Effect of exercise on bone health in middle aged and older adults: hierarchical network meta-analysis of randomised trials

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ABSTRACT

OBJECTIVE

To determine the type and dose of exercise needed to maintain bone mineral density (BMD) and reduce fracture risk in adults aged ≥40 years.

DESIGN

Hierarchical bayesian network meta-analysis and multivariable dose-response network meta-analysis.

DATA SOURCES

PubMed, Embase, the Cochrane Library, and Web of Science from inception to January 2026.

ELIGIBILITY CRITERIA FOR SELECTING STUDIES

Randomised controlled trials comparing structured exercise interventions with non-exercise control or alternative exercise modalities in middle aged (40-60 years) and older (>60 years) adults.

MAIN OUTCOME MEASURES

The primary outcomes were changes in BMD (g/cm^2) at the lumbar spine, femoral neck, and total hip. The secondary outcome was incidence of fractures. Evidence certainty was rated using the Confidence in Network Meta-Analysis tool across six predefined domains.

RESULTS

A total of 124 trials (18 429 participants) was included. For lumbar spine BMD, low certainty evidence showed that brisk walking or jogging (mean difference 0.013 g/cm^2, 95% credible interval (CrI) 0.006 to 0.021) and low to moderate certainty evidence showed that combined aerobic-resistance exercises (0.013 g/cm^2, 0.010 to 0.016) probably result in improvements compared with controls. For femoral neck BMD, brisk walking or jogging (0.009 g/cm^2, 0.001 to 0.018; low to moderate certainty) and mind-body exercise (0.007 g/cm^2, 0.002 to 0.013; moderate certainty) may provide the greatest benefit. For total hip BMD, only brisk walking or jogging (0.021 g/cm^2, 0.005 to 0.038; low certainty) may provide the greatest benefit. Dose-response relations appeared non-linear and were generally an inverted U-shape. Minimal clinically important difference might be reached at about 400 metabolic equivalents of task in minutes per week (METs-min/week) for lumbar spine and around 600 METs-min/week for femoral neck and total hip BMD. . In fracture analyses (26 trials, 11 132 participants), mixed aerobic exercise (odds ratio 0.29, 95% CrI 0.11 to 0.78; low certainty) and mind-body exercise (0.58, 0.36 to 0.93; low certainty) may reduce fracture risk, whereas other modalities had neutral effects.

CONCLUSIONS

Exercise is effective in attenuating age related decline in BMD in adults aged ≥40 years. Based on low to moderate certainty evidence, brisk walking or jogging and combined aerobic-resistance exercises probably offer favourable benefits for BMD. Clinically meaningful benefits might generally be achieved at doses around 600 METs-min/week—equivalent to about 2-3 hours of brisk walking or jogging, while mixed aerobic and mind-body exercise may additionally reduce fracture risk. Given the overall low to moderate confidence in several estimates, these findings provide cautious support for the integration of dose specific, modality tailored exercise prescriptions into bone health guidelines.

SYSTEMATIC REVIEW REGISTRATION

PROSPERO CRD42024553562.

Introduction

Osteoporosis and related fragility fractures are major contributors to disability and premature mortality in ageing populations, affecting more than 200 million people worldwide.[1 2] Lifetime fracture risk is estimated at 30-50% in women and 15-30% in men.[3 4] Age related declines in bone mineral density (BMD) are strongly associated with reduced bone strength and increased fracture risk. In turn, treatment related changes in BMD are strongly correlated with fracture risk reduction.[5] Because BMD, muscle strength, and balance collectively account for a large proportion of bone strength, non-drug interventions increasingly prioritise modifiable lifestyle factors.[6] Among these, structured exercise serves as a highly accessible, cost effective adjunct to pharmacotherapy, offering both targeted skeletal and broad systemic benefits.[7]

Although current clinical guidelines unanimously endorse physical activity for osteoporosis management, specific quantitative recommendations for the optimal modalities and dosages remain largely inconsistent. For instance, while some professional societies propose that 30 minutes of daily walking may be sufficient to prevent osteoporosis,[8] the World Health Organization (WHO) recommends 150-300 minutes of moderate intensity or 75-150 minutes of vigorous intensity aerobic activity each week, combined with muscle strengthening activities, to achieve general health benefits.[9] In practice, however, clinicians frequently hesitate to prescribe high volume or high impact exercise to older (>60 years) adults owing to concerns about potential falls and skeletal adverse events.[10] According to the American College of Sports Medicine, the primary goals of incorporating exercise are to maintain bone mass in adults and to attenuate bone loss in older individuals.[11] Recent consensus statements advocate for integrated approaches combining exercise with adequate nutrition, vitamin D, and anti-osteoporotic drugs, but they also acknowledge persistent

uncertainty about the long term efficacy of specific exercise types and their dose-response dynamics in older adults. Previous trials and meta-analyses have yielded valuable evidence but are fundamentally limited by methodological constraints.[12] Most are restricted to traditional pairwise comparisons of exercise versus non-exercise control or focused on single exercise modalities such as resistance training or mind-body practices.[13-16] Others have restricted eligibility to specific demographic groups, such as exclusively men or postmenopausal women,[16 17] thereby limiting their generalisability. While a previous network meta-analysis suggested that mind-body exercise may be particularly effective for improving BMD in people with osteopenia,[18] it lacked the methodological framework to map dose-response trajectories or evaluate critical patient level modifiers, including age, sex, body mass index (BMI), baseline BMD, and adherence rates.[19-21] Consequently, clinicians still lack quantitative, modality specific, and population specific guidance on how much exercise is needed to improve bone health safely and effectively.[22-24]

To address these gaps, we conducted a hierarchical bayesian network meta-analysis of randomised trials. Moving beyond previous pairwise or modality specific syntheses that broadly confirm "exercise works," this study integrated a multivariable dose-response framework with a harmonised energy expenditure metric (metabolic equivalents of task (METs) in minutes per week) across 124 trials. This novel approach systematically estimates the minimal doses required to achieve MCIDs for specific exercise modalities and systematically examines how baseline characteristics (age, sex, and BMI) modify these therapeutic thresholds.

Methods

Our review was prospectively registered in PROSPERO and conducted in accordance with the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020 and PRISMA extension for network meta-analysis (PRISMA-NMA) guidelines[23] (see supplementary appendix file 1).

Search strategy and eligibility criteria

We systematically searched PubMed, Embase, the Cochrane Central Register of Controlled Trials (CENTRAL), and Web of Science from inception to January 2025, and updated the search to January 2026. The PubMed strategy combined medical subject headings and free text terms related to exercise and bone outcomes (eg, "exercise", "physical activity", "aerobic training", "resistance training", "tai chi", "yoga", "bone mineral density", "osteoporosis", "osteopenia"). Supplementary appendix file 2 provides search strategies for all the databases. No language restrictions were applied.

We included randomised clinical trials that enrolled middle aged or older adults (≥40 years), compared one or more structured exercise interventions with non-exercise control or with another exercise modality or intensity, and reported changes in BMD of the lumbar spine, femoral neck, or total hip, measured by dual energy x ray absorptiometry in g/cm^2, or incident fractures, or both during follow-up. We excluded trials that examined only acute effects of exercise (intervention duration <4 weeks), did not provide sufficient data to derive effect estimates, or focused exclusively on secondary osteoporosis due to systemic glucocorticoid treatment or active malignancy, or in which participants initiated or changed anti-osteoporotic pharmacotherapy (eg, bisphosphonates) at the time of randomisation.

Study selection and data extraction

All records were imported into EndNote 21, with duplicate citations removed. Two reviewers (CBL and LWL) independently screened titles and abstracts, assessed full texts for eligibility, and resolved disagreements through discussion or consultation with a third reviewer when necessary. Reasons for exclusion at the full text stage were recorded and are summarised in a PRISMA flow diagram.

Using a piloted standardised form, two reviewers independently extracted data on study and participant characteristics (country, setting, sample size, mean age, sex distribution, BMI, baseline BMD, comorbidities), intervention details (exercise type, frequency, session duration, intensity, programme duration, supervision, co-interventions such as calcium or vitamin D supplementation), and outcomes (change in lumbar spine, femoral neck, and total hip BMD; incident fractures; adherence; and adverse events). To quantify and harmonise the intensity across exercise modalities compared with control, we used the Compendium of Physical Activities[25] and expressed exercise intensity as METs in minutes per week (METs-min/week). When necessary, we contacted corresponding authors for missing or unclear information. Multi-arm trials were extracted in a way that preserved randomised comparisons within the network.

Exercise interventions were classified a priori into six mutually exclusive categories: mixed aerobic exercises, resistance training, combined aerobic-resistance exercises, brisk walking or jogging, mind-body exercises (eg, tai chi, yoga), and whole body vibration. Control groups were defined as usual care, no structured exercise, or low intensity stretching or relaxation not expected to influence BMD.

Equity, diversity, and inclusion statement

The author team includes junior, mid-career, and senior investigators from sports medicine and orthopaedics, with representation of different genders. The included trials enrolled participants across a range of ages, both sexes, diverse bodyweight categories, and various comorbid conditions. Our analyses explicitly examined effect modification by sex and age, as well as BMI. However, data on race and ethnicity and socioeconomic status were rarely reported and could not be incorporated, which we acknowledge as a limitation for assessing equity in exercise effects on bone health.

Data synthesis and analysis

Bayesian network meta-analyses

We performed bayesian network meta-analyses for continuous BMD outcomes and binary fracture outcomes using hierarchical random effects models implemented in R (brms package). Treatment effects for BMD were summarised as mean differences in g/cm^2 between exercise and comparator groups, and fracture outcomes as odds ratios, both with 95% credible intervals (CrIs). The transitivity and consistency assumptions underlying network meta-analysis were assessed by comparing distributions of key effect modifiers across comparisons and by evaluating local and global inconsistency. We used the netmeta package and the Confidence in Network Meta-Analysis (CINeMA) framework to evaluate the credibility of relative treatment effects across the network.[26]

Given that middle aged and older adults typically experience an age related bone loss of 1-2% annually,[11 27] we prespecified the MCID limits to reflect this dynamic decline. Specifically, we defined 1% and 2% of the baseline mean BMD from the pooled studies as the lower and upper limits of the MCID, respectively. These thresholds were used both to interpret the clinical relevance of estimated effects and as reference values in CINeMA when grading imprecision. Ranking probabilities of each exercise modality were derived from posterior distributions (supplementary appendix file 3 provides

details of model specification, priors, convergence diagnostics, and additional sensitivity analyses).

Dose-response network meta-analyses

To characterise dose-response associations between exercise and changes in BMD, we used the MBNMA dose package to fit multivariable bayesian dose-response network meta-analysis models. Exercise dose was harmonised across trials using METs-min/week, calculated from reported frequency, session duration, and intensity. Interventions were first coded at an overall level (any exercise versus control) to estimate the optimal total exercise dose for change in BMD, and then at the modality level (specific exercise categories) to estimate modality specific dose-response curves and the minimal dose required to reach the prespecified MCIDs for BMD.

To explore whether dose-response relations varied across populations, we incorporated potential effect modifiers as covariates, including mean age, sex distribution, and BMI. To evaluate model fit and non-linearity, we compared alternative functional forms (eg, linear, spline, and fractional polynomial models), with selection based on deviance information criterion and posterior predictive checks. Convergence of bayesian MCMC models was successfully confirmed using trace plots, density plots, and the Gelman-Rubin statistic (see supplementary appendix file 19). Supplementary appendix file 3 describes the analytical details in full.

Risk of bias and certainty of evidence

Risk of bias was assessed using the Cochrane Risk of Bias tool version 2.0 (RoB 2.0) for randomised trials, which evaluates five domains: bias arising from the randomisation process, bias due to deviations from intended interventions, bias due to missing outcome data, bias in measurement of the outcome, and bias in selection of the reported result. We categorised summary assessments as low, some concerns, or high risk of bias.[28] Discrepancies were resolved by consensus. We then used the CINeMA web application to rate the certainty of evidence for each network comparison across six domains: within study bias, reporting bias, indirectness, imprecision, heterogeneity, and incoherence.[26] Supplementary appendix file 17 shows detailed implementation of the CINeMA methods and specific thresholds.

Prespecified sensitivity analyses included restricting to trials judged at low or unclear risk of bias, excluding trials enrolling participants with major comorbidities, and excluding trials with routine vitamin D or calcium supplementation. When at least 10 studies contributed to a comparison, we explored potential publication bias and small study effects using comparison adjusted funnel plots and Egger's regression test.

Patient and public involvement

This study was a secondary analysis of published trial data. No patients or members of the public were involved in the design, conduct, reporting, or dissemination planning of the study. No dedicated funding or infrastructure for patient and public involvement was available for this project, and the study was initiated as a methodological evidence synthesis based entirely on published data. We acknowledge this as a limitation and recognise that future evidence synthesis in this area would benefit from public input, particularly in outcome prioritisation and dissemination.

Results

Characteristics of the included studies

Overall, 124 eligible randomised controlled trials comprising 480 arms and 18 429 participants were included for analysis (fig 1). Supplementary appendix file 4 lists the excluded studies and reasons for exclusion. Supplementary appendix file 5 details the characteristics of the included studies. Of the trials, 90 (73%) enrolled female participants only, 24 (19%) enrolled people of both sexes, and 10 (8%) enrolled male participants only. Analysis for efficacy outcomes (fig 2) comprised 94 records (222 arms, 6553 participants,) for lumbar spine BMD, 86 records ((201 arms, 6462 participants) for femoral neck BMD, 49 records (115 arms, 3670 participants) for total hip BMD, and 26 records (62 arms, 11 132 participants) for all cause fracture risk. Intervention durations ranged from 12 to 208 weeks. The included trials were conducted globally, with contributions from the US (n=22), Australia (n=13), China (n=14), and England (n=9). Orthopaedic comorbidities and vitamin D supplementation were reported in 31 studies and 27 studies, respectively. Table 1, table 2, and table 3 show the qualitative differences in participant characteristics.

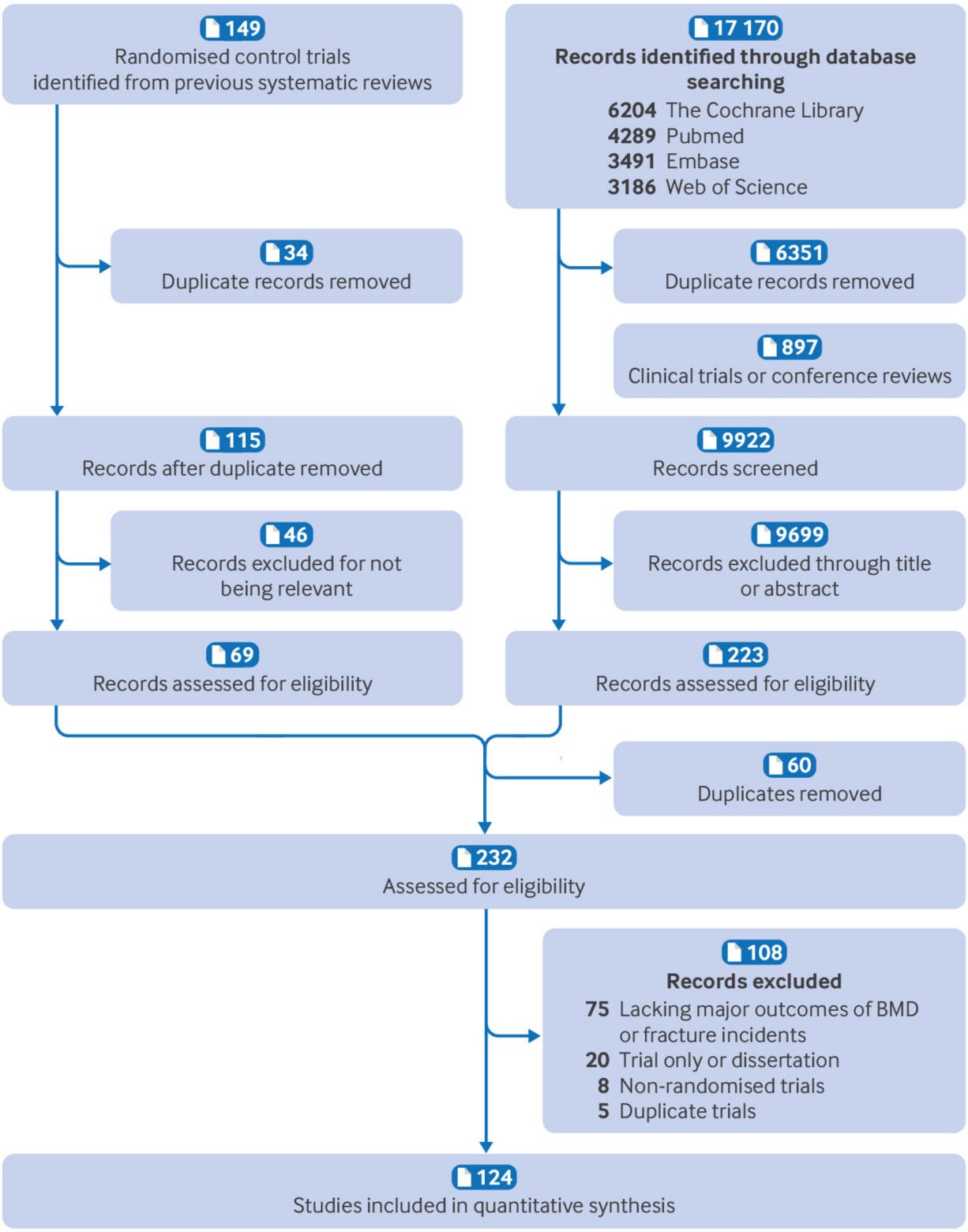

Fig 1 | PRISMA flow diagram of study selection. BMD=bone mineral density

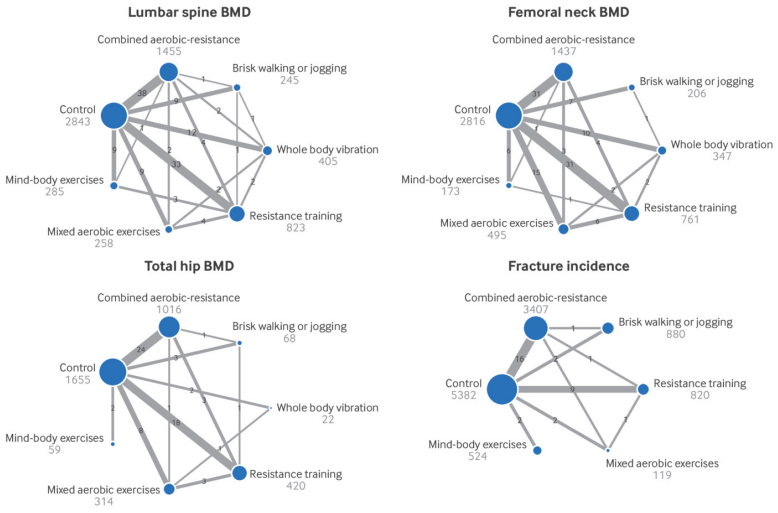

Fig 2 | Network plots of available exercise types for BMD of the lumbar spine, femoral neck, and total hip, and for fracture incidence. Circle size corresponds to the number of participants in the treatment comparison and line thickness represents the number of trials comparing the two treatments. The absence of a line between two treatments indicates that no direct trials reported the outcome of interest for those specific treatments. BMD=bone mineral density

Table 1 | Characteristics of trials reporting outcomes for lumbar spine BMD in adults aged ≥40 years

Exercise	k	No	Countries	Mean (SD)						% (No) of participants				
				Age (years)	% female	BMI	Baseline BMD (g/cm²)	Dose (METs·min/wk)	Duration (weeks)	Comorbidities	Vitamin D supplement	Normal weight	Overweight	Obese
Brisk walking or jogging	10	245	Canada, China, Egypt, Iran, Japan, Korea, Spain, UK, US	58.7 (10.96)	96.3 (11.7)	25.7 (2.89)	0.98 (0.13)	910 (551)	41.4 (25.98)	28 (68)	8 (19)	36 (87)	33 (81)	11 (28)
Combined aerobic+resistance exercises	40	1469	Australia, Brazil, Canada, China, Egypt, Germany, Greece, Japan, Norway, Pakistan, Portugal, Saudi Arabia, Sweden, UK, US	61.74 (7.36)	75.85 (39.1)	26.7 (3.03)	0.99 (0.14)	757 (298.5)	44.1 (20.59)	23 (340)	30 (440)	16 (237)	79 (1157)	4 (66)
Control	94	2843	Australia, Belgium, Brazil, Canada, China, Denmark, Egypt, Finland, France, Germany, Greece, Iran, Italy, Japan, Korea, Lebanon, Norway, Pakistan, Portland, Portugal, Saudi Arabia, Sweden, Switzerland, Turkey, UK, US	61.41 (7.86)	81.68 (33.98)	26.1 (2.74)	0.98 (0.13)	0 (0)	NA	23 (646)	25 (704)	28 (801)	62 (1771)	5 (143)
Mind-body exercises	9	285	China, US	60.24 (7.4)	82.78 (35.98)	23.9 (1.97)	0.89 (0.17)	594 (185.63)	41.33 (14.04)	19 (54)	21 (59)	62 (178)	21 (59)	0 (0)
Mixed aerobic exercises	11	258	Australia, Finland, Turkey, UK, US	57.52 (7.82)	78.64 (40.25)	27 (3.45)	1.02 (0.12)	599 (321.07)	42.36 (13.38)	18 (46)	33 (86)	25 (64)	60 (154)	16 (40)
Resistance training	45	1048	Australia, Belgium, Brazil, Canada, China, Denmark, Egypt, France, Germany, Italy, Korea, Lebanon, Portland, Switzerland, Turkey, US	62.03 (8.26)	72.64 (38.06)	26 (2.24)	1.02 (0.12)	598 (221.17)	40.93 (22.14)	16 (167)	16 (170)	23 (240)	67 (697)	4 (40)

Whole body vibration	13	405	Belgium, Canada, China, Egypt, France, Germany, Greece, Spain, Switzerland, Turkey, US	58.34 (7.33)	95.62 (15.81)	26.1 (2.46)	0.94 (0.08)	269 (208.05)	36.31 (16.89)		25 (101)	41 (167)	62 (251)	34 (139)	4 (15)

BMD=bone mineral density; BMI=body mass index; METs=metabolic equivalents of task; SD=standard deviation.

Table 2 | Characteristics of trials reporting outcomes for femoral neck BMD in adults aged ≥40 years

Exercise	k	No	Countries	Mean (SD)						% (No) of participants				
				Age (years)	% female	BMI	Baseline BMD (g/cm²)	Dose (METs·min/wk)	Duration (weeks)	Comorbidities	Vitamin D supplement	Normal weight	Overweight	Obese
Brisk walking or jogging	8	206	Canada, Iran, Japan, Korea, Spain, UK, USA	60.45 (9.38)	100 (0)	26.2 (3.09)	0.78 (0.08)	980 (601.12)	44.5 (28.38)	24 (49)	0 (0)	23 (48)	39 (81)	14 (28)
Combined aerobic+resistance exercises	33	1451	Australia, Brazil, Canada, China, Finland, Germany, Italy, Japan, Pakistan, Portugal, Sweden, UK, USA	64.04 (6.26)	78.03 (37.64)	27 (3.01)	0.8 (0.1)	718 (298.2)	47.52 (22)	20 (285)	40 (579)	14 (208)	80 (1168)	5 (66)
Control	86	2816	Australia, Belgium, Brazil, Canada, China, Denmark, Egypt, Finland, France, Germany, Iran, Italy, Japan, Korea, Lebanon, Pakistan, Portland, Portugal, Spain, Sweden, Switzerland, Turkey, UK, USA	62.69 (7.91)	84.77 (31.19)	26.4 (2.69)	0.79 (0.11)	0 (0)	NA	23 (652)	29 (806)	24 (664)	66 (1872)	5 (134)
Mind-body exercises	6	173	China, USA	58.32 (6.77)	90.83 (22.45)	23.8 (2.57)	0.77 (0.15)	587 (221.44)	36 (14.59)	31 (54)	34 (59)	38 (66)	34 (59)	0 (0)
Mixed aerobic exercises	16	495	Australia, Canada, Finland, Portugal, Turkey, UK, USA	62.95 (8.6)	91.56 (25.93)	26.7 (2.94)	0.79 (0.12)	657 (285.44)	50.69 (28.77)	42 (209)	34 (167)	26 (129)	66 (326)	8 (40)
Resistance training	41	974	Australia, Belgium, Brazil, Canada, China, Denmark, Finland, France, Italy, Korea, Lebanon, Portland, Portugal, Spain, Switzerland, Turkey, UK, USA	62.94 (7.3)	77.12 (34.84)	26.3 (2.36)	0.81 (0.09)	599 (202.66)	38.98 (19.39)	13 (130)	16 (152)	21 (208)	67 (655)	4 (40)

Whole body vibration	11	347	Belgium, Canada, China, Egypt, France, Spain, Switzerland, Turkey, USA	59.93 (10.35)	94.82 (17.19)	26.2 (2.57)	0.75 (0.08)	233 (165.49)	34.18 (11.95)		25 (88)	48 (167)	68 (237)	22 (76)	4 (15)

BMD=bone mineral density; BMI=body mass index; METs=metabolic equivalents of task; SD=standard deviation.

Table 3 | Characteristics of trials reporting outcomes for total hip BMD in adults aged ≥40 years

Exercise	k	n	Countries	Mean (SD)						% (No) of participants				
				Age (years)	% female	BMI	Baseline BMD (g/cm²)	Dose (METs-min/wk)	Duration (weeks)	Comorbidities	Vitamin D supplement	Normal weight	Overweight	Obese
Brisk walking or jogging	3	68	Canada, Egypt, Japan	44.87 (9.02)	100 (0)	23.8 (1.25)	0.87 (0.08)	1192 (811.82)	37.33 (13.32)	0 (0)	0 (0)	100 (68)	0 (0)	0 (0)
Combined aerobic-resistance exercises	25	1,030	Australia, Brazil, Canada, Egypt, Germany, Greece, Italy, Japan, Portugal, Saudi Arabia, Sweden, UK, USA	61.76 (7.39)	63.16 (44.4)	27.5 (3.16)	0.9 (0.09)	801 (308.87)	41.68 (19.91)	23 (235)	39 (406)	5 (47)	89 (917)	6 (66)
Control	49	1,655	Australia, Brazil, Canada, China, Egypt, Finland, France, Germany, Greece, Italy, Japan, Lebanon, Portland, Portugal, Saudi Arabia, Spain, Sweden, Turkey, UK, USA	61.07 (9.39)	72.04 (40.25)	26.6 (2.8)	0.88 (0.1)	0 (0)	NA	28 (469)	34 (564)	18 (300)	74 (1218)	7 (108)
Mind-body exercises	2	59	China, USA	52.25 (9.26)	100 (0)	25.9 (0.14)	0.91 (0.11)	420 (169.71)	36 (2.83)	73 (43)	100 (59)	0 (0)	100 (59)	0 (0)
Mixed aerobic exercises	8	314	Canada, Finland, Portugal, Turkey, UK, USA	67.42 (8.48)	83.12 (35.75)	27.1 (3.68)	0.85 (0.13)	686 (150.09)	56.12 (39.37)	63 (197)	38 (120)	20 (64)	67 (210)	13 (40)
Resistance training	26	522	Australia, Brazil, Canada, Egypt, Germany, Italy, Lebanon, Portland, Portugal, Spain, USA	61.03 (9.57)	68.08 (40.29)	26.4 (2.92)	0.9 (0.09)	671 (211.46)	39.62 (23.36)	23 (118)	24 (124)	17 (88)	62 (323)	8 (40)
Whole body vibration	2	22	France, Turkey	46.8 (11.6)	71.5 (40.31)	25.1 (2.12)	0.81 (0.05)	500 (70.71)	26 (0)	68 (15)	68 (15)	32 (7)	68 (15)	0 (0)

BMD=bone mineral density; BMI=body mass index; METs=metabolic equivalents of task; SD=standard deviation.

Network geometry

According to the CINeMA framework, the global test for inconsistency was statistically significant, as were the results of the global transitivity tests for lumbar spine (χ^2=970.1, df=108, P<0.001) and total hip (χ^2=714.8, df=51, P<0.001), but not for femoral neck (χ^2=2303.9, df=97, P=1.00) and all cause fractures (χ^2=26.5, df=27, P=0.49). Detailed node splitting analysis revealed that for all comparisons where both direct and indirect evidence were available (closed loops), no statistically significant inconsistency was detected (all local). The major concerns flagged by CINeMA were strictly isolated to comparisons relying solely on indirect evidence, where formal statistical inconsistency cannot be calculated (not applicable). Therefore, while cautious interpretation is warranted for these specific indirect comparisons, the overall network demonstrates robust local coherence.

Effects on changes in bone mineral density

Supplementary appendix file 7 presents forest plots of changes in BMD for each study. Figure 3 presents the predicted effects of each exercise modality compared with controls. For lumbar spine BMD, brisk walking or jogging was the most effective intervention (n=245, κ=10, mean difference 0.013 g/cm^2, 95% CrI 0.006 to 0.021; low certainty evidence), followed by combined aerobic-resistance exercises (n=1456, κ=39, 0.013 g/cm^2, 0.010 to 0.016; low to moderate certainty evidence), whole body vibration (n=405, κ=13, 0.009 g/cm^2, 0.004 to 0.013; low certainty evidence), and resistance training (n=850, κ=37, 0.005 g/cm^2, 0.002 to 0.008; low certainty evidence). For femoral neck BMD, brisk walking or jogging again showed the greatest effectiveness (n=206, κ=8, 0.009 g/cm^2, 0.001 to 0.018; low to moderate certainty evidence), followed by mind-body exercise (n=173, κ=6, 0.007 g/cm^2, 0.002 to 0.013; moderate certainty evidence), resistance training (n=787, κ=34, 0.005 g/cm^2, 0.003 to 0.007; low to moderate certainty evidence), and combined aerobic-resistance exercises (n=1438, κ=32, 0.005 g/cm^2, 0.002 to 0.007; low to moderate certainty evidence). For total hip BMD, only brisk walking or jogging resulted in a significant improvement (n=68, κ=3, 0.021 g/cm^2, 0.005 to 0.038; low certainty evidence).

Exercise intervention	Mean difference (95% CI)	No of participants	κ
Lumbar BMD			
Mind-body exercises	0.000 (-0.003 to 0.003)	285	9
Mixed aerobic exercises	0.001 (-0.002 to 0.005)	258	11
Resistance training	0.005 (0.002 to 0.008)	850	37
Whole body vibration	0.009 (0.004 to 0.013)	405	13
Combined aerobic-resistance	0.013 (0.010 to 0.016)	1456	39
Brisk walking or jogging	0.013 (0.006 to 0.021)	245	10
Femoral BMD			
Mind-body exercises	0.007 (0.002 to 0.013)	173	6
Mixed aerobic exercises	-0.009 (-0.011 to -0.006)	495	16
Resistance training	0.005 (0.003 to 0.007)	787	34
Whole body vibration	0.000 (-0.005 to 0.005)	347	11
Combined aerobic-resistance	0.005 (0.002 to 0.007)	1438	32
Brisk walking or jogging	0.009 (0.001 to 0.018)	206	8
Total hip BMD			
Mind-body exercises	0.005 (-0.004 to 0.013)	59	2
Mixed aerobic exercises	-0.018 (-0.022 to -0.014)	314	8
Resistance training	0.001 (-0.003 to 0.005)	446	20
Whole body vibration	0.023 (-0.008 to 0.055)	22	2
Combined aerobic-resistance	0.001 (-0.002 to 0.005)	1017	24
Brisk walking or jogging	0.021 (0.005 to 0.038)	68	3

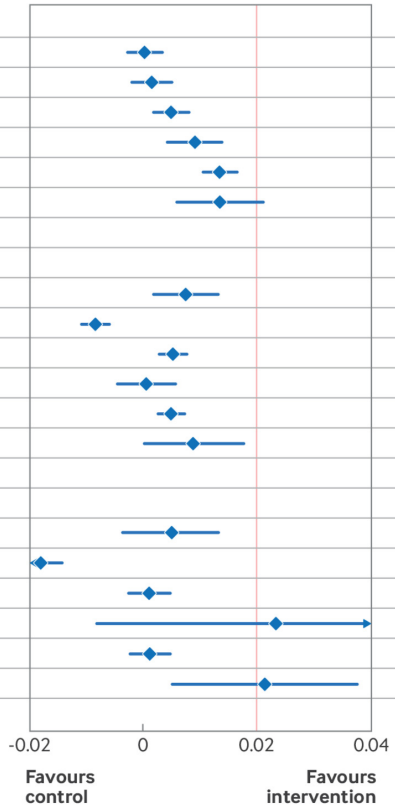

Fig 3 | Forest plots of predicted effects of different exercise modalities on BMD at lumbar spine, femoral neck, and total hip in adults aged ≥40 years. BMD=bone mineral density; CI=confidence interval; MCID=minimal clinically important difference

No statistically significant differences in lumbar spine BMD were found for participants engaging in mind-body exercise or mixed aerobic exercise. Whole body vibration did not statistically significantly affect femoral neck BMD. Furthermore, total hip BMD was not significantly altered by combined aerobic-resistance exercises, mind-body exercise, resistance training, or whole body vibration.

Dose-response relations and moderation effects

Initial examination of the data identified potential dose-response associations between age, exercise intensity, BMI, and changes in BMD (see supplementary appendix file 8). Figure 4 illustrates the non-linear dose-response relations between exercise dose (METs-min/week) and BMD outcomes. For lumbar spine BMD, effects peaked at 914 METs-min/week (mean difference 0.023 g/cm^2, 95% CrI 0.016 to 0.031) and gradually plateaued thereafter (ie, 0.019 g/cm^2, 0.012 to 0.027 at 600 METs-min/week; 0.023 g/cm^2, 0.015 to 0.031 at 1200 METs-min/week) aligning with WHO guidelines.[8] The predicted minimal dose to reach the MCID was 391 METs-min/week. For femoral neck, effects peaked at 1060 METs-min/week (mean difference 0.009 g/cm^2, 0.002 to 0.018 at 600 METs-min/week; 0.032 g/cm^2, 0.025 to 0.042 at 1200 METs-min/week), with a minimal dose of 600 METs-min/week required for MCID. Total hip effects peaked at 1022 METs-min/week (mean difference 0.005 g/cm^2, 95% CrI -0.008 to 0.019 at 600 METs-min/week; 0.029 g/cm^2, 0.015 to 0.055 at 1200 METs-min/week), requiring a minimal dose of 641 METs-min/week for MCID. Table 4 details the recommended optimal doses for improving BMD. Figure 5 details exercise specific dose-response curves, revealing inverted U-shaped relations for nearly all types of exercises except mind-body exercise. Brisk walking required 427 METs-min/week (lumbar spine), 753

METs-min/week (femoral neck), and 789 METs-min/week (total hip) for MCID.

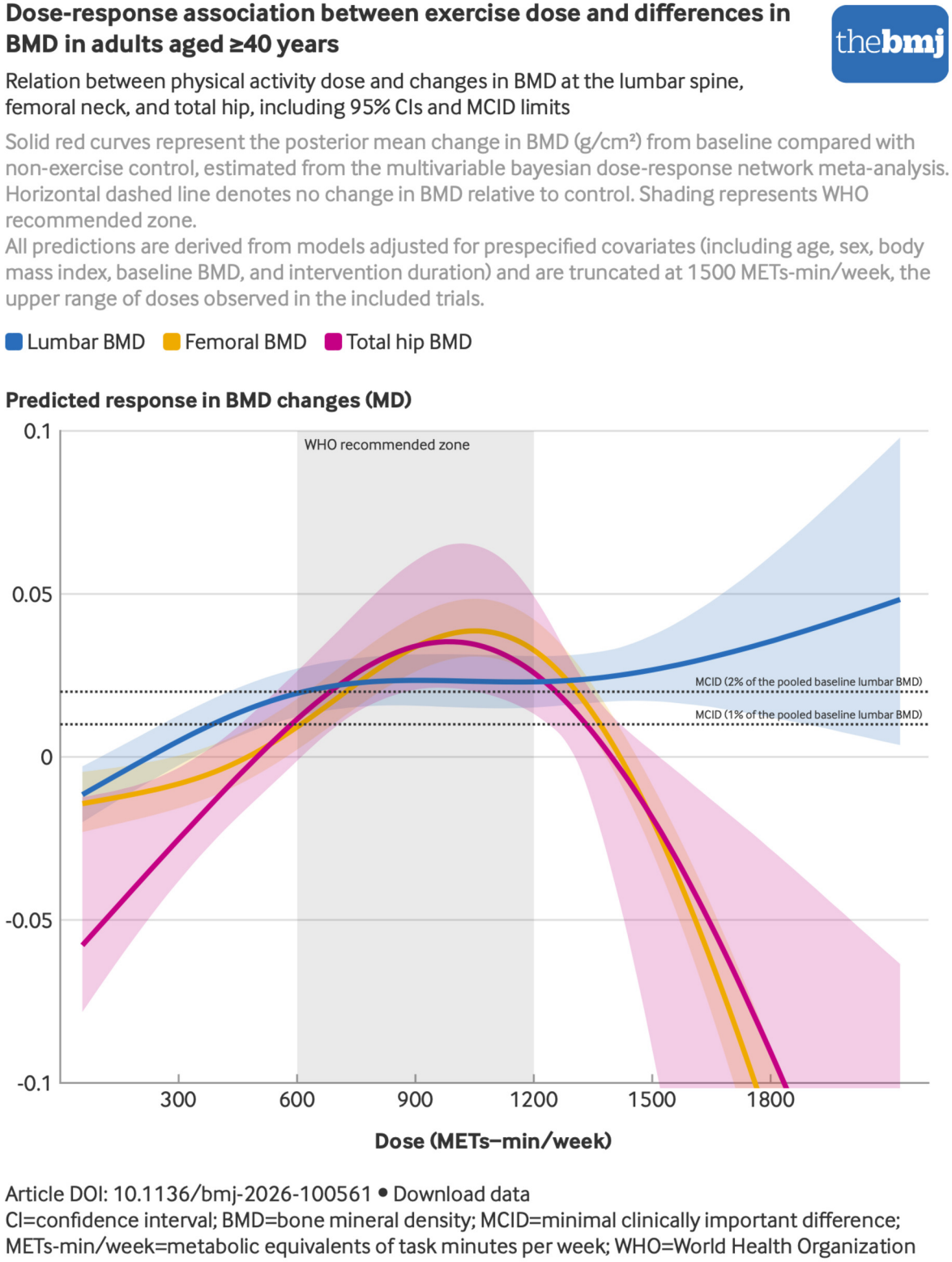

Fig 4 | Association between exercise dose and bone mineral density at lumbar spine, femoral neck, and total hip in adults aged ≥40 years. An interactive version of this graphic is available at https://public.flourish.studio/visualisation/30019338/

Table 4 | Minimal effective and optimal doses (METs-min/week) to improve BMD of the lumbar spine, femoral neck, and total hip in adults aged ≥40 years by subgroup

Subgroups	Lumbar spine BMD			Femoral neck BMD			Total hip BMD		
	MCIDL	MCIDU	Optimal	MCIDL	MCIDU	Optimal	MCIDL	MCIDU	Optimal
All subgroups	391	600	914	600~1375	684~1333	1061	641~1364	721~1304	1022
Type of physical activity									
Combined aerobic-resistance exercises	168	350	970	377	717	980	985	1397	1600
Mixed aerobic exercises	798	1425	1600	1216	NA	1600	NA	NA	1600
Resistance training	465	NA	1600	351~934	NA	634	380~1402	NA	834
Brisk walking or jogging	427	952	1600	753	1217	1600	789	1319	1600
Mind-body exercises	1251	NA	1600	1025	1461	1600	NA	NA	1600
Whole body vibration	307	NA	1600	262~1485	1107	792	43~1285	86~1229	607
Sex									
Male	79~1362	160~1280	704	340~1443	NA	835	474~1240	NA	827
Female	335~	696~	1600	341	734	1600	489	926	1600
Age									
Middle aged (40-60 years)	217~	443~	1600	459	1008	1600	265	537	1600
Older (60-80 years)	302~	NA	879	417	NA	1054	NA	NA	1600
BMI									
Healthy BMI (18-25)	212~	439~	1234	299	631	1600	189	387	1335
Overweight/obesity (>25)	381~1565	NA	898	588~1405	NA	953	NA	NA	871

BMD=bone mineral density; BMI=body mass index; MCID=minimal clinically important difference (L represents lower limit and U represents upper limit); METs-min/week=metabolic equivalents of task minutes per week; NA=not applicable.

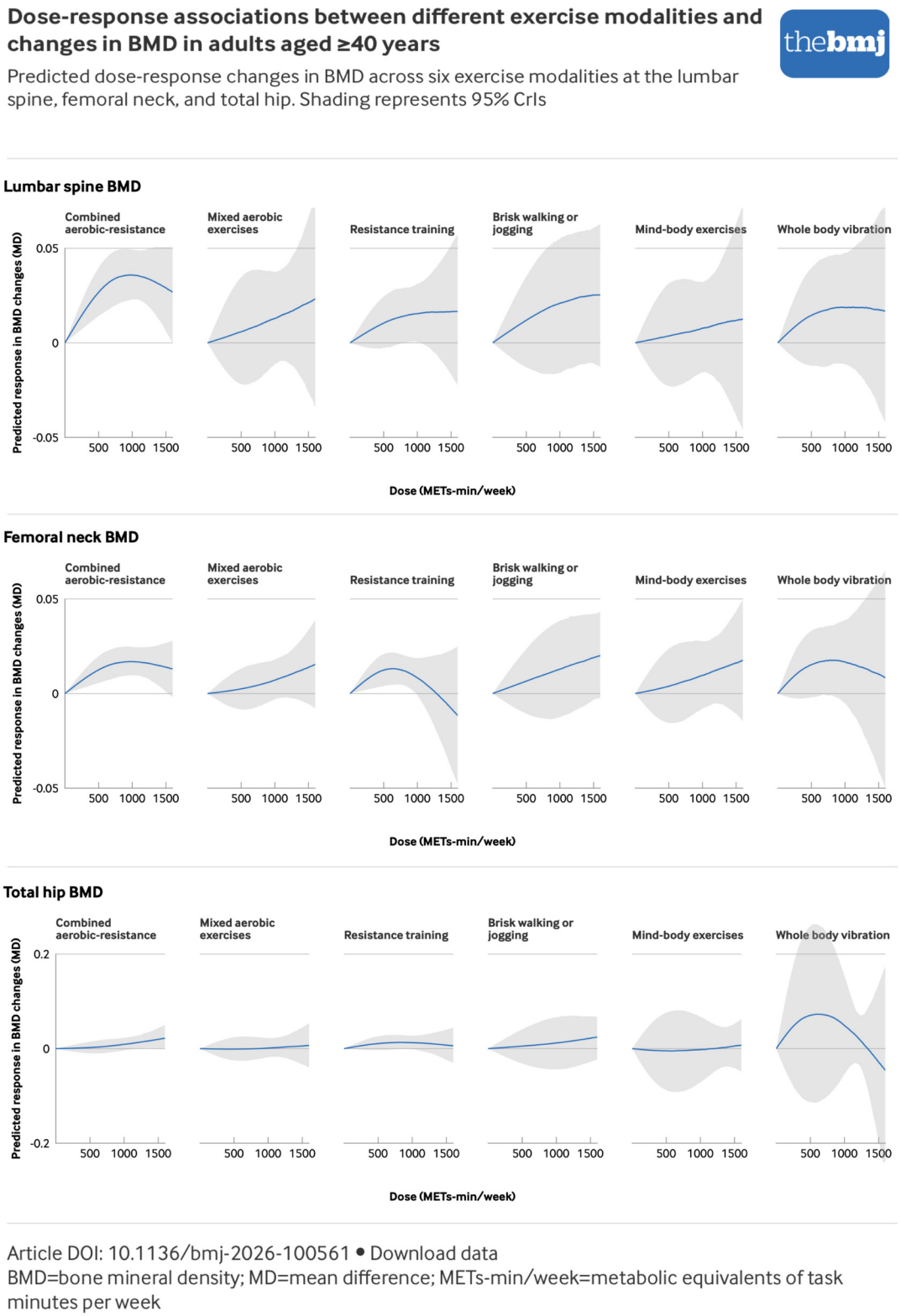

Fig 5 | Predicted dose-response changes in bone mineral density across six exercise modalities in adults aged ≥40 years. An interactive version of this figure is available at https://public.flourish.studio/visualisation/30030276/

Models incorporating age, sex, BMI, and vitamin D supplementation explained more variance (higher R^2) than those including exercise modality alone (see supplementary appendix file 9). Subgroup analyses indicated that although integrating age, sex, and BMI did not alter the shape of dose-response curves, it modified the magnitude of treatment effects. Notably, men more readily reached

the MCID thresholds for BMD improvements compared with women across all body sites (very low certainty evidence, see supplementary appendix file 10.1 and table 4). Similarly, middle aged (40-60 years) participants achieved these clinically meaningful thresholds more readily than older adults (>60 years) (very low certainty evidence, see supplementary appendix file 10.2 and table 4). Furthermore, participants with a normal baseline BMI were more likely to attain clinically important BMD benefits through exercise than those classified with overweight or obesity (very low certainty evidence, see supplementary appendix file 10.3 and table 4); weak evidence suggested that shorter interventions (ie, lumbar spine BMD at 26 weeks: mean difference 0.018 g/cm^2, 95% CrI 0.010 to 0.027) were marginally more effective than longer ones (ie, lumbar spine BMD at 52 weeks: 0.012 g/cm^2, 0.003 to 0.020), although wide credible intervals indicated substantial uncertainty (see supplementary appendix file 11). When age and intervention length were combined, exercise effects were more pronounced in middle aged adults than in older adults (see supplementary appendix file 12). The presence of comorbidities enhanced responsiveness to exercise (see supplementary appendix file 13), whereas vitamin D supplementation showed no statistically significant impact on outcomes (see supplementary appendix file 14).

Effects of all exercise types on fracture risk

A total of 26 randomised controlled trials involving 11 132 participants reported on fracture endpoints. Mixed aerobic exercise showed the greatest reduction in fracture risk (n=119, odds ratio 0.29, 95% CrI 0.11 to 0.78; low certainty evidence), followed by mind-body exercises (n=524, 0.58, 0.36 to 0.93; low certainty evidence) (fig 6). No statistically significant effects on fracture risk were observed for brisk walking or jogging (n=880, 0.68, 0.44 to 1.06; low certainty evidence), combined aerobic-resistance exercises (n=3407, 0.94, 0.79 to 1.13; low certainty evidence), and resistance training (n=820, 0.91, 0.53 to 1.57; low certainty evidence). Overall, brisk walking or jogging appeared to offer the most favourable balance between BMD benefits and fracture risk. Meanwhile, combined aerobic-resistance exercises, while highly ranked for BMD benefits, were less effective for overall fracture risk.

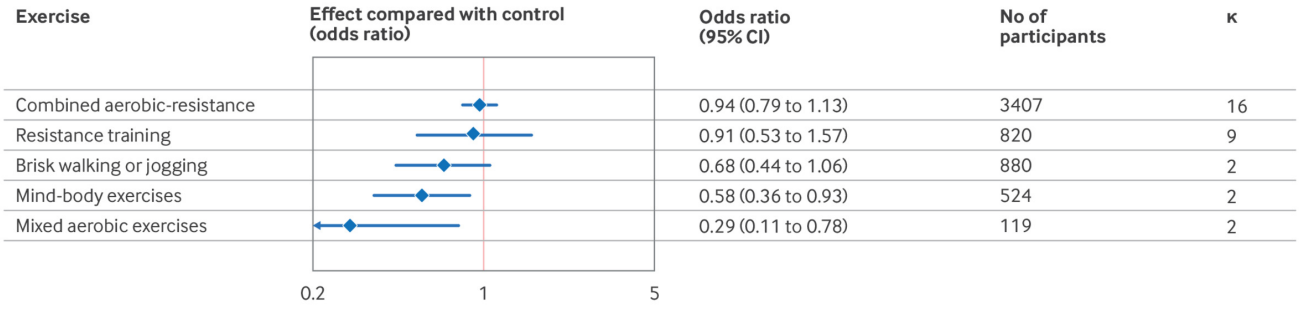

Fig 6 | Forest plots of predicted effects of different exercise modalities on fracture incidence in adults aged ≥40 years. CI=confidence interval

Risk of bias within studies

Supplementary file 15 provides the risk of bias ratings based on the Cochrane RoB 2.0 tool. Because masking of participants and staff is unfeasible in exercise trials, 73.4% of studies (91/124) were judged to have some concerns or a high risk of performance bias. Overall, 28 trials (22.6%) were rated as low risk, 59 (47.6%) as some concerns, and 37 (29.8%) as high risk. Sensitivity analyses showed that estimates for BMD of the lumbar spine, femoral neck, and total hip remained stable when stratified by randomisation and attrition bias criteria (see supplementary appendix file 16). Multilevel Egger's test showed significance in the lumbar spine and total hip (see supplementary appendix file 18; lumbar spine: F1,108=9.10, P=0.003; femoral neck: F1,98=3.71, P=0.057; total hip: F1,55=4.81, P=0.033), indicating funnel plot asymmetry. This asymmetry is likely driven by small study effects, whereby trials with smaller sample sizes reported unusually large effect sizes. However, the pooled effect estimates remained statistically robust even after accounting for this bias, suggesting that potential publication bias did not alter our primary conclusions.

Credibility assessment

Overall confidence in the network estimates, assessed using the CINeMA framework, ranged from moderate to very low (see supplementary appendix file 17). Downgrading was predominantly driven by high within study bias. Reporting bias was also difficult to robustly assess because direct comparisons for specific nodes often contained too few studies, leading to some concerns. Concerns about indirectness were generally minor. However, imprecision and heterogeneity led to further downgrading for certain comparisons, as the CrIs crossed the predefined zone of clinical equivalence.

Incoherence was minimal across the network, meaning direct and indirect evidence usually agreed. Ultimately, confidence in the effects of highly ranked modalities (eg, brisk walking or jogging) was low to moderate, with evidence for several other interventions graded as very low.

Discussion

In this hierarchical bayesian network meta-analysis of 124 randomised trials involving nearly 18 429 middle aged (40-60 years) and older (>60 years) adults, we found that structured exercise was associated with a modest yet clinically meaningful mitigation of age related declines in BMD at the lumbar spine, femoral neck, and total hip. Brisk walking or jogging and combined aerobic-resistance exercises appeared to be among the most beneficial interventions for improving BMD. Concurrently, mind-body and mixed aerobic exercises were associated with a potential reduction in fracture risk. Crucially, multivariable dose-response analyses suggested that clinically important gains in BMD are generally achieved at around 600 METs-min/week—translating to roughly 2-3 hours of brisk walking or jogging, with benefits plateauing near 900-1000 METs-min/week.

Comparison with other studies

Our findings extend the existing literature in several ways. Previous meta-analyses have predominantly relied on pairwise comparisons of single modalities versus non-exercise control, or they have

focused on specific interventions such as resistance training, whole body vibration, or mind-body exercise within selected demographic subsets, particularly postmenopausal women.[13-16] While a previous network meta-analysis indicated the potential of mind-body exercise in populations with osteopenia, it neither quantified dose-response relations nor systematically explored demographic effect modifiers.[18] By harmonising 124 trials across six exercise modalities using METs-min/week, our analysis establishes a unified framework. This approach shifts the paradigm from the binary inquiry of whether "exercise works" to more precise, clinically actionable questions.

Synthesis of direct and indirect evidence revealed that brisk walking or jogging and combined aerobic-resistance exercises yielded the most substantial improvements in weightbearing skeletal regions (lumbar spine, femoral neck, and total hip), showing broadly comparable efficacy. This somewhat contrasts with earlier prevailing views that heavily prioritised high impact or high intensity resistance training.[29] While the latter is physiologically highly osteogenic, safety and feasibility concerns often prompt the prescription of low to moderate loads in older adults, which frequently fail to breach the necessary osteogenic threshold.[12] In contrast, brisk walking or jogging inherently guarantee a repetitive, moderate impact load generating ground reaction force of 1.5 to 2.0 times bodyweight, that robustly stimulates the osteocyte mechanotransduction network—the interconnected bone cell system that converts physical strain into bone regulating biochemical signals—through high frequency dynamic strain.[30] This biomechanical distinction explains why moderate intensity, weightbearing activities such as brisk walking or jogging may have been underappreciated when previously grouped within broad impact exercise categories. By analysing brisk walking or jogging as distinct entities rather than subsuming them into a generic impact exercise category, we highlighted their robust skeletal benefits, which are complemented by high accessibility and patient adherence. Importantly, the absence of associated fracture risks supports their integration as foundational components of bone health regimens.

Our dose-response analyses provide critical quantitative insight into how much exercise might be needed to achieve clinically meaningful BMD benefits. When pooling all exercise modalities by METs, we identified non-linear, largely inverted U-shaped associations between weekly exercise dose and BMD changes, characterised by gains plateauing and occasionally declining at the highest volumes. Modality specific analyses showed similar patterns, albeit with different dose thresholds. It is plausible that the observed attenuation at higher volumes (femoral neck and total hip) partially reflects declining adherence in intensive trial arms. Additionally, given the scarcity of trials investigating these extreme high doses, this apparent decline may also be a statistical artefact driven by random variation rather than a true biological decrement. Across the network, MCIDs for lumbar spine, femoral neck, and total hip BMD were typically reached at around 600 METs-min/week, while optimal gains clustered near 900-1000 METs-min/week. For brisk walking or jogging, MCID level benefits were achieved at moderate weekly volumes compatible with 2-3 hours, whereas resistance training and whole body vibration generally required higher doses to achieve comparable effects. These findings are consistent with mechanostat theory, which posits that bone responds to mechanical loading only when strain magnitude,[31] rate, and frequency exceed a critical threshold,[32] and with the known site and mode specific effects of resistance versus impact or weightbearing activities.[33]

When evaluating the clinical significance of our dose-response curves, we avoided adopting an arbitrary, uniform threshold. Given the dynamic nature of age related bone loss, we instead established site specific MCIDs with lower and upper limits defined as 1% and 2% of the pooled baseline BMD, respectively. This approach aligns with the American College of Sports Medicine consensus,[11] which identifies a 1-2% net BMD benefit as the physiological ceiling for exercise adaptations in adults and precisely mirrors the expected annual rate of bone loss in this population.[27] Therefore, achieving these seemingly small MCID thresholds is far from negligible; rather, it signifies the maximal expected physiological success of an intervention effectively offsetting a full year of skeletal deterioration. Utilising this benchmark allowed us to pragmatically differentiate exercise modalities that offer genuine therapeutic utility from those yielding merely statistically significant, yet clinically trivial, effects. Notably, in our category specific dose-response analyses, individual exercise modalities rarely achieved the upper MCID limit (2%). However, this does not indicate a lack of meaningful clinical efficacy for single exercise types. Against the backdrop of continuous age related skeletal decline, achieving even the lower MCID limit (1%) signifies a substantial physiological success, as it effectively offsets a full year of natural bone deterioration.[11]

We also observed substantial heterogeneity in exercise responsiveness across participant subgroups. Exercise yielded more pronounced BMD effects in middle aged individuals and those with a healthy BMI, whereas responses were blunted in older adults and those with overweight or obesity. In the latter cohorts, higher exercise doses were typically required to reach MCID thresholds. This rightward shift in dose-response curves corroborates experimental evidence indicating an age related decline in bone mechanosensitivity.[34-38] This is also consistent with American College of Sports Medicine consensus that structural adaptations to mechanical loading in mature skeletons are inherently limited.[11] Clinically, these data caution against one-size-fits-all prescriptions and advocate for progressive loading exercise volume or intensity in older patients and those with higher bodyweight to achieve comparable skeletal strengthening benefits to those seen in other patient groups. The duration of intervention also influenced treatment efficacy. While continuous training lasting at least 12 weeks elicited detectable BMD improvements, these benefits exhibited a modest attenuation beyond three to 12 months despite adequate adherence. This temporal trajectory corresponds with the three to four month bone remodelling cycle and supports the concept of skeletal desensitisation to monotonous, unvarying mechanical loads.[39,40] Consequently, long term skeletal adaptation likely necessitates periodised training—systematically varying intensity, modality, and loading patterns—although rigorous trial data confirming specific periodisation protocols remain sparse. Our findings also underscore the need for future trials to explicitly evaluate the effects of different training structures and to include longer follow-up to determine whether early BMD gains can be maintained or augmented.

Fear of fracture or injury is a major barrier to exercise participation among individuals with low BMD or previous fractures. Our analyses offer clinical reassurance: no exercise modality was associated with increased fracture incidence, and appropriately supervised regimens proved safe. Although signals suggested a potential fracture reduction with mind-body and mixed aerobic exercises, these secondary outcomes are based on a relatively small, methodologically heterogeneous subset of trials, leading to substantial uncertainty and limited robustness of comparative inferences. Therefore, while exercise is evidently safe, claims regarding its direct efficacy in preventing incident fractures must be interpreted with caution and necessitate confirmation through

rigorously designed, adequately powered trials with standardised hard endpoints.

Strengths and limitations of this study

Ultimately, our study bridges a critical gap in physical activity guidelines, which currently provide broad volume targets but lack modality specific osteogenic prescriptions. By combining hierarchical bayesian network meta-analysis with multivariable dose-response modelling, our work provides empirically derived estimates of the exercise doses at which BMD benefits become clinically meaningful, how these thresholds vary across exercise types and patient subgroups, and the approximate upper bounds beyond which additional volume yields diminishing returns. These results can be used to move from generic advice (do weightbearing and resistance exercise) towards more precise prescriptions (aim for around 600 METs-min/week, equivalent to 2-3 hours of brisk walking or jogging, with higher volumes or added resistance training for older adults or those with overweight or obesity). It is imperative, however, that exercise remains one pillar of a comprehensive osteoporosis management strategy, complementing pharmacotherapy, nutritional support, and fall prevention measures.

This study has several limitations. Firstly, the assumption of clinical transitivity is inherently prone to marked trial level variations in baseline BMD, supervision protocols, and participant adherence. Grouping heterogeneous interventions into broader composite intervention categories within our network meta-analysis risks exposure misclassification, which could attenuate the validity of indirect estimates. Secondly, utilising METs-min/week to harmonise exercise doses introduces a biological caveat. While a MET robustly capture metabolic expenditure, it does not perfectly index peak mechanical strain or loading rates, which are the true drivers of osteogenesis. Therefore, the estimated dose thresholds for achieving MCID should be strictly interpreted as exercise modality derived approximations to facilitate public health translation (aligning with WHO guidelines), rather than definitive mechanical or clinical cut-offs. Thirdly, estimating true exercise dose assumes a true zero baseline in control groups, whereas inevitable incidental physical activity (contamination) likely attenuates observed effect sizes. Fourthly, evidence of small study effects and potential publication bias was detected, particularly for BMD outcomes. Notably, several small trials evaluating brisk walking or jogging reported outsized effect estimates. Despite strong physiological plausibility, these specific estimates may be inflated and should be interpreted judiciously. Finally, because formal statistical interaction analyses were not conducted, the observed trends across age, sex, and BMI subgroups should be interpreted with caution. This limitation is further compounded by the noticeable underrepresentation of men in the included trials, which restricts the generalisability of our findings across sexes and highlights an urgent need for adequately powered, sex balanced osteogenic exercise trials in older adults. These limitations should be considered when interpreting our results and translating them into clinical practice.

Policy implications

Our findings support incorporating modality specific targets into clinical practice guidelines for bone health. Recommending a baseline of 600 METs-min/week, roughly 2-3 hours of brisk walking or jogging, provides a feasible, low cost strategy for health systems, particularly in resource constrained settings. When possible, ideal management should involve individualised care. Exercise professionals could take responsibility for progressive loading doses in older patients or those with overweight, who may require stronger stimuli to overcome blunted sensitivity to mechanical stimuli. Health services should promote exercise as a safe adjunct within comprehensive osteoporosis management, alongside pharmacotherapy, nutritional support, and fall prevention measures.

Conclusions

This hierarchical bayesian network meta-analysis of randomised trials supports the prescription of structured exercise to preserve bone health in ageing adults. However, considering the varying certainty of evidence (ranging from very low to moderate), these findings offer several cautious implications for clinical practice. Firstly, based on low to moderate certainty quality evidence, brisk walking or jogging and combined aerobic-resistance exercises probably provide the greatest BMD benefits. Secondly, a minimum of about 600 METs-min/week is generally required for clinically meaningful benefits. This is achievable with about 2-3 hours of brisk walking or jogging, representing a highly accessible target. Finally, exercise prescriptions need to be tailored and periodised, as age and increased adiposity may blunt skeletal sensitivity to mechanical stimuli, and older adults with overweight or obesity may typically require higher doses to achieve similar effects. Ultimately, moving beyond a one-size-fits-all approach towards a precision strategy is essential for optimising the skeletal benefits of exercise.

What is already known on this topic

Clinical guidelines consistently endorse multimodal treatment approaches, including exercise, drug, and dietary interventions, for managing osteoporosis in ageing adults

Clinical decision making for exercise prescription currently relies heavily on expert opinion and empirical experience

What this study adds

In this network meta-analysis of 124 trials, brisk walking or jogging appeared to yield improvements in bone mineral density (BMD) comparable to combined aerobic-resistance exercises, offering highly accessible intervention options for ageing populations

Clinically meaningful BMD gains were generally observed at a threshold of 600 METs-min/week (2-3 hours of brisk walking), suggesting that extremely high intensity regimens may not be strictly necessary

Mixed aerobic and mind body exercises were associated with a reduced risk of incident fractures, supporting the safety and broader functional value for aging populations

Contributors: XY, ZL, and NB, as the senior authors of this study, provided study leadership and academic oversight, contributed to the overall study conception and methodological framework, interpreted the findings, and critically revised the manuscript for important intellectual content. CL, LL, and LZ performed the data analysis, drafted the initial manuscript, and revised the manuscript. QG, JM, and YX provided clinical expertise. HJ, TY, and HQ conducted the literature search, performed data extraction, and contributed to data interpretation. All authors gave crucial feedback on the revised report and approved the final version of the manuscript. XY is the corresponding author and ZL (zhiwen.luo_fudan@hotmail.com) is the guarantor. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

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Competing interests: All authors have completed the ICMJE uniform disclosure form at www.icmje.org/disclosure-of-interest/ and declare: support from the National Natural Science Foundation of China; no financial relationships with any organisations that might have an interest in the submitted work in the previous three years; no other relationships or activities that could appear to have influenced the submitted work.

Transparency: The lead author (XY) affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned and registered have been explained.

Dissemination to participants and related patient and public communities: We plan to disseminate the findings of this research to diverse audiences to maximise its clinical and public health impact. For the academic and clinical communities, the results will be presented at national and international academic conferences (through oral and poster presentations) and incorporated into educational teaching sessions

for medical and allied health students. We will also share our findings with relevant policymakers and clinical guideline committees to inform future practice. Furthermore, we will widely share our findings across diverse social media and short video platforms (such as TikTok, X, and WeChat).

Provenance and peer review: Not commissioned; externally peer reviewed.

Ethical approval: Not required.

Data sharing: The analytical codes used to analyse the data in the paper, anonymised data underlying the findings, along with sufficient annotations and instructions, are in the supplemental files or on GitHub (https://github.com/xiaojiangyang/bmd_data_analysis).

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Supplementary information: Appendix files 1-19