

1                   **Sedentary behaviour and bone health in older adults: a systematic review**

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22 **Declarations**

23 **Conflict of Interest**

24 Dawn A. Skelton is a Director of a not for profit training company, Later Life Training,  
25 which provides training to health and leisure professionals to deliver strength and balance  
26 training.

27 Lauren McMichan, Michael Dick, Sebastien F.M. Chastin, Neville Owen, David W. Dunstan,  
28 William D. Fraser, Jonathan C.Y. Tang, Carolyn A. Greig, Sandra Agyapong-Badu,  
29 Alexandra Mavroeidi declare no conflict of interests.

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44 **Abstract:**

45 Purpose:

46 Older adults spend more than 8 hours/day in sedentary behaviours. Detrimental effects of  
47 sedentary behaviour (SB) on health are established, yet little is known about SB and bone  
48 health (bone mineral density; BMD) in older adults. The purpose of this review is to examine  
49 associations of SB with BMD in older adults.

50 Methods:

51 Five electronic databases were searched: Web of Science (Core Collection); PubMed;  
52 EMBASE; Sports Medicine and Education; and PsycInfo. Inclusion criteria were: healthy  
53 older adults mean age  $\geq 65$  years; measured SB; measured BMD using dual-energy X-ray  
54 absorptiometry. Quality was assessed using National Institute of Health Quality Assessment  
55 Tool for Observational Cohort and Cross-Sectional Studies.

56 Results:

57 After excluding duplicates 17,813 papers were assessed; 17,757 were excluded on  
58 title/abstract, 49 at full text, resulting in two prospective and five cross-sectional  
59 observational studies reviewed. Four were rated 'good' and three were rated 'fair' using the  
60 quality assessment criteria. Findings varied across the studies and differed by gender. In  
61 women, four studies reported significant positive associations of SB with BMD at different  
62 sites, and two found significant negative associations. Five studies which examined both men  
63 and women, men reported negative or no associations of SB with femoral neck, pelvic, whole  
64 body, spine or leg BMD.

65 Conclusion:

66 While these findings suggest differences between men and women in the associations of SB  
67 with BMD, they may be due to the varying anatomical sections examined for BMD, the  
68 different methods used to measure SB, the varied quality of the studies included and the  
69 limited number of published findings.

70

71 **Keywords:**

72 Sedentary behaviour, older adults, bone health, bone mineral density

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76 **Abbreviations:**

77 BMD = Bone Mineral Density

78 DXA = Dual-X-Ray Absorptiometry

79 FN = Femoral Neck

80 LPA = Light Physical Activity

81 LS = Lumbar Spine

82 MVPA = Moderate-to-Vigorous Physical Activity

83 PA = Physical Activity

84 SB = Sedentary Behaviour

85 ST = Sedentary Time

86 TB = Total Body

87 TF = Total Femur

88 TH = Total Hip

89 TS = Total Spine

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## 100           **Introduction**

101           Sedentary behaviour (SB) can be defined as “any waking activity characterized by an  
102 energy expenditure  $\leq$  1.5 metabolic equivalents (METs), while in a sitting, reclining or lying  
103 posture” [1]. High volumes of SB can be detrimental to health, particularly in people who do  
104 not undertake sufficient amounts of moderate-vigorous physical activity (MVPA) [2, 3].  
105 Adverse health consequences include higher risk of cardiovascular disease [4], diabetes  
106 mellitus [5], and reduced cognitive function [6]. SB encompasses many behaviours  
107 performed routinely throughout the day, for example, sitting at a chair/sofa, driving to and  
108 from places, and watching television [7]. Older adults (aged 65+ years) can accumulate  $>$  8  
109 hours of time spent in SB daily [8, 9], with an average being 9.4 hours/day [10].

110           The beneficial effects of daily weight bearing physical activities on bone health are  
111 well established [11]. Aging is a natural process, within which bone mass deterioration  
112 occurs, including changes to the structure and composition [12] of bone tissue. Although  
113 some bone loss is typical of the aging process, osteoporosis is not an inevitable disease of the  
114 old, with many risk factors for osteoporosis and osteoporotic fracture being modifiable [13];  
115 low levels of PA have long been recognised as such a risk factor. A published consensus  
116 statement on Exercise and Osteoporosis recommends meeting the PA guidelines  
117 (accumulation of 150 mins/week of moderate PA) for health and reducing prolonged SB  
118 alongside more specific recommendations for exercise (resistance training and impact) [14].  
119 There is a high prevalence of fractures in those over the age of 50 years, with one in two  
120 women and one in five men fracturing a bone [15]. It is estimated that 500,000 fragility  
121 fractures occur in the United Kingdom every year [16], with hospital costs of hip fractures  
122 alone estimated at £1.1 billion [17].

123 Mechanical forces (through gravitation or muscular loading) are essential for the  
124 maintenance of bone health, therefore reducing these forces can have a detrimental effect  
125 [18]. Space flight and bed rest studies have shown that reducing mechanical forces leads to  
126 substantial reductions in bone strength [19]. Although the space-flight and bed-rest evidence  
127 is from extreme and unusual circumstances, SB also involves the reduction of mechanical  
128 forces, and could have a detrimental effect of bone health. A recent systematic review  
129 explored the effects of SB on bone health in children, adolescents and young adults [20]. The  
130 review yielded 17 studies. It was reported that there was a moderately negative association  
131 between SB and bone health in the lower extremities. It was also reported that one less hour  
132 of sedentary time mimics the positive effect of 18 minutes of MVPA in femoral neck bone  
133 mineral density (BMD); however, this finding was weighted heavily on one strong  
134 longitudinal study in boys [21].

135 Gender also appears to play an important role on bone quality, with men exhibiting up  
136 to 20% higher BMD compared to women [22]. This was evident in a study which analysed  
137 data from the National Health and Nutrition Examination Study where negative associations  
138 between SB and hip BMD in adult women, but not men, were identified [23].

139 Despite the emerging evidence on the potential detrimental influence that SB may  
140 have on skeletal health in younger populations, little is known about the associations of SB  
141 and bone health (specifically, BMD) in older adults. Therefore, the purpose of this study was  
142 to systematically review the evidence on associations of SB with BMD (total and site-  
143 specific) in older adults.

144

## 145 **Methods**

### 146 Protocol and Registration

147 The protocol for this systematic review was registered on Prospero  
148 [CRD42019138999] in June 2019. The review was modelled using the PRISMA guidelines  
149 [24, 25].

150

### 151 Eligibility Criteria

152 Studies which explored the associations of SB on BMD in healthy older adults (mean  
153 age  $\geq$  65 years old) were included in the review. Other inclusion criteria were studies which  
154 measured SB, and measured BMD using Dual-Energy X-ray Absorptiometry (DXA). Studies  
155 were peer reviewed, and in the English language.

156

### 157 Information Sources

158 Five electronic databases were searched: Web of Science (Core Collection), PubMed,  
159 EMBASE, Sports Medicine and Education, and PsycInfo. The search strategy was originally  
160 conducted in March 2019. The search strategy was then repeated using additional search  
161 terms to broaden the search results. This was conducted in June 2019.

162

### 163 Search

164 The search strategy used for the databases is shown in Table 1. Note adaptations to  
165 truncations and limiting factors were made based on the individual databases.

166

167 **Table 1** Search Strategy

Population	(Adult* OR "Older Adult*" OR Elderly OR Geriatric OR Ageing OR Aged)
Search Operator	AND
Outcome	(Bone OR "Bone Health" OR "Bone Mineral Density" OR "Bone Mineral" OR "Bone Mass" OR "Bone Fracture*" OR "Bone Strength" OR Osteoporosis OR "Bone Mineral Content")
Search Operator	AND
Exposure	(Sedentar* OR "sedentary behavior" OR "Sedentary Behaviour" OR "Sedentary Time" OR "Sitting Time" OR Sitting OR "screen time" OR "television viewing" OR inactiv* OR "activity restriction" OR "Computer use" OR "stationary behaviour" OR "stationary behavior" OR lying OR reclining OR "non-screen based behaviour" OR "non-screen based behavior")
Limits	English only. Humans only.

168

169 Study Selection

170 Articles retrieved from the search strategy were imported into EndNote Reference

171 Manager, version X8.2 (Thomson Reuters, Philadelphia, PA) and duplicates were removed.



172 Articles were then exported to a Microsoft Excel, version 2016 (Microsoft Corp, Redmond,  
173 WA) spreadsheet where titles were screened. Articles included based on title screening were  
174 reviewed at abstract level, and then reviewed as full text. We also reviewed the bibliography  
175 of full text papers to identify any additional related papers. All articles were reviewed by the  
176 first author (LM) and a sample (10%) was double checked by another reviewer (AM) as per  
177 PROPSERO protocol. Any articles where there was uncertainty at abstract and full text level  
178 were also checked by the senior author (AM). If there were any discrepancies, a discussion  
179 between the two authors was conducted until an agreement was reached. Exclusion of  
180 articles were based on criteria and were excluded if they did not assess SB and BMD in older  
181 adults (mean age  $\geq 65$  years). Studies which included multiple age ranges but performed a  
182 sub-analysis on older adults were included in the review.

183

#### 184 Data Collection Process and Data Items

185 Data were extracted and imported into a standardised Microsoft Word, version 2016  
186 (Microsoft Corp, Redmond, WA) table. Data extracted were: author(s)/year of publication;  
187 study design; sample size; gender; age range; SB measurement method and outcomes; BMD  
188 measurement methods and outcomes; overall results. Where pivotal data was missing we  
189 aimed to contact the authors and request such data.

190

#### 191 Quality Assessment

192 Quality of studies included in the review was assessed using the ‘Quality Assessment  
193 Tool for Observational Cohort and Cross-Sectional Studies [26]. The tool consists of a 14-  
194 item checklist: clearly stated research question; specific study population; rate of  
195 participation of eligible persons; subject selection process; justification of sample size;

196 exposure measured prior to outcome(s); suitable timeframe between exposure and outcome;  
197 levels of exposure; exposure measures clearly defined; exposure(s) assessed more than once  
198 over time; outcome measures defined valid, reliable and consistent; blinding of outcome  
199 assessors; loss to follow-up; and, adjustment for key confounders. Studies were then awarded  
200 a rating of good, fair or poor. Quality was assessed by the first and last authors (LM/AM) to  
201 ensure agreement. It should be noted that one of the co-authors (SFMC) was the co-author of  
202 3 of the included studies.

203

#### 204 Summary of Measures

205 Primary exposure measures were SB (self-reported by questionnaire or objectively  
206 measured) and BMD measures were the outcomes. Studies included objective and subjective  
207 methods of assessing SB. The anatomical sites that were evaluated were grouped into three  
208 separate categories; lower extremities (including the femoral neck (FN), total femur (TF),  
209 hip, legs), trunk (including ribs, lumbar spine (LS)) and total body (TB). Markers of bone  
210 health were measured using DXA in all included studies since comparison of bone health is  
211 not possible if different assessments methods are used.

212

### 213 **Results**

#### 214 Study Selection

215 The initial search strategy yielded 19,194 potentially relevant studies (Figure 1.).  
216 Following deduplication, this number was reduced to 17,813. Seventeen thousand seven  
217 hundred fifty seven articles were excluded based on title and abstract. Forty-nine articles  
218 were excluded at full text (see supplementary material for complete list of excluded studies),

219 leaving seven included for review [23, 27-32]. One of those studies (Chastin et al [23]) did  
 220 not present data for the over 65s separately in their published manuscript. However, as SFMC  
 221 is a co-author in the current review, he was able to repeat the main paper analysis from the  
 222 NHANES database refining it to those aged over 65 years; this sub analysis was included in  
 223 the current review.

224

225 Study Characteristics

226 Five studies were cross-sectional [23, 27, 29-32] and two were longitudinal [28, 29].  
 227 Sample size ranged from 112 [30] to 1134 [29] participants. Two studies included women  
 228 only [27, 29]. Mean age of participants ranged from  $64.5 \pm 7.2$  years [28] to  $76.9 \pm 5.3$  years  
 229 (men) and  $76.7 \pm 4.7$  years (women) [31]. A full summary of study characteristics and results  
 230 are shown in Table 2. Four studies were rated good [23, 28-30] for quality, whilst three were  
 231 rated fair [27, 31, 32].

232

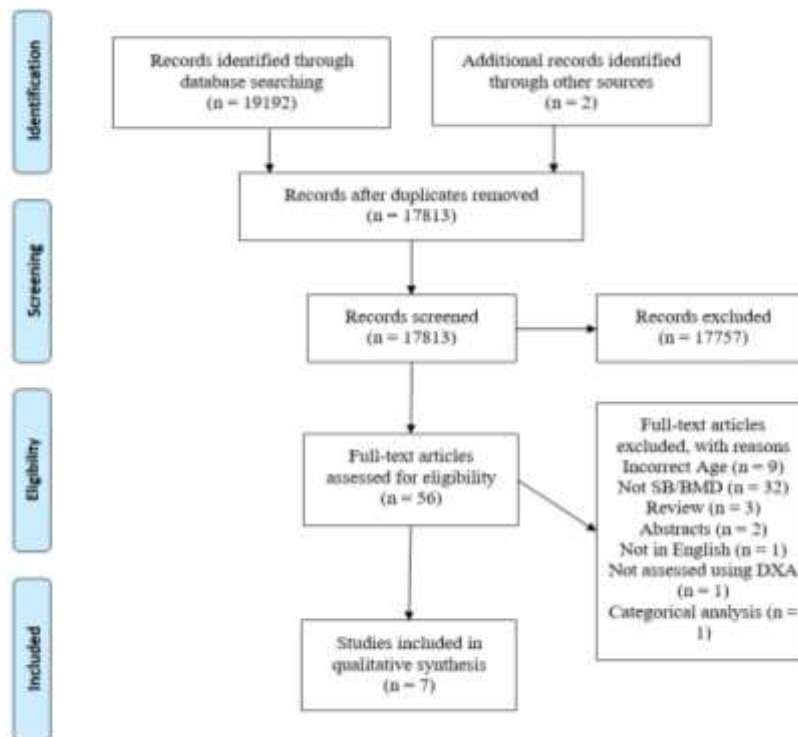


Fig 1 PRISMA diagram [25] of the screening process

233

234 Measurement of BMD and SB

235 All studies measured BMD using DXA. Six studies used Hologic models [23, 27, 28, 30-32],  
236 whilst one used a Lunar model [29]. Measures of SB differed between studies. Two studies  
237 used questionnaires to assess SB [27, 29]. The questionnaires asked how many hours per day  
238 participants were sedentary. Five studies assessed SB using objective measures  
239 (accelerometry) [23, 28, 30-32]. Two studies [31, 32] used ActiTrainer/ActiGraph wGT3X-  
240 BT, two used ActiGraph GT1M [23, 28], and one used GENEActiv Action  
241 [30]. Accelerometer placement was different between studies, with the majority of the studies  
242 [23, 31, 32] using hip mounted accelerometers and one study [30] using a leg mounted  
243 accelerometer. All studies asked participants to wear their accelerometers for 6-7 consecutive  
244 days but some participants had to remove their accelerometer during waking hours when  
245 engaging in water based activities [23, 31, 32]. Every study had its own unique wear-time  
246 protocol. For example, data were excluded from the analysis if participants did not wear  
247 device for at least 5 days and wore the device for less than 10 hours per day [23, 28] but these  
248 criteria were different for the studies by Rodrigues- Gomez et al who included only results  
249 with at least 4 valid days that included at least 8h/day of wear time [31, 32].

250

251 Total Body BMD

252 Four studies measured total BMD [28, 30-32]. McMillan et al [28] found no significant  
253 associations over time between SB and total BMD in either men or women, using prospective  
254 linear regression analyses.

255 Rodriguez-Gomez et al [31] reported a borderline significant positive association  
256 between SB and total body BMD when both genders were analysed together. There were

257 gender differences when analyses were separated. There were no significant associations  
258 between SB and total body BMD for men. For women, significant positive associations were  
259 found between SB and total body BMD ( $\gamma = 0.022$ ;  $p = 0.00$ ). Gender differences were also  
260 reported in Rodriguez-Gomez et al [32] who found a significantly negative association  
261 between SB and total body BMD ( $\gamma = -0.015$ ;  $p = 0.041$ ) in robust healthy men, but reported  
262 significant positive associations between SB and total body BMD ( $\gamma = 0.020$ ;  $p = 0.003$ ) in  
263 robust healthy women. It is important to note that the two Rodriguez-Gomez [31, 32]  
264 analyses are based on the same cohort and models from both studies were adjusted for age,  
265 gender, BMI, fat and lean mass, alcohol, smoking, nutrition, calcium, education, level of  
266 income, marital status, frailty, arthritis, and thyroid disease.

267 Onambele-Pearson et al [30] also found differences between men and women. For  
268 daily SB, there were no significant associations with total BMD for men, whilst there was a  
269 significant positive association ( $r = 0.317$ ,  $p < 0.01$ ) for women. However, when analyses  
270 were adjusted (age, total fat mass, general anthropometry) this was non-significant.

271 Onambele-Pearson et al [30] also explored the association between SB bouts and BMD.  
272 Whilst breaks in SB did not have a significant impact on total BMD in women, there was a  
273 positive association in men ( $r = 0.330$ ,  $p < 0.01$ ). There was also positive association in men  
274 when SB bouts were  $\geq 5$  mins ( $r = 0.373$ ,  $p < 0.01$ ).

275

#### 276 Lower Extremities

277 In a prospective study, Nguyen et al [29] reported that, over time, sedentary lifestyle  
278 significantly reduced BMD in the femoral neck (FN) ( $-1.5 \pm 0.2\%$ ,  $p < 0.001$ ) in women.  
279 Adjusted analyses (accounting for age, PA, baseline weight, weight change over time and  
280 baseline BMD) also suggested a significant reduction in femoral neck BMD ( $-1.35 \pm 0.8\%$ ,  $p$

281 < 0.05). The other longitudinal study included in the review (McMillan et al [28]) also  
282 conducted analyses separately by gender. Their adjusted (model 2) prospective multivariate  
283 linear regression analyses, showed a significantly positive association between SB and total  
284 hip BMD ( $\beta = 0.199$ ,  $p = 0.046$ ) in women. For adjusted (model 2) prospective multivariate  
285 linear regression analyses in men, there were significantly negative associations between SB  
286 and femoral neck BMD ( $\beta = -0.232$ ,  $p = 0.047$ ). Model 2 analyses were adjusted for age,  
287 height, lean mass and smoking.

288 Onambele-Pearson et al [30] reported no significant associations for daily SB for men  
289 and BMD ; in women, there were significant positive associations between daily SB and  
290 lower limb BMD ( $r = 0.272$ ,  $r_{adj}^n = 0.260$ ,  $p < 0.05$ ). Similar findings were reported for breaks  
291 in SB ( $r = 0.299$ ,  $r_{adj}^n = \text{non-significant}$ ,  $p < 0.05$ ), and for bouts of SB < 5 mins ( $r = 0.334$ ,  
292  $r_{adj}^n = \text{non-significant}$ ,  $p < 0.01$ ). There was also a positive association between breaks in SB  
293 and pelvic BMD in women only ( $r = 0.232$ ,  $r_{adj}^n = \text{non-significant}$ ,  $p < 0.05$ ).

294 Braun et al [27] reported a negative association in older women between ST and  
295 femoral BMD ( $b$  (SE) =  $-0.0028$  (0.0001);  $p = 0.027$ ). These analyses were adjusted for  
296 race/ethnicity, milk consumption or supplement use, BMI, smoking, osteoporosis history,  
297 prednisone or cortisone use, and menopausal status.

298 Rodriguez-Gomez et al [31] reported significant positive associations between SB and  
299 leg leg BMD ( $\gamma = 0.028$ ,  $p = 0.00$ ). There were no significant associations reported for any  
300 femoral region assessed. When men and women were examined separately, there were no  
301 associations between SB and leg/femoral region BMD in men. In women, there were  
302 significantly positive associations for leg BMD ( $\gamma = 0.063$ ,  $p = 0.00$ ), but no associations for  
303 femoral regions. In the pelvic region, a significant negative association was reported between  
304 SB and BMD ( $\gamma = -0.027$ ,  $p = 0.05$ ) in men only.

305           Rodriguez-Gomez et al [32] reported significant positive associations between SB and  
306 leg BMD ( $\gamma = 0.035$ ,  $p = 0.000$ ) in robust (those who do not exhibit any of the frailty criteria  
307 set out by Fried et al [33]) older adults. No associations were reported for femoral neck.  
308 When analyses were conducted separately for men and women, men were found to have  
309 negative associations for leg BMD ( $\gamma = -0.018$ ,  $p = 0.036$ ). However, in women there were  
310 positive associations between SB and leg BMD ( $\gamma = 0.066$ ,  $p = 0.000$ ). No associations were  
311 reported for femoral neck in either gender.

### 312           Trunk

313           Only two studies reported significant associations between SB and areas of the trunk  
314 [23, 30]. In women, Onambele-Pearson et al [30] reported significant positive association  
315 between daily SB and spine BMD ( $r = 0.233$ ,  $p < 0.05$ ), although this was non-significant  
316 when adjusted for confounders. There were significant positive associations between SB  
317 breaks and SB bouts of  $< 5$  minutes, and BMD of the ribs ( $r = 0.266$ ,  $p < 0.05$ ;  $r = 0.328$ ,  $p <$   
318  $0.01$ , respectively). The association between breaks in SB and BMD were non-significant  
319 when adjusted for confounders. There was a negative association between W50% min  
320 (defined as “the bout duration below which half of all sedentary time is accrued” [30]) and rib  
321 BMD ( $r = -0.224$ ,  $p < 0.05$ ; non-significant after adjusting). For men, breaks in SB and SB  
322 bouts  $\geq 5$  minutes were positively associated with rib BMD ( $r = 0.282$ ,  $p < 0.05$ ;  $r = 0.349$ ,  $p <$   
323  $0.01$ , respectively).

324           A significant negative association with sedentary time (ST – total duration of daily SB  
325 bouts) and spine BMD with ( $p = 0.05$ ) and a significant positive association between  
326 fragmented ST and spine BMD ( $p = 0.05$ ) were reported for the unpublished sub-analysis of  
327 the NHANES data by Chastin et al [23], yet there were non-significant differences between

328 women and men. Analyses were adjusted for age, BMI, ethnicity, parathyroid hormones,  
329 smoking, alcohol (men only) and prednisone use (women only). (Table 2).

330

### 331 Quality Assessment

332 Of the seven studies included in the review, four were rated good [23, 28-30] and  
333 three were rated fair [27, 31, 32]. Table 3 provides a full summary of each study and the  
334 criteria which the assessment was based on.



335 **Table 2** Overview of study attributes and findings on sedentary behaviour with bone outcomes

Author	Sample size, gender (♂/♀), age (years)	SB outcomes measured	SB assessment method	Bone assessment method	Sites of anatomical assessment	Conclusions/results
<b>CROSS-SECTIONAL STUDIES</b>						
Chastin et al (sub analysis of ref [23])	591 (n =259 ♀) Age = 75.2 ± 6.7	Total ST (Daily) Bouts of SB	Accelerometry (ActiGraph GT1M)	DXA	TF, FN, Trochanter Ward triangle, Intertrochanter, Spine	No significant association for men or women between ST or bouts of SB with TF, FN, Trochanter Ward triangle, Intertrochanter BMD.  Significant negative association with spine BMD for ST (p =0.05), sub analysis per gender leads to non-significant results.  Significant positive association between more fragmented ST (shorter bout duration) and spine BMD (p=0.05), sub analysis per gender leads to non-significant results.
Onambele-Pearson et al [30]	112 (n = 61 ♀) Age = 72.5 ± 6.4	ST (hours/day), Bouts of SB	Accelerometry (GENEActiv Action)	DXA	Ribs, Spine, Pelvis, Upper Limbs, Lower Limbs, Total Body	♂ = Significant positive association between breaks in SB and BMD for ribs (p < 0.05) and total BMD (p < 0.01). SB bouts > 5 minutes were positively associated with lower limbs (p < 0.05), ribs and total BMD (p < 0.01). No significant associations reported for total ST.  ♀ = Significantly positive association between total ST and spine, lower limb (p < 0.05) and total (p < 0.01) BMD. Significant positive correlation between breaks in SB and ribs, pelvis and lower limbs (p < 0.05). For bouts < 5 minutes, there were positive associations for ribs and lower limbs (p < 0.01). There was a negative association between W50% and rib BMD (p < 0.05).
Rodriguez-Gomez et al [31]	871 (n =476 ♀) ♂ age = 76.9 ± 5.3 ♀ age = 76.7 ± 4.7	Total ST, separately for ♂ and ♀	Accelerometry (ActiTrainer & Actigraph wGT3X-BT)	DXA	TB, LS (L1-L4), FN, TH (greater trochanter, inter trochanter, Ward's triangle) and FN), BMD &	♂♀: SB positively associated with leg /BMD (p = 0.00) and whole body BMD (p = 0.05).  ♂: SB negatively associated with pelvic BMD (p = 0.05)  ♀: SB was positively associated with whole body /BMD (;p = 0.00) and leg /BMD (p = 0.00).  ♀: Reduce time spent in SB to reduce fracture risk.

Rodriguez-Gomez et al [32]	540 (n = 289 ♀), ♂ & ♀ Age = 76.0 ± 4.4 (robust individuals only)	Total ST	Accelerometry (ActiTrainer & Actigraph wGT3X-BT)	DXA	TB, LS (L1-L4), FN, TH, Leg BMD &	SB significantly positively associated with leg BMD/ (p = 0.000) for whole sample. ♂SB significantly negatively associated with TB BMD (p = 0.041) and leg BMD/ (p = 0.036) in robust men. ♀SB significantly positively associated with TB BMD/ (p = 0.000) and leg BMD/ (p = 0.000) in robust women.
Braun et al [27]	327 ♀ only Age ≥ 65	SB (mins/day)	Questionnaire	DXA	FN, LS (L1-L4) (trochanter, inter trochanter, Ward's triangle, TF, TS)	SB significant predictor of decreased Femoral BMD (p = 0.027), yet not a significant association in spinal BMD (p > 0.05).

#### LONGITUDINAL PERSPECTIVE STUDIES

McMillan et al [28]	209, (n = 111 ♀), Age = 64.5 ± 7.2	SB (mins/day), separately for ♂ and ♀	Accelerometry (ActiGraph GT1M)	DXA	TH, LS, FN, Pelvis, Legs & TB	♂: Negative association between SB and FN /BMD (p = 0.047) over 2.2 years. ♀: SB was positively associated with TH /BMD (; p = 0.046) over 2.2 years.
Nguyen et al [29]	1134 ♀ only n = 366 sedentary Age = 69.9 ± 7.4 <sup>†</sup> (N=1134; N = 827 at follow up)	ST (hours/day)	Questionnaire	DXA	FN	ST was significantly associated with reduced BMD (-1.5 ± 0.2%, p < 0.001). 47% of individual's with significant bone loss (n = 163) were categorised within the sedentary group.

336 Abbreviations: BMD bone mineral density, DXA dual-X-ray-absorptiometry, FN femoral neck, LPA light physical activity, LS lumbar spine, MVPA moderate-to-vigorous physical activity, PA  
337 physical activity, SB sedentary behaviour, ST sedentary time, TB total body, TF total femur, TH total hip, TS total spine. <sup>†</sup> Mean age was calculated by as follows ((age of sedentary group x n  
338 sedentary group) + (age of moderately active group x n moderately active group) + (age active group x n active group ))/(total N of participants)).

339

340 **Table 3** Summary of the quality assessment for each study using the National Institute of Health Quality Assessment Tool for Observational Cohort and Cross-Sectional  
 341 Studies\*.

	Chastin et al [23]	Braun et al [27]	McMillan et al [28]	Nguyen et al [29]	Onambele-Pearson et al [30]	Rodriguez-Gomez et al [31]	Rodriguez-Gomez et al [32]
1) Was the research question or objective in this paper clearly stated?	Y	Y	Y	Y	Y	Y	Y
2) Was the study population clearly specified and defined?	Y	Y	Y	Y	Y	Y	Y
3) Was the participation rate of eligible persons at least 50%?	Y	Y	Y	Y	CD	CD	CD
4) Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants?	Y	Y	Y	Y	Y	Y	Y
5) Was a sample size justification, power description, or variances and effect estimates provided?	N	N	N	N	Y	N	N
6) For the analyses in the paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?	CD	CD	CD	CD	NA	NA	NA
7) Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?	NA	NA	Y	Y	NA	NA	NA
8) For exposures that can vary in amount or level, did the study examine different levels of exposure as related to the outcome (e.g. categories of exposure, or exposure measured as continuous variable)?	Y	N	NA	NA	Y	Y	Y
9) Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Y	Y	Y	Y	Y	Y	Y
10) Was the exposure(s) assessed more than once over time?	NA	N	Y	Y	NA	NA	NA
11) Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Y	Y	Y	Y	Y	Y	Y
12) Were the outcome assessors blinded to the exposure status of participants?	NA	NA	NA	NA	NA	NA	NA
13) Was loss to follow up after baseline 20% or less?	NA	NA	Y	N	NA	NA	NA
14) Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?	Y	Y	Y	Y	Y	Y	Y
Rating	Good	Fair	Good	Good	Good	Fair	Fair

342 \* Y = Yes, N = No, CD = Cannot Determine, NA = Not Applicable

343 **Discussion**

344 This review examined the associations between sedentary behaviour (SB) and BMD  
345 in older adults (mean age  $\geq$  65 years). Following the screening of potentially relevant articles,  
346 seven were included for review. Studies varied with respect to: measurement of SB  
347 (subjective vs objective measures); anatomical measures of BMD; and whether they were  
348 cross-sectional or longitudinal in nature. All studies used DXA as a method to assess BMD.

349 Summary of Evidence

350 Longitudinal studies [28, 29] that explored the associations of SB on BMD over time,  
351 reported negative associations between higher levels of SB with BMD for both sexes and at  
352 all sites measured (except for total hip BMD in the female subgroup of the McMillan study  
353 [28]). Disparities may have arisen due to the larger sample size of women in Nguyen's [29]  
354 study in comparison to McMillan et al [28] and both studies measured SB differently  
355 (subjectively vs objectively, respectively).

356 The results from the cross-sectional studies however revealed a different pattern  
357 between men and women. Some verified the deleterious associations of higher levels of SB  
358 on BMD [27] in women, while others failed to identify a significant association when sub  
359 analysis by gender took place [23] (possibly due to the smaller numbers of participants in  
360 each subgroup). However; the majority of the studies [30-32] found a disparity in results  
361 between men and women. In women, positive associations were observed between SB and  
362 BMD (at different measuring sites) while the opposite was true for their male counterparts. It  
363 appears that, as discussed by Rodriguez-Gomez et al [31], other movement behaviours could  
364 have an impact on the SB and BMD association. It is common to find concomitant higher SB  
365 and higher MVPA levels, thus the MVPA could have a positive association on BMD in the  
366 presence of high levels of SB [31]. In addition, it was also highlighted that greater sedentary

367 time could result in more frequent breaks in sitting time. More frequent postural changes  
368 could result in higher volumes of mechanical load bearing, thus resulting in a positive  
369 association on BMD [31].

370         Likewise, Onambele-Pearson et al [30] reported higher BMD in women who reported  
371 more frequent sedentary bouts and identified that this frequency of interruption to SB could  
372 contribute the higher BMD. This is consistent with other research in post-menopausal  
373 women, whereby a greater number of breaks in SB resulted in a 10% reduction in the odds of  
374 being diagnosed with osteoporosis/osteopenia [35]. A small study in frailer older adults found  
375 that breaking SB on a roughly hourly basis throughout the day improved physical function  
376 (timed up and go and 30 second chair stand) over a 10-week period, with no significant  
377 change in total ST or PA [36]. Similarly, Aunger et al [37] reported clinically significant  
378 improvement in physical function with non-significant increases in daily steps and time spent  
379 upright, despite non-significant decreases in SB. This modest body of emerging evidence  
380 suggests that regular interruptions to ST may be beneficial to bone health in older adults.  
381 Further investigation is warranted, with a particular emphasis being on the wider application  
382 of thigh-worn accelerometers which have been shown to have higher accuracy for detecting  
383 postural changes than wrist and waist-worn accelerometers.

384         Measurement of SB also varied between the studies included in this review. The two  
385 studies that measured SB subjectively using questionnaires, reported negative associations  
386 between femoral BMD and SB [27, 29] in women, which appears to contradict the findings  
387 of objectively measured studies. This could be attributed to the underestimation of SB and  
388 overestimation of PA; a bias which is commonly acknowledged when subjectively measuring  
389 PA [39]. It is reported that a random error of 2.5 hours per day is observed in subjective  
390 assessment of total SB and that subjective measures are not valid in assessing SB bouts [40].  
391 Studies that used objective measures of SB reported more positive associations between SB

392 and BMD in women [28, 30-32]. It has been recently suggested, that moving to a single SB  
393 question assessing the whole day (via means of a visual analogue scale) might be worth  
394 considering for future studies, in cases where the use of a device-based measurement of PA is  
395 not practically possible [41].

396

### 397 Strengths and Limitations

398 This is the first review to explore the associations between SB and BMD in healthy  
399 older adults. However, there are a number of limitations influencing interpretation of the  
400 study findings. We appreciate that in order to reduce the risk of bias ideally two independent  
401 reviewers should have carried out all the steps of study selection and data extraction. In this  
402 study and due to time and resource limits the primary author (LM) screened the titles and  
403 abstracts, and excluded any irrelevant articles and only a sample (10%) of the studies were  
404 checked by one other reviewer (AM). As per PROSPERO protocol, when there were  
405 discrepancies in the inclusion or exclusion criteria discussion took place until an agreement  
406 was made.

407 Of the studies reviewed, two were prospective, and five were cross-sectional in  
408 design, as such any associations found here are not of a causal inference, and the possibility  
409 of bi-directional associations in the cross sectional studies cannot be ruled out. It should also  
410 be noted that the reported significant associations between SB and BMD, do not necessarily  
411 translate to clinically important associations and thus caution should be applied when  
412 interpreting these for such use. The generalisability of the results from this study should also  
413 be considered in light to the moderate quality of the studies included in the review, and the  
414 low numbers of participants in the subgroup (gender specific) analysis. In addition only  
415 healthy adults were assessed (clinical population were excluded from this review), therefore

416 there was no analysis on different populations and different health status in older adults. This  
417 included omitting the analysis of those who were deemed as ‘frail’ [32].

418         Likewise, the role of body weight as a confounder was not analysed in detail as part  
419 of this review. There is extensive body of findings suggesting that a higher body weight or  
420 body mass index can be associated with higher BMD [42, 43, 44] and reduced fracture risk  
421 [45]. These associations are probably attributable to the accentuated mechanical loading on  
422 the skeleton due to the increase in body mass although the exact mechanism is still not fully  
423 understood [46]. Indeed future studies should interpret data in the context of a number of  
424 confounders (including body weight and/or BMI) but also comorbidities, which are common  
425 in this older population and can induce sedentary behaviour.

426 There were various anatomical sites assessed using DXA and various methods of monitoring  
427 objectively and subjectively SB (different accelerometer types and questionnaires); in the  
428 absence of standardised assessments what may be concluded from the findings of the studies  
429 is limited. Although BMD measurement remains the most useful diagnostic tool for  
430 identifying patients with osteoporosis other technologies (e.g. ultra-high-resolution peripheral  
431 QCT, and 3D magnetic resonance imaging [MRI]) could noninvasively assess bone cross-  
432 sectional geometry and trabecular architecture. The combination of these, as well the  
433 assessment of number of fractures, may provide a more comprehensive picture of bone  
434 strength/health, compared with 2-dimensional BMD measurements in future studies. In  
435 addition this review included studies that used different densitometers to assess BMD, which  
436 is inevitably a limitation due to the well-established inherent measurement differences between  
437 scanners. In order to make progress in this field, we need well-designed longitudinal studies  
438 in this age group, with objective measures of SB and PA, and assessment of bone outcomes  
439 beyond just DXA.

440 **Conclusion**

441 This systematic review aimed to determine the associations between SB and BMD in  
442 healthy older adults (mean age  $\geq 65$  years). In conclusion, the research suggests there are  
443 gender difference in the associations of SB with BMD, with SB seemingly positive  
444 association on BMD in older women, but having a negative or no association in older men.  
445 However, there were only seven studies included in the review, with men being assessed in  
446 five of those studies, thus limiting the conclusions that can be drawn and thus these gender  
447 specific results should be treated with caution though due to the inherited issues with the  
448 relative small numbers of participants in subgroup analyses In order to better understand the  
449 associations of SB on BMD in older adults, there is a particular need to examine variations in  
450 patterns of sedentary time, using objective measures, including sit-stand transitions and how  
451 these might vary between men and women.

452

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