = 0.025). Two-way RM-ANOVA revealed a significant interaction (leg x time) effect for BMD at the lower neck but not at the upper neck or trochanter (Table 4). Lower neck BMD increased in EL by 1.4% and decreased in the CL by 0.8%.

[Figure 3]

There were significant main effects of time for cross-sectional moment of inertia, section modulus and minimum neck width, although the interaction term was not significant ($0.137 < P < 0.261$) (Table 4). Specifically, cross-sectional moment of inertia increased significantly in the EL (430.3 ± 162.3 mm^4, $P = 0.012$; paired t test) but not in the CL (199.2 ± 158.6 mm^4, $P = 0.218$). Similarly, section modulus increased significantly in the EL (18.7 ± 7.4 mm^3, $P = 0.016$) but not in the CL (5.5 ± 7.4 mm^3, $P = 0.465$), whereas minimum neck width increased significantly in the CL (0.11 ± 0.08 mm, $P = 0.004$) but not in the EL (0.27 ± 0.09 mm, $P = 0.166$).

There was a tendency for vertebrae L1-L4 BMD to increase pre- to post-exercise (pre 1.258 ± 0.030 vs. post 1.270 ± 0.030 g/cm^2 $P = 0.060$). Vertebra L4 also significantly increased (by 1.8%) pre- to post-exercise (pre 1.336 ± 0.038 vs. post 1.360 ± 0.224 g/cm^2 $P = 0.038$) but other individual vertebrae (L1, L2 and L3) did not change following the 12 month high impact exercise intervention ($0.274 < P < 0.619$).

[Table 4]

4. Discussion

This is the first study to document the influence of high impact, unilateral exercise on femoral neck BMD in older men in a longitudinal, randomised trial. The study demonstrated that a 12 month high impact exercise intervention increased femoral neck BMD and BMC in healthy community-dwelling older men. The within-subjects unilateral design of the study (EL vs. CL) reduces the possibility that our findings have been influenced by individual differences in exercise response, lifestyle modifications (physical activity, diet) and age-related changes that can often confound longitudinal exercise trials in older people.

Musculoskeletal loading can be quantified by measuring the vertical GRF during landing from impact exercise. In the present study, absolute GRF during landing increased by 13% during the first 6 months of the exercise intervention and demonstrates a progression of musculoskeletal loading that may be necessary for continued adaptation. GRFs during landing of 3.5 to 8.0 times body weight from a single countermovement jump and continuous drop jumps (from 61 cm) have produced the greatest increases in femoral neck BMD in children [29]. The prescribed high impact exercises in the present study elicited

landing GRFs of 2.7 to 3.0 times body weight, which were higher than the typical peak GRFs generated by healthy older adults during walking, running 3.3 m.s^{-1}(1.1 to 1.9 times body weight [30-31]), and two-footed drop jumps from 15-20 cm (1.9 to 2.1 times body weight [32]).

The 1.6% net gain in femoral neck BMD and the 1.3% net gain in femoral neck BMC in our study are in contrast with findings from previous studies in postmenopausal women which found no changes in femoral neck BMD or BMC following 6, 12 and 18 months of vertical jumping exercises [14-15]. Other than sex and related hormonal differences, discrepancies between studies may be attributed to differences in the exercise prescription. Evidence from animal experiments and human interventions have shown that the adaptive response of bone is maximised when loading cycles are interspersed with short, regular rest periods [33-34] and when loading bouts are performed frequently i.e. 7 days a week [25]. The exercises employed in previous interventions were performed 2-3 days [14] and 6 days a week [15], without rest intervals (50 jumps [14] and 100 jumps [15]). Thus, less frequent and prolonged periods of loading may have impaired and saturated the bone's adaptive response in postmenopausal women. Furthermore, continued adaptation to exercise requires progressive overload and the mechanostat theory suggests that bone can become accustomed to constant loading of a similar magnitude until a higher magnitude load is applied [35]. As the authors did not monitor the vertical GRF during the exercise programmes [14-15] it is difficult to determine whether musculoskeletal loading was of a sufficient magnitude to produce an adaptive response in BMD in these postmenopausal women.

The magnitude of change we observed in femoral neck BMD (1.6%) was similar to the change previously documented in older men following a 12 and 18 month progressive resistance training incorporating high impact exercise (1.8% and 1.9% [21-22]). However, the duration of the exercises intervention employed by these authors was longer than the present study, the population was younger (70 ± 4 vs. 61 ± 7 yrs) and the high impact exercises formed only a very small component of an extensive resistance training programme.

In contrast to findings for a similar high impact unilateral exercise intervention in premenopausal women [25], the overall exercise effect differed significantly according to hip site ($P = 0.025$). Specifically, the greatest changes were found at the lower neck, where

BMD increased in the EL by 1.4% and decreased in the CL by 0.8%. The inferior region of the femoral neck is the primary weight-bearing site [36]. The greatest increase at the lower femoral neck may be due to hopping generating greatest strains in this region; it is likely that hopping will produce axial compression and bending that is greatest on the infero-medial surface of the femoral neck, although the multidirectional movements were intended to distribute strains more widely.

The high magnitude of loading associated with performing high impact exercises has the potential to result in injury [37]. In the present study, three men withdrew due to musculoskeletal injuries related to the exercises but the majority of participants (n=9) withdrew because of health problems or injuries that were unrelated to the exercise intervention e.g. lower back strain from gardening, stomach ulcer. Seventy percent of participants completed the 12 month high impact, unilateral exercise intervention and this is comparable to the 73% completion rate reported for a similar but shorter (6 months) high impact unilateral exercise intervention (50 multi-directional hops, 7 days per week) in premenopausal women [25]. Participant adherence to the exercise programme in the present study was 91% (306 sessions completed out of 336 prescribed sessions) which is higher than the adherence reported for a vertical jumping programme in postmenopausal women (82%) [14] and for combined resistance (65% [21] and 63% [22]) and progressive resistance exercise programmes (71% [38]) in older men (50-80 yrs). The high participant adherence and low number of adverse events documented in the present study demonstrates the feasibility of the high impact exercises in older men and may be attributed to the low time demands of this intervention (~2-3 minutes to complete the hopping exercises) and the convenience of a home-based exercise programme requiring no specialist equipment. It should be noted however, there is likely to be a higher risk of injury for frail older adults performing high impact exercises so it is essential that this type of exercise is individually prescribed.

Exercise can affect the distribution of bone as well as the quantity of bone [39]. To document changes in hip geometry following high impact exercise, CSA, section modulus and minimum neck width were assessed. We found that CSA increased significantly in the EL relative to the CL (+1.2% vs. -1.2%) and section modulus (a surrogate of bending strength) increased significantly in the EL (2.3%) only. These changes demonstrate increases in strength, conferring greater resistance to fracture. Minimum femoral neck width

(a surrogate estimate of bone size) did not change with exercise, but increased significantly (0.7%) in the CL. Our hip geometry results confirm findings from a previous cross-sectional study which demonstrated that athletic populations participating in high impact (i.e. volleyball, hurdling) and odd impact (i.e. squash, football) loading sports had similar femoral neck widths but larger section modulus (22% and 26%) compared to non-athletic referents [40]. Moreover, the extent to which 2 to 3 minutes of daily high impact exercise increased CSA and section modulus in the current study was similar to the increases previously achieved following a longer (~12-18 months) and more demanding (>3 hours a week) combined resistance and high impact exercise programme in older men (1.8% and 2.1% [21-22]).

The loss of BMD (-0.9%) and increased femoral neck width (+0.7%) we observed in the CL are also consistent with annual age-related changes in femoral neck BMD (-0.8% [41]) and femoral neck width in older men (+0.3% [42]). The increase in neck width may partly compensate the BMD loss to maintain strength in bending [43], but if a wider diameter and thinner cortex were subject to fall, this could increased the risk of fracture [44, 45]. The maintenance of femoral neck width and the gains in BMD and section modulus we observed with exercise, most likely suggest that high impact exercise produces an increase in cortical thickness by reducing endocortical resorption at the femoral neck rather than changes in periosteal expansion. Such a suggestion is compatible with findings from one study using MRI which found that athletes taking part in high and odd impact sports had a ~20% thicker cortex at the femoral neck [46]. Similarly, results from a 12 month combined aerobic step and jumping intervention in postmenopausal women revealed a 3.6% increase in section modulus and 3.7% increase in the ratio of cortical bone to total bone area at the distal tibia, indicating an exercise-induced thickening of the bone cortex [47].

The main limitation of this study pertains to the exclusion of unhealthy individuals and any selection bias due to the voluntary participation that could skew our sample of older men towards a healthier and fitter population than the average. The generalisability of our findings is therefore limited to healthy, community-dwelling men (65-80 yrs), who are capable of performing high impact exercise. It was not the aim of the present study to conduct an intention to treat analysis; we therefore acknowledge that our results may yield a smaller effect size than clinical studies performing this type of analysis. We did not have a control group who did not have any intervention; the control leg may have been affected by

any systemic or crossover effects of the exercise. Given that any exercise effects on the control leg are likely to be beneficial rather than detrimental, use of a control leg rather than control group seems more likely to underestimate rather than overestimate exercise effect. In a previous study of a similar intervention in premenopausal women [25], changes in the control leg of exercisers were similar to changes in an independent control group. Furthermore, the study of bone geometric features in the present investigation is restricted by the inherent limitations of HSA algorithms and DXA technology particularly in older adults [48]. The geometric properties (i.e. CSA, section modulus) were derived from two-dimensional DXA data. This involves a number of assumptions about the distribution of three-dimensional bone tissue [49]. Bone strength is affected by the distribution of bone (e.g. cortical thinning at structurally important regions of the proximal femur may predispose older adults to hip fracture [44, 50]) and this may be affected by exercise. To more fully understand the effects of exercise on bone strength, there is a need for further evaluation of exercise effects using techniques such as computed tomography or magnetic resonance imaging that allow three-dimensional imaging, to detect changes in geometric parameters such as cortical thickness and to allow estimation of bone strength through modelling techniques such as finite element analysis.

Given that hip fractures are a major public health problem among older adults [1] and low femoral neck BMD is strongly associated with higher hip fracture incidence [51], our findings have important implications for informing preventative strategies against the risk of osteoporotic hip fracture in older men. Brief (2 to 3 minutes) but regular high impact exercise repeated on both legs may be suitable for integration into exercise interventions aimed at preventing osteoporotic hip fractures in healthy community-dwelling older men, with suitable screening and advice on progression. Further randomised longitudinal trials are required to determine whether this type of exercise is feasible and effective for improving bone health in a broader range of older adults.

In conclusion, a 12 month high impact, unilateral exercise intervention was effective for inducing modest increases in femoral neck BMD and BMC in older men. The high participant adherence and low number of adverse events indicates that this type of exercise is safe and feasible in healthy older men. Pragmatically, these findings suggest that carefully targeted high impact exercises may be suitable for incorporation into exercise interventions aimed at preventing osteoporotic hip fractures in healthy community-dwelling older men.

Conflict of Interest

None declared.

5. References

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Figure Legends

Figure 1 Consort flow diagram illustrating the progress of participants' involvement through the stages of the study.
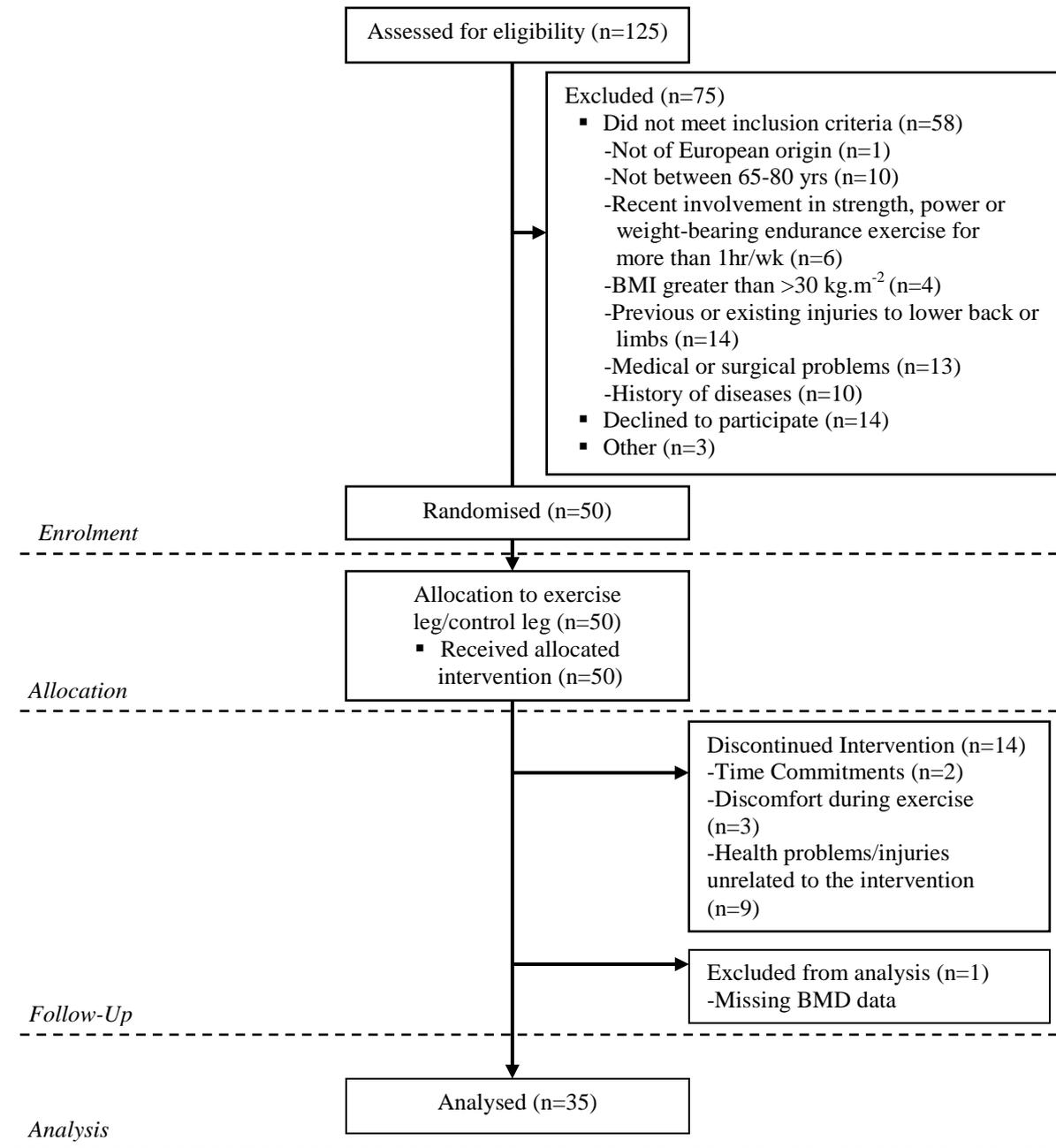
Figure 2 Demonstrative video stills showing the first of ten typical exercise hops of an older man: (a) start position of a typical hop on the exercise leg (b) countermovement prior to take off (c) flight of hop (d) landing on the exercise leg.
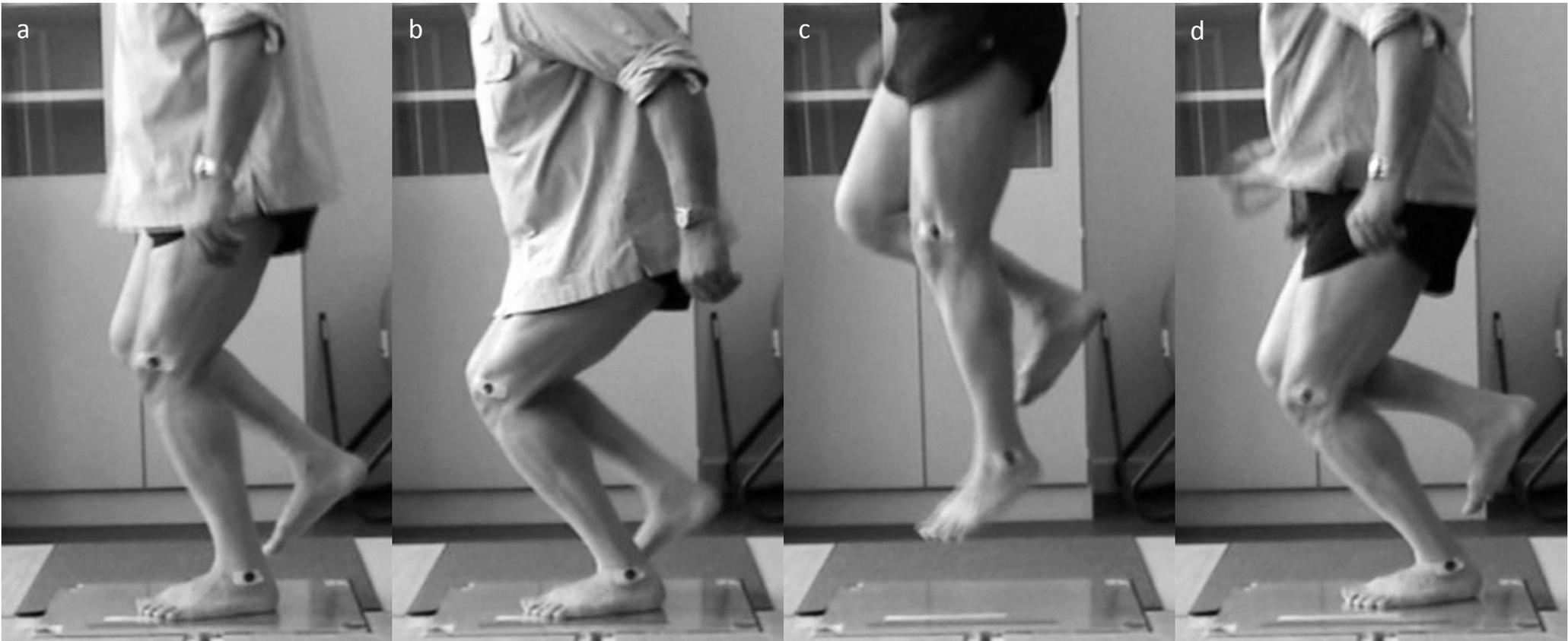
Figure 3 Percentage change in BMD (A) and BMC (B) at the femoral neck for the exercise leg (*n* = 35) and control leg (*n* = 35) in older men following the 12 month unilateral high impact exercise intervention. Values are mean ± SEM.
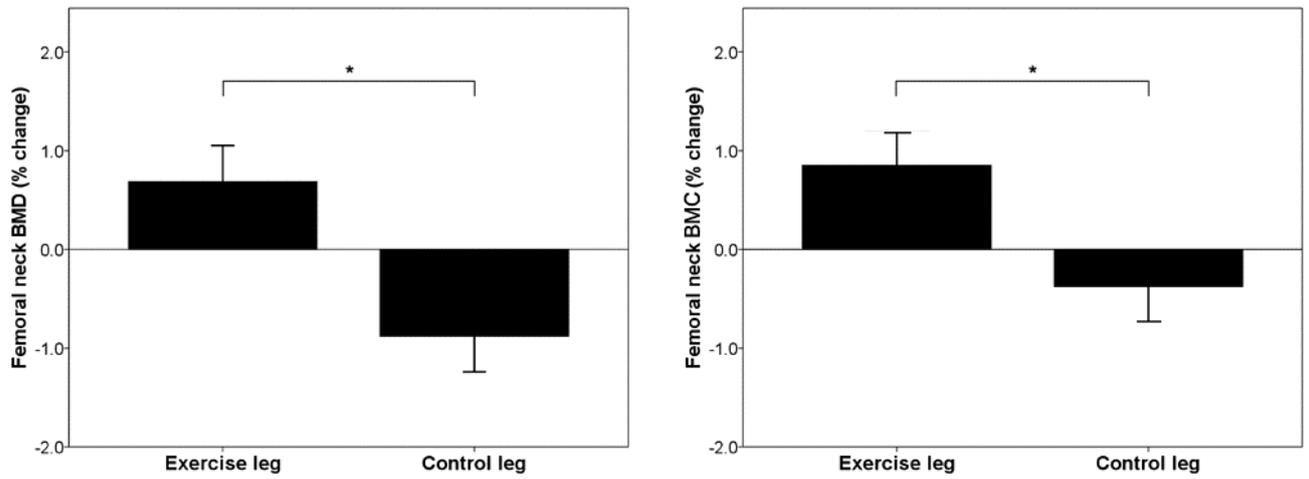
* significant difference as determined by paired samples t-test ($P < 0.05$).

Table 1 Typical progression of the 12 month high impact, unilateral exercise intervention

Week	Sessions per week	Exercise volume (sets x repetitions)	Rest duration between sets (s)	Hop direction *	Self-rated hop height	Arm movement
1	3	3x10	15	V	Low	support
2	3	3x10	15	V	Low	support
3	3	3x10	15	V	Moderate	support
4	3	4x10	15	V	Moderate	Arm swing
5	4	4x10	15	V	High	Arm swing
6	4	4x10	15	V	High	Arm swing
7	5	5x10	15	V	High	Arm swing
8	5	5x10	15	V	High	Arm swing
9	6	5x10	15	M	High	Arm swing
10	6	5x10	15	M	High	Arm swing
11-52	7	5x10	15	M	High	Arm swing

V = vertical, M = multidirectional (vertical, medio-lateral, anterio-posterior and rotational)

Table 2 Anthropometric, lifestyle, physical activity and dietary characteristics of participants at baseline.

	Older men (n=35)		
Age (y)	69.9	±	4.0
Height (m)	1.753	±	0.063
Weight (kg)	80.4	±	8.4
BMI (kg/m^2)	26.2	±	2.3
Total body fat (%)	26.9	±	4.9
Proportion of men with previous fractures (%)	48.6		
Current physical activity (hrs/wk)	1.8	±	2.0
Baecke physical activity questionnaire score:			
- Work index score	2.7	±	0.5
- Sport index score	2.8	±	1.0
- Leisure index score	2.6	±	0.5
- Total index score	8.2	±	1.5
Energy Intake (MJ/day)	9.8	±	2.1
Total Fat (% energy)	34.2	±	7.9
CHO (% energy)	46.6	±	6.7
Protein (% energy)	14.5	±	2.6
Alcohol (% energy)	4.6	±	4.7
Calcium intake (mg/day)	1068.2	±	259.6
Vitamin D intake (µg/day)	3.3	±	1.8

Values are mean ± SD. BMI-Body mass index.

Table 3 Peak vertical ground reaction forces during takeoff and landing averaged over 10 hops in older men before and after 6 months of high impact exercises.

	Older men (n=35)							
	Pre			Post			*P*	
Peak GRF during take off (N)	1771	±	37	1847	±	44	0.022[*]	
Peak GRF during take off (N/kg)	2.25	±	0.05	2.31	±	0.04	0.133	
Peak GRF during landing (N)	2132	±	56	2402	±	85	<0.001[*]	
Peak GRF during landing (N/kg)	2.72	±	0.08	3.02	±	0.11	0.001[*]	

Values are presented as mean ± SEM. [*]significantly different from baseline as determined by paired t-test *P* < 0.05.

Table 4 Hip BMD, BMC and geometry parameters in the EL ($n = 35$) and CL ($n = 35$) of older men before and after a 12-month high impact unilateral exercise intervention

	EL (n=35)				CL (n=35)				P		
	Pre		Post		Pre		Post		Time	Leg	Leg x Time
BMD											
Femoral neck (g/cm^2)	0.948	± 0.018	0.954	± 0.017	0.954	± 0.018	0.945	± 0.018	0.642	0.875	0.003*
- Upper neck (g/cm^2)	0.769	± 0.019	0.770	± 0.019	0.779	± 0.019	0.771	± 0.019	0.304	0.627	0.138
- Lower neck (g/cm^2)	1.122	± 0.019	1.133	± 0.018	1.124	± 0.020	1.115	± 0.020	0.711	0.456	0.001*
Trochanter (g/cm^2)	0.920	± 0.017	0.923	± 0.017	0.919	± 0.018	0.923	± 0.018	0.130	0.973	0.897
Total hip (g/cm^2)	1.027	± 0.018	1.030	± 0.017	1.029	± 0.018	1.027	± 0.018	0.856	0.985	0.206
BMC											
Femoral neck (g)	5.50	± 0.14	5.54	± 0.13	5.51	± 0.14	5.49	± 0.14	0.505	0.782	0.022*
- Upper neck (g)	2.20	± 0.07	2.20	± 0.06	2.22	± 0.07	2.21	± 0.07	0.738	0.631	0.265
- Lower neck (g)	3.30	± 0.08	3.34	± 0.07	2.22	± 0.07	2.21	± 0.07	0.172	0.367	0.018*
Trochanter (g)	16.57	± 0.52	16.45	± 0.54	16.40	± 0.59	16.49	± 0.57	0.898	0.810	0.114
Total hip (g)	40.44	± 0.92	40.49	± 0.91	40.29	± 0.97	40.35	± 0.97	0.551	0.659	0.966
Geometry											
Section Modulus (mm^3)	887.8	± 27.9	906.5	± 28.0	901.4	± 28.0	906.8	± 28.4	0.044*	0.538	0.157
CSMI (mm^4)	17636.7	± 701.7	18367.0	± 721.6	18132.2	± 718.1	18331.7	± 730.9	0.016*	0.757	0.261
Minimum neck width (mm)	36.5	± 0.4	36.6	± 0.1	36.4	± 0.4	36.7	± 0.4	0.006*	0.977	0.137
CSA (mm^2)	173.2	± 26.5	174.9	± 24.9	174.5	± 26.4	172.3	± 26.2	0.688	0.700	0.012*

. Values are mean ± SEM and the displayed *P* value denotes the ANOVA interaction and main effects. * significant effects observed at *P* < 0.05.