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Effects of body mass index on bone loading due to physical activity

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<https://orcid.org/0000-0001-5451-9535> (2018) Effects of body mass index on bone loading due to physical activity. *Journal of Applied Biomechanics*, 34 (1). pp. 7-13. ISSN 1065-8483

<http://dx.doi.org/10.1123/jab.2016-0126>

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### **Rights Retention Statement:**

1 **Effects of BMI on Bone Loading due to Physical Activity**

2

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4

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10 **Funding:** Kellogg's Company

11 **Conflict of Interest Disclosure:** None of the authors has any conflict of interest. This study  
12 was supported by Kellogg's Company who funded the project and discussed initial ideas that  
13 helped inform the design. They were not involved in data collection, analysis or  
14 interpretation.

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20 **Running Title:** Bone loading and physical activity

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22 As accepted for publication in *Journal of Applied Biomechanics*, ©Human Kinetics

23 DOI: <https://doi.org/10.1123/jab.2016-0126>

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25

26 **Abstract**

27 The aim of the current study was to compare bone loading due to physical activity between  
28 lean and, overweight and obese individuals. Fifteen participants (lower BMI group: BMI < 25  
29 kg/m<sup>2</sup>, n=7; higher BMI group: 25 kg/m<sup>2</sup> < BMI < 36.35 kg/m<sup>2</sup>, n=8) wore a tri-axial  
30 accelerometer on one day to collect data for the calculation of bone loading. The International  
31 Physical Activity Questionnaire (short form) was used to measure time spent at different  
32 physical activity levels. Daily step counts were measured using a pedometer. Differences  
33 between groups were compared using independent t-tests. Accelerometer data revealed  
34 greater loading dose at the hip in lower BMI participants at a frequency band of 0.1–2 Hz ( $P$   
35 = .039, Cohen's  $d = 1.27$ ) and 2–4 Hz ( $P = .044$ ,  $d = 1.24$ ). Lower BMI participants also had  
36 a significantly greater step count ( $P = .023$ ,  $d = 1.55$ ). This corroborated with loading  
37 intensity ( $d \geq 0.93$ ) and questionnaire ( $d = 0.79$ ) effect sizes to indicate higher BMI  
38 participants tended to spend more time in very light, and less time in light and moderate  
39 activity. Overall participants with a lower BMI exhibited greater bone loading due to physical  
40 activity; participants with a higher BMI may benefit from more light and moderate level  
41 activity to maintain bone health.

42

43 *Keywords:* pedometer, accelerometry, loading intensity, loading frequency

44

45 **Word count:** 4757 words

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## 49 **Introduction**

50           The prevalence of overweight and obesity is increasing, with the World Health  
51 Organisation reporting that over 1.9 billion adults worldwide were overweight in 2014, of  
52 which over 600 million were obese.<sup>1</sup> Although reasons for the development of being  
53 overweight or obese are multifactorial,<sup>2</sup> a decrease in physical activity has been shown to  
54 have an inverse relationship with body mass.<sup>3,4</sup> Furthermore, obese people who undertake  
55 more physical activity have been shown to be metabolically healthier than their less active  
56 counterparts.<sup>5,6</sup>

57           It is still unclear as to the effects of being overweight or obese on bone health. A high  
58 body mass has been associated with increases in bone mineral density due to the load on  
59 weight-bearing bones,<sup>7</sup> and the increased secretion of bone active hormones.<sup>8</sup> Although this  
60 implies obesity has a positive effect on bone health, more recently it has been suggested that  
61 obese people have poor bone quality and increased fracture risk.<sup>9-11</sup> This may be due to  
62 factors such as the excess weight due to adiposity and the changes this induces at a cellular  
63 level.<sup>9,11</sup> Also, when the mechanical loading effects of total body weight on bone mass are  
64 adjusted for, an inverse relationship between bone mass and fat mass has been reported.<sup>12</sup>

65           Physical activity can counteract some of the negative effects of adiposity on bone  
66 health and it is generally accepted that certain types of exercise strengthen bone.<sup>13,14</sup>  
67 Exercises that are particularly osteogenic are weight-bearing intermittent dynamic activities  
68 which are high impact, applied at a high strain rate, and are unusual or diverse.<sup>15</sup> Mechanical  
69 loading has been shown to alter cellular mechanics to favour osteoblastogenesis, and at the  
70 expense of adipogenesis.<sup>16</sup> Bone benefits from mechanical loading via dynamic loads through  
71 physical activity<sup>17</sup> rather than static loads due to excess adiposity alone, indicating there is no  
72 mechanical advantage to the bone as a result of obesity unless accompanied by a greater lean  
73 mass and a physically active lifestyle.<sup>9</sup> It is therefore important that the contribution of

74 physical activity to factors associated with bone remodelling and adaptation in overweight  
75 and obese people are better understood.

76 Factors that determine bone adaptation to mechanical loading include loading  
77 magnitude, loading frequency (rate), and duration of loading.<sup>14</sup> Various methods have been  
78 used to quantitatively assess these factors in physical activity, including questionnaires,  
79 pedometers, and accelerometers. Among these methods, self-report questionnaires and  
80 pedometers are convenient ones to use. Both methods have been employed in studies  
81 reporting positive associations between physical activity and various measures of bone  
82 health.<sup>18-21</sup> Questionnaires rely on the participants' subjective interpretation of participation  
83 in physical activity and have been shown to correlate weakly with objective measures such as  
84 pedometers and accelerometers.<sup>22,23</sup> However, although pedometers are regarded as an  
85 objective measurement device the data obtained does not offer the same level of detail as  
86 accelerometers. Specifically, they are not able to give precise information about the  
87 characteristics of the activity (e.g. loading magnitude or loading frequency) in relation to  
88 bone adaptation. Generally, pedometers have been regarded as less accurate than  
89 accelerometers in physical activity assessment<sup>24,25</sup> and are affected by increasing BMI and  
90 waist circumference, and greater pedometer tilt in overweight and obese adults leading to an  
91 underestimation of actual steps.<sup>25</sup>

92 Accelerometers offer researchers the opportunity to gather more precise information  
93 about the characteristics of the physical activity which are specifically associated with bone  
94 adaptation. To quantify the specific elements of physical activity that have an osteogenic  
95 effect, Turner & Robling<sup>14</sup>, developed the osteogenic index which incorporates the important  
96 factors identified as leading to bone formation (loading magnitude, loading frequency and  
97 duration of loading). Accelerations recorded on accelerometers attached to participants  
98 correlate with the mechanical loading forces acting on the body during physical activity.

99 Therefore, it is possible to use acceleration data to assess the loading intensity (magnitude of  
100 loading x loading frequency<sup>14</sup>) of physical activity on the underlying skeleton, at the site  
101 which the accelerometer is attached to. Previous research has shown that loading intensity  
102 can be calculated using a combination of the magnitude and frequency of the acceleration  
103 signals.<sup>26,27</sup> From these data the duration of activities at each intensity level can be derived  
104 thus quantifying bone loading with respect to the three elements identified by Turner &  
105 Robling,<sup>14</sup> as important to osteogenesis. The primary aim of the present study was to compare  
106 bone loading estimates due to physical activity in lean (participants with a lower BMI) and  
107 overweight and obese individuals (participants with a higher BMI) using our accelerometry  
108 based method to quantify the loading intensity and overall loading dose at the hip. Secondary  
109 aims were to compare physical activity levels between the two groups using questionnaire  
110 and pedometer data. The following hypotheses were tested: 1) There is an association  
111 between mechanical loading during daily physical activity and BMI (lower BMI versus  
112 higher BMI) when assessed by accelerometry based methods; 2) There is an association  
113 between physical activity levels and BMI (lower BMI versus higher BMI) as assessed by  
114 questionnaire and pedometer.

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## Methods

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Fifteen participants volunteered to take part in the study and were divided into lower  
BMI (BMI < 25 kg/m<sup>2</sup>) and higher BMI (BMI > 25 kg/m<sup>2</sup>) groups (Table 1). The higher BMI  
group comprised both overweight (n = 6) and obese (n = 2) participants. All participants gave  
written informed consent prior to participating in the study, which had been approved by the  
Institutional Ethics committee (Ref: LSC 11/010). The volunteers were a subset of those  
taking part in an investigation into the mechanisms that may link body mass index with  
breakfast consumption.<sup>28</sup>

124

125 \*\*Table 1 about here\*\*

126

127         The protocol required that a tri-axial accelerometer (MSR 145B, MSR Electronics  
128 GmbH, Henggart, Switzerland) was attached to the skin on the right side of the pelvis directly  
129 above the hip joint centre (Figure 1), using double-sided wig tape applied to the rear of the  
130 sensor and further secured with Finepore tape over the top of the sensor. In agreement with  
131 the participant the accelerometer was pre-set to record data (10 Hz) for one specified day  
132 between 9 am – 9 pm. This required the participant to attach the accelerometer themselves on  
133 the morning of the data collection, and therefore detailed instructions and demonstrations on  
134 how and where to attach the accelerometer were provided in advance. Twelve hours of data  
135 collection was chosen due to limitations in the amount of data the accelerometer could store  
136 when recorded at 10 Hz. The specified time period was chosen as this represented the portion  
137 of the entire day when participants would be going about their daily routines. Whilst wearing  
138 both the pedometer and accelerometer participants were instructed to follow their normal  
139 routines. As the accelerometer was worn for one day only, a day that reflected a typical day's  
140 activity was chosen. This was agreed with the participant beforehand and days likely to result  
141 in less or more than normal activity were avoided. Typical physical activity levels of  
142 participants were measured using the short form of the International Physical Activity  
143 Questionnaire (IPAQ-SF), which has been previously reported as a valid and reliable measure  
144 of physical activity.<sup>29</sup> It was completed by participants at the start of the study. Additional  
145 daily physical activity data were collected using a pedometer (Yamax Digiwalker SW-200,  
146 Tokyo, Japan). Participants were instructed to wear the pedometer either on the waist band, if  
147 available, or on the front pocket of their clothing. They attached the pedometer as they arose  
148 in the morning and only removed it when going to bed, with the exception of bathing. The

149 number of steps per day was recorded by the participant for a period of two distinct weeks.  
150 These weeks coincided with participation in the larger study where participants were assigned  
151 to one week of following a breakfast eating protocol and one week of skipping breakfast.<sup>28</sup>

152

153 \*\*Figure 1 about here\*\*

154

155 Prior to processing the acceleration data it was screened to ensure 12 hours of wear  
156 time was indicated in the signal. The details of the method for analysing acceleration data can  
157 be found in our previous publications.<sup>26,27</sup> A short introduction of this method is provided  
158 below. The 12 hours of accelerometer data were exported to a personal computer and  
159 processed using a custom written computer programme in MATLAB (Version R2014a,  
160 MathWorks Inc., Natick, MA). The resultant acceleration was calculated from the data and  
161 filtered using a Butterworth band pass filter (0.1-5 Hz) to remove static gravitational  
162 acceleration and noise.<sup>27</sup> The resultant acceleration was divided into 5 s segments. A Fast  
163 Fourier transformation was applied to each 5 s segment to obtain the Fourier series of the  
164 acceleration signal in the frequency domain. Loading intensity in body weights per second  
165 (BW/s) was then calculated for each 5 s segment from its Fourier series by summing the  
166 product of acceleration magnitude and frequency across 0.1 to 5 Hz:

$$LI = \sum_{f_i=0.1}^{5 \text{ Hz}} \frac{(A_i \times f_i)}{g}$$

167

(1)

168 where  $LI$  is the loading intensity (BW/s),  $f_i$  is the  $i$ th frequency in the Fourier series (Hz), only  
169 terms with frequency between 0.1 and 5 Hz were used,  $A_i$  is the acceleration ( $\text{m/s}^2$ ) at  
170 frequency  $f_i$ . and  $g$  is the gravitational acceleration ( $9.81 \text{ m/s}^2$ ).

171

172 Then the time (s) spent on activity with loading intensities (calculated for the 0.1-5 Hz  
 173 frequency band) of < 5 BW/s (very light), > 5 BW/s (light), > 10 BW/s (moderate), > 15  
 174 BW/s and > 20 BW/s (vigorous) was calculated by multiplying the number of segments  
 175 within each intensity category by the duration of each segment (5 s).

176 Overall loading dose (BW) was calculated by summing the product of loading  
 177 intensity and duration (i.e. 5 s) at each segment across the 12 hour recording period:

$$LD = \sum_k 5 \times LI$$

178 (2)

179 while *LD* is the loading dose, *LI* is the loading intensity, and *k* is the number of segments in  
 180 the twelve hour recording period.

181 Loading dose was also calculated at frequency bands 0.1-2, 2-4, and 4-5 Hz  
 182 separately by the following methods. First, loading intensity at each frequency band was  
 183 calculated as (for example, at 0.1-2 Hz band):

$$LI_B = \sum_{f_i=0.1}^{2\text{ Hz}} \frac{(A_i \times f_i)}{g}$$

184 (3)

185 where *LI\_B* is the loading intensity at a frequency band (e.g. 0.1-2Hz in this case) (BW/s), *f<sub>i</sub>*  
 186 is the *i*th frequency in the Fourier series (Hz), *A<sub>i</sub>* is the acceleration (m/s<sup>2</sup>) at frequency *f<sub>i</sub>*. and  
 187 *g* is the gravitational acceleration (9.81 m/s<sup>2</sup>).

188 Then loading dose at a frequency band (BW) was calculated by summing the product  
 189 of loading intensity in that frequency band and duration (i.e. 5 s) at each segment across the  
 190 12 hour recording period:

$$LD_B = \sum_k 5 \times LI_B$$

191 (4)

192 where  $LD_B$  is the loading dose at a specific frequency band (e.g. 0.1-2, 2-4, or 4-5 Hz), and  
193  $k$  is the number of segments in the twelve hour recording period.<sup>26</sup>

194 The resulting data from the above calculations represented the total amount of bone  
195 loading and bone loading at different frequency bands over the twelve hour period. Although  
196 it is not possible to distinguish the exact activity undertaken in each of the frequency bands  
197 calculated, association of the frequency bands with common activities is such that the faster  
198 moving activities contain greater high frequency components. For example a greater amount  
199 of the loading intensity due to fast running is above 4 Hz when compared to slow walking.<sup>27</sup>

200 IPAQ-SF Data: Questionnaires were analysed in accordance with guidelines produced  
201 by the IPAQ Research Committee.<sup>30</sup> Physical activity of the previous week relating to leisure,  
202 domestic, work, and transport activities was assessed and reported as separate scores for  
203 walking, and moderate and vigorous intensity activities as well as total activity. Data for each  
204 category were expressed as metabolic equivalent minutes per week (MET-min/week). Time  
205 spent sitting was also evaluated and reported as minutes/day. One participant's data from  
206 each group was excluded due to partial completion of the IPAQ-SF questions.

207 Pedometer Data: The mean daily pedometer scores for each of the two weeks of data  
208 collection were calculated and a dependent t-test was conducted, which ascertained that there  
209 was no statistically significant difference between the breakfast eating and skipping weeks  
210 ( $t(13) = 0.515, P = .615$ ), which has also been reported in a previous study.<sup>31</sup> Therefore the  
211 pedometer data collected were pooled and an average daily step count over a two week  
212 period was obtained.<sup>32</sup> The mean daily step count for the day on which the accelerometer was  
213 worn was also calculated for each group. Step data were not available for one member of the  
214 lower BMI group.

215 The data was analysed statistically. Variables were tested for equality of variance  
216 using Levene's test. Independent t-tests were used to assess differences between lower BMI

217 and higher BMI groups. The level of significance for a two-tailed test was set at  $P < .05$ .  
218 Cohen's  $d$  ( $d$ ) effect size was calculated as the difference between means divided by the  
219 pooled standard deviation and reported as 0.2 - 0.49 small, 0.5 - 0.79 medium,  $\geq 0.8$  large.<sup>33</sup>  
220 Statistical analysis was carried out using SPSS (IBM SPSS Statistics Version 20; IBM Corp,  
221 NY, USA) and Excel (Microsoft, Redman, WA, USA).

222

223

## Results

224 A significantly greater mechanical loading dose, and large effect size, was observed  
225 for lower BMI participants at frequency bands of 0.1-2 Hz and 2-4 Hz (Table 2). This  
226 indicates that loading dose was higher in lower BMI participants in both low and high  
227 frequency ranges. For duration of activity at differing loading intensities there were no  
228 significant differences. However, large effect sizes were observed for the duration of activity  
229 with loading intensities  $< 5$  BW/s to  $> 10$  BW/s. Whilst not significant Table 2 shows lower  
230 BMI participants undertaking low intensity ( $< 5$  BW/s) activities for less time and higher  
231 intensity activities ( $> 5$  and  $> 10$  BW/s) for more time.

232

233 \*\*Table 2 about here\*\*

234

235 Analysis of steps taken indicated there was a significant difference and large effect  
236 size between lower BMI and higher BMI groups in the number of steps taken on the day the  
237 accelerometer was worn, with lower BMI participants recording significantly more steps.  
238 When comparing mean daily step count averaged from a two week period there was no  
239 significant difference between the groups (Table 3).

240 The IPAQ-SF questionnaire revealed no significant difference in time spent on  
241 moderate physical activity between groups. Nevertheless there was a large effect size ( $d =$

242 0.79), with the data indicating lower BMI participants reported spending more time  
243 undertaking a moderate level of activity than those who were in the higher BMI group (Table  
244 3). No significant differences and only low to moderate effects were noted for measures of  
245 vigorous and walking activity, and sitting time between groups.

246

247 \*\*Table 3 about here\*\*

248

249

250

### **Discussion**

251 The primary aim of this study was to compare bone loading estimates between lean  
252 (lower BMI group) and overweight and obese individuals (higher BMI group), assessed by  
253 accelerometry. The key findings were that the lower BMI participants experienced a greater  
254 loading dose at frequencies up to 4 Hz. This indicates a greater amount of total bone loading  
255 normalised to body weight during the twelve hour period that the participants were recorded,  
256 at loading frequencies in the 0.1-2 Hz and 2-4 Hz frequency bands.

257 Accelerations of the upper body generated during daily activities ranging from slow  
258 walking, to fast running and stair climbing have been shown to contain frequencies within the  
259 above range of 0.1 to 4 Hz. These activities also contain some higher frequency components  
260 above 4 Hz.<sup>27,34</sup> As the intensity of activity increases, for example by increasing the speed at  
261 which it is performed, the portion of higher frequency components contained in the signal  
262 increases. This indicates that light and moderate physical activity has frequencies mainly in  
263 the lower frequency range and as the physical activity becomes more vigorous greater  
264 increases in the higher frequency components are observed.<sup>27</sup> The results of this study  
265 therefore indicate that lower BMI participants exhibit a higher loading dose in light and  
266 moderate physical activity but not in vigorous activity.

267 Low velocity, low impact activities have been shown to beneficially modify bone  
268 geometry<sup>35</sup>, which is achievable through light and moderate physical activity. In addition  
269 increased loading frequency has been associated with increased bone formation<sup>36</sup>, therefore  
270 our results suggest mechanical loading induced due to physical activity may be compromised  
271 in the higher BMI group at both low and high frequency ranges, limiting the osteogenic  
272 effects of their physical activity. At the higher (4-5 Hz) loading frequencies differences were  
273 not significant although the effect size was still quite large, suggesting the trend may  
274 continue. It is also possible participants engaged in activities with a mechanical loading  
275 frequency above 5 Hz. The loading dose of physical activity that generated frequencies above  
276 5 Hz were not analysed in the current study due to filtering the acceleration signal with a cut-  
277 off frequency of 5 Hz. This was to reduce errors contained in the measurement of the  
278 acceleration signal as a result of high frequency signals that were contaminated by skin  
279 movement, rather than the true signal generated by the physical activity undertaken.

280 With respect to the intensity of the physical activity, only moderate and vigorous  
281 activity levels and high impacts have been shown to improve bone density in adolescents and  
282 middle aged women.<sup>26,37,38</sup> Previous work by Kelley et al.<sup>27</sup>, has demonstrated that types of  
283 activities generating very light (< 5 BW/s), light (> 5 BW/s), moderate (> 10 BW/s) and  
284 vigorous (> 15 BW/s) loading intensities include slow walking, fast walking, slow running  
285 and, normal and fast running respectively, for acceleration data recorded at the lumbar spine.  
286 In the current study the measure of duration of physical activity at specific loading intensities  
287 allowed the amount of time engaged in activities with the potential of improving bone density  
288 at the site of the hip to be quantified.

289 Although not significant the effect sizes noted in the current study suggests higher  
290 BMI participants may spend more time engaging in low intensity (very light) exercise < 5  
291 BW/s, whilst the lower BMI participants engaged in more activity at intensities greater than 5

292 or 10 BW/s (light and moderate activity) (Table 2). This supports the results on loading dose  
293 where participants with a lower BMI had a higher dose at both 0.1-2 Hz and 2-4 Hz. It further  
294 highlights that a greater portion of the physical activity the lower BMI participants engaged  
295 in at these doses were of the intensity of normal walking or greater. Whereas the higher BMI  
296 group had a greater portion of their low intensity physical activity spent in slow walking or  
297 similar. If higher BMI participants are generally lacking in moderate activity, this could  
298 explain the poor bone quality and increased fracture risk previously reported.<sup>9-11</sup> It is  
299 recommended further research is undertaken to corroborate this evidence.

300 At higher intensities (> 15 and > 20 BW/s) the differences in duration of loading  
301 intensity were not significant, nor were the effect sizes noteworthy (Table 2). High intensity  
302 physical activity is likely to contain a greater proportion of high frequency components.<sup>27</sup>  
303 Therefore, this again supports our results on loading dose where no significant differences  
304 were found between the groups for physical activity at frequencies of 4-5 Hz.

305 Overall, the significantly greater loading dose found in the lower BMI group,  
306 supported by the findings for loading intensity, provide an insight into the characteristics of  
307 their physical activity which are positively related to osteogenesis. Loading dose was  
308 calculated by multiplying the loading intensity by time duration. Therefore the significant  
309 differences in loading dose mean that the physical activity of the lower BMI group must have  
310 one or all of the following characteristics: 1) their loading magnitude during physical activity  
311 was larger, 2) their physical activity loading frequency was larger, or 3) they spent more time  
312 on light or moderate physical activity than the higher BMI group. These changes correspond  
313 with the factors identified by Turner & Robling that determine bone adaptation, namely  
314 increased loading magnitude, loading frequency (rate), and duration of loading.<sup>14</sup>

315 The mean total time spent by either group in activities > 15 BW/s was no more than  
316 10 minutes in the twelve hour period, demonstrating that neither group engaged in much

317 vigorous activity. This correlates with previous research that suggested engaging in activities  
318 with a high acceleration response are rare.<sup>39</sup> However, it has been shown that the  
319 mechanosensitivity of bone declines after 20 loading cycles and bone formation improves  
320 with rest periods between loading cycles.<sup>14,40,41</sup> Therefore, as the short periods of vigorous  
321 physical activity engaged in by both groups reaches the intensity levels associated with  
322 increases in bone mineral density,<sup>26,37,38</sup> further research into whether this small amount of  
323 vigorous physical activity is sufficient to maintain and enhance bone health is warranted. In  
324 addition examining the nature of the activities undertaken during vigorous physical activity  
325 would inform such exercise interventions.

326         Acceleration signals attenuate as they travel through the body<sup>42</sup> therefore to confirm  
327 whether the physical activity undertaken produces the required loading at the site of interest  
328 the accelerometer should be placed near that site. Jämsä et al.,<sup>37</sup> indicated an association  
329 between physical activity and proximal femur bone mineral density, dependent on  
330 acceleration levels generated at this site via an accelerometer worn near the iliac crest. In the  
331 current study the data indicates the osteogenic potential of activities in relation to the hip in  
332 lower BMI and higher BMI participants, rather than generalised links between physical  
333 activity and its contribution to bone health.

334         Secondary aims of the study were to compare physical activity levels between the two  
335 groups using questionnaire and pedometer data. The results from the IPAQ-SF and  
336 pedometers showed that the only significant difference between lower BMI and higher BMI  
337 groups was a greater mean daily step count, on the day the accelerometer was worn, in lower  
338 BMI participants. Whilst this significant result would suggest that the lower BMI participants  
339 experience a greater amount of bone loading the accelerometer data for lower BMI  
340 participants revealed that just over half an hour of activity within the twelve hour recording  
341 period was of a moderate intensity or greater, the level associated with increases in bone

342 mineral density.<sup>26,37,38</sup> Therefore, caution should be applied when using a pedometer to  
343 quantify physical activity levels in studies investigating bone health. This could further  
344 explain why previous research has failed to find an association between pedometer data and  
345 instruments designed to measure bone specific physical activity,<sup>32</sup> or bone strength.<sup>43</sup>

346         Although the day chosen to wear the accelerometer was to be reflective of typical  
347 activity (i.e. avoid a day of particularly high or low activity with respect to the rest of the  
348 week) the results indicate the number of steps performed on the day the accelerometer was  
349 worn for the lower BMI group were higher than the average daily count for a two week  
350 period (Table 3). Further investigation of the daily step data indicated that the step count for  
351 the day the accelerometer was worn was between the maximum and minimum daily step  
352 counts over a two week period for all except one lower BMI and one higher BMI participant.  
353 For both of those participants the step count on the day the accelerometer was worn  
354 represented their maximum daily score. As daily activity is likely to vary across a week it  
355 would appear that our data is representative of a typical day in the majority of participants  
356 when sampling for one day only.

357         It appears that the significant difference observed in steps taken between groups on  
358 the day the accelerometer was worn is potentially due to a combination of the following  
359 factors. The step count range on that day was smaller for the lower BMI (10650 to 14828  
360 steps) compared to higher BMI (3562 to 14562 steps) participants. Also when compared to  
361 the range of steps/day recorded over the 2 week period for each group (lower BMI: 1225 to  
362 17252; higher BMI: 1813 to 25746), the data was in the upper end of the range for the lower  
363 BMI group and lower end of the range for the higher BMI group. Exploration of the daily  
364 step counts over the two week period supports this. Therefore, it is possible that having been  
365 instructed to wear the accelerometer on days representative of their typical daily physical

366 activity the lower BMI group tended to avoid days of low activity as they were not the norm  
367 and vice versa for the higher BMI group.

368 The IPAQ-SF data did not reveal any significant differences in physical activity levels  
369 between groups. However the effect size ( $d = 0.79$ ) suggested greater engagement in  
370 moderate physical activity by lower BMI participants which corroborates the accelerometer  
371 data ( $d = 0.93$  for time of intensity  $> 10$  BW/s). As previous studies have also found physical  
372 activity measured from questionnaire data to be positively associated with measures of bone  
373 health,<sup>19-21</sup> it is possible that physical activity questionnaires may be a more effective, quick  
374 and easy way to assess measures of physical activity in studies relating to bone health than a  
375 pedometer. However, as many physical activity questionnaires, including the IPAQ-SF,  
376 define physical activity through energy expenditure calculated in METs,<sup>21,30</sup> they do not  
377 distinguish between weight-bearing and non-weight bearing exercise and thus underestimate  
378 the loading of physical activity on the skeletal system.<sup>21</sup> Additionally, there are limitations to  
379 relying on recall to estimate physical activity level through questionnaires and the IPAQ-SF  
380 has been shown to overestimate physical activity.<sup>22</sup>

381 It is acknowledged that there are some limitations to the present study that must be  
382 taken into account when interpreting the data. The sample size for this study is small and the  
383 variability in the physical activity data collected by all three methods can be considered high.  
384 Therefore we acknowledge that interpretation of the p-values and effect sizes must be  
385 considered with caution. However, albeit a small sample novel data is presented in relation to  
386 the primary aim which gives us a first estimate of what the effect sizes are in relation to the  
387 hypothesis tested. Future studies should consider grouping lower BMI and higher BMI  
388 participants into sedentary and active categories to investigate the interaction of BMI and  
389 physical activity levels. Where possible data for multiple days should be recorded to get a  
390 fuller picture of physical activity during typical daily routines, to differentiate between week

391 days and weekends a seven day collection period has been suggested.<sup>44</sup> This is illustrated in  
392 the current pedometer datasets where two of the higher BMI participants displayed the  
393 pattern of engaging in a very large number of steps one day/week during the two week  
394 pedometer data collection period. However to ensure the statistical analysis of the pedometer  
395 data in the current study was not influenced by outliers Grubbs Test<sup>45</sup> was performed; as no  
396 outliers were detected all pedometer data was included in the subsequent analysis. In line  
397 with the current data collection and processing protocols it is possible participants engaged in  
398 activities with a mechanical loading frequency above 5 Hz which would have been removed  
399 by the filtering process adhering to Nyquist's theorem. Also there is the possibility of skin  
400 movement artefact and additional adipose tissue affecting the accelerometer signal. However  
401 the influence of soft tissue on the measurement of bone acceleration was minimised in this  
402 study by filtering acceleration data at the cut-off frequency of 5 Hz, as a previous study found  
403 that bone accelerations can be reliably measured using skin mounted accelerometers for  
404 frequency up to around 5 Hz.<sup>42</sup>

405 In summary, magnitude, frequency and duration of mechanical loading are important  
406 parameters to determine bone formation and maintenance. This study is the first to  
407 quantitatively assess mechanical loading at the hip in overweight and obese (higher BMI)  
408 participants using these parameters based on acceleration signals during free-living. This  
409 enables us to reveal the key nature of physical activity that is related to bone health in higher  
410 BMI participants. Lower BMI participants engaged in physical activity that elicited a greater  
411 mechanical loading dose to the hip than did higher BMI participants, and had a greater step  
412 count. The use of accelerometry to estimate external mechanical loading proved an effective  
413 means of providing details of the characteristics of physical activity associated with  
414 osteogenesis beyond what the pedometer data provided. The osteogenic potential of  
415 mechanical loading dose in the higher BMI group was compromised at a range of

416 frequencies. Analysis of the loading dose and intensity data indicated the higher BMI  
417 participants took part in less light and moderate physical activity and therefore have less  
418 potential for positive benefits to bone geometry or density. Thus higher BMI participants may  
419 benefit from more light and moderate level physical activity to maintain bone health.  
420 Intensity of physical activity data revealed that just over half an hour of total activity within  
421 the twelve hour recording period was of a level associated with increasing bone density  
422 (moderate and vigorous physical activity) for both groups. Indicating pedometer data alone  
423 should not be relied on when studying the effects of exercise on bone health.

#### 424 **Acknowledgements**

425 This study was supported by Kellogg's Company who funded the project and discussed  
426 initial ideas that helped inform the design. They were not involved in data collection, analysis  
427 or interpretation. Trial registered with the ISRCTN, trial number ISRCTN89657927  
428 (<http://www.controlled-trials.com/ISRCTN89657927/>).

429

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563

**Table 1** Participant demographics (mean  $\pm$  SD).

| Group      | n | Sex      | Age (y)        | Height (m)      | Body Mass (kg)  | BMI (kg·m <sup>-2</sup> ) |
|------------|---|----------|----------------|-----------------|-----------------|---------------------------|
| Lower BMI  | 7 | 4 female | 34.6 $\pm$ 7.2 | 1.73 $\pm$ 0.10 | 67.1 $\pm$ 5.8  | 22.5 $\pm$ 1.3            |
| Higher BMI | 8 | 6 female | 26.6 $\pm$ 6.0 | 1.71 $\pm$ 0.11 | 85.1 $\pm$ 15.7 | 28.9 $\pm$ 3.4            |

BMI = body mass index

**Table 2** Accelerometer physical activity data for lower BMI and higher BMI groups.

| Variable                                    | Mean $\pm$ SD     |                   | <i>t</i> | <i>df</i> | <i>P</i> | <i>d</i> |
|---|-------------------|-------------------|----------|-----------|----------|----------|
|   | Lower BMI         | Higher BMI        |          |           |          |          |
| Overall Loading Dose (BW) 0.1-5 Hz          | 90890 $\pm$ 16175 | 71063 $\pm$ 20714 | 2.043    | 13        | .062     | 1.14     |
| 0.1-2 Hz Loading Dose (BW)*                 | 16474 $\pm$ 3615  | 12222 $\pm$ 3563  | 2.290    | 13        | .039     | 1.27     |
| 2-4 Hz Loading Dose (BW)*                   | 48203 $\pm$ 8429  | 37008 $\pm$ 10714 | 2.224    | 13        | .044     | 1.24     |
| 4-5 Hz Loading Dose (BW)                    | 27429 $\pm$ 5068  | 22658 $\pm$ 6925  | 1.502    | 13        | .157     | 0.83     |
| Duration of Loading Intensity < 5 BW/s (s)  | 37922 $\pm$ 1514  | 39507 $\pm$ 1876  | 1.782    | 13        | .098     | -0.99    |
| Duration of Loading Intensity > 5 BW/s (s)  | 5278 $\pm$ 1514   | 3693 $\pm$ 1876   | 1.782    | 13        | .098     | 0.99     |
| Duration of Loading Intensity > 10 BW/s (s) | 2092 $\pm$ 1475   | 1001 $\pm$ 1042   | 1.672    | 13        | .118     | 0.93     |
| Duration of Loading Intensity > 15 BW/s (s) | 307 $\pm$ 288     | 440 $\pm$ 594     | -0.560   | 10.384    | .587     | -0.30    |
| Duration of Loading Intensity > 20 BW/s (s) | 170 $\pm$ 297     | 226 $\pm$ 375     | -0.321   | 13        | .753     | -0.18    |

\* Statistically significant difference; *d* = effect size

**Table 3** International Physical Activity Questionnaire short form (IPAQ-SF) and pedometer physical activity data for lower BMI and Higher BMI groups.

| Variable                                    | Mean $\pm$ SD    |                 | <i>t</i> | <i>df</i> | <i>P</i> | <i>d</i> |
|---|------------------|-----------------|----------|-----------|----------|----------|
|   | Lower BMI        | Higher BMI      |          |           |          |          |
| <b>IPAQ-SF Data</b>                         |                  |                 |          |           |          |          |
| Walking (MET-min/week)                      | 1524 $\pm$ 1577  | 966 $\pm$ 1177  | 0.729    | 11        | .481     | 0.44     |
| Moderate Physical Activity (MET-min/week)   | 593 $\pm$ 478    | 291 $\pm$ 338   | 1.330    | 11        | .210     | 0.79     |
| Vigorous Physical Activity (MET-min/week)   | 1013 $\pm$ 513   | 1406 $\pm$ 1273 | -0.748   | 8.135     | .476     | -0.42    |
| Total Physical Activity (MET-min/week)      | 3130 $\pm$ 1696  | 2664 $\pm$ 1329 | 0.557    | 11        | .589     | 0.33     |
| Time Sitting (min/day)                      | 470 $\pm$ 219    | 377 $\pm$ 83    | 1.043    | 11        | .319     | 0.62     |
| <b>Pedometer Data</b>                       |                  |                 |          |           |          |          |
| Mean Daily Step Count                       | 9386 $\pm$ 982   | 8272 $\pm$ 2910 | 1.009    | 8.996     | .340     | 0.53     |
| Step Count (on day accelerometer was worn)* | 12575 $\pm$ 1798 | 8175 $\pm$ 3797 | 2.608    | 12        | .023     | 1.55     |

\* Statistically significant difference; *d* = effect size

## Figure Captions

**Figure 1** – Location and co-ordinate system of the accelerometer.

