

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

2

3 *Author names:* Tina Smith,¹ Sue Reeves,² Lewis Halsey,² Jörg Huber,³ and Jin Luo⁴

4

5 ¹Faculty of Education, Health & Wellbeing, University of Wolverhampton, Walsall, UK;

6 ²Department of Life Sciences, University of Roehampton, London, UK; ³Centre for Health

7 Research, University of Brighton, Falmer, UK; ⁴School of Applied Sciences, London South

8 Bank University, London, UK

9

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.

15 **Correspondence Address:** Dr Tina Smith, Faculty of Education, Health & Wellbeing,
16 University of Wolverhampton, Gorway Road, Walsall, WS1 3BD

17 Email: Tina.Smith@wlv.ac.uk

18 Tel: +44 (0)1902 322824

19

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

21

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

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

24

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/m², n=7; higher BMI group: 25 kg/m² < BMI < 36.35 kg/m², 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

46

47

48

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.¹ Although reasons for the development of being
53 overweight or obese are multifactorial,² a decrease in physical activity has been shown to
54 have an inverse relationship with body mass.^{3,4} Furthermore, obese people who undertake
55 more physical activity have been shown to be metabolically healthier than their less active
56 counterparts.^{5,6}

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,⁷ and the increased secretion of bone active hormones.⁸ 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.⁹⁻¹¹ 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.^{9,11} 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.¹²

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.^{13,14}
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.¹⁵ Mechanical
69 loading has been shown to alter cellular mechanics to favour osteoblastogenesis, and at the
70 expense of adipogenesis.¹⁶ Bone benefits from mechanical loading via dynamic loads through
71 physical activity¹⁷ 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.⁹ 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.¹⁴ 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.¹⁸⁻²¹ 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.^{22,23} 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^{24,25} 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.²⁵

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 & Robling¹⁴, 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 frequency¹⁴) 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.^{26,27} 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,¹⁴ 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.

115

116

Methods

117

118

119

120

121

122

123

Fifteen participants volunteered to take part in the study and were divided into lower
BMI (BMI < 25 kg/m²) and higher BMI (BMI > 25 kg/m²) 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.²⁸

124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148

****Table 1 about here****

The protocol required that a tri-axial accelerometer (MSR 145B, MSR Electronics GmbH, Henggart, Switzerland) was attached to the skin on the right side of the pelvis directly above the hip joint centre (Figure 1), using double-sided wig tape applied to the rear of the sensor and further secured with Finepore tape over the top of the sensor. In agreement with the participant the accelerometer was pre-set to record data (10 Hz) for one specified day between 9 am – 9 pm. This required the participant to attach the accelerometer themselves on the morning of the data collection, and therefore detailed instructions and demonstrations on how and where to attach the accelerometer were provided in advance. Twelve hours of data collection was chosen due to limitations in the amount of data the accelerometer could store when recorded at 10 Hz. The specified time period was chosen as this represented the portion of the entire day when participants would be going about their daily routines. Whilst wearing both the pedometer and accelerometer participants were instructed to follow their normal routines. As the accelerometer was worn for one day only, a day that reflected a typical day's activity was chosen. This was agreed with the participant beforehand and days likely to result in less or more than normal activity were avoided. Typical physical activity levels of participants were measured using the short form of the International Physical Activity Questionnaire (IPAQ-SF), which has been previously reported as a valid and reliable measure of physical activity.²⁹ It was completed by participants at the start of the study. Additional daily physical activity data were collected using a pedometer (Yamax Digiwalker SW-200, Tokyo, Japan). Participants were instructed to wear the pedometer either on the waist band, if available, or on the front pocket of their clothing. They attached the pedometer as they arose 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.²⁸

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.^{26,27} 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.²⁷ 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 (m/s^2) at
170 frequency f_i . and g is the gravitational acceleration (9.81 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_i*
 186 is the *i*th frequency in the Fourier series (Hz), *A_i* is the acceleration (m/s²) at frequency *f_i*. and
 187 *g* is the gravitational acceleration (9.81 m/s²).

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.²⁶

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.²⁷

200 IPAQ-SF Data: Questionnaires were analysed in accordance with guidelines produced
201 by the IPAQ Research Committee.³⁰ 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.³¹ Therefore the
211 pedometer data collected were pooled and an average daily step count over a two week
212 period was obtained.³² 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, ≥ 0.8 large.³³
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

241 The IPAQ-SF questionnaire revealed no significant difference in time spent on
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.^{27,34} 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.²⁷ 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 geometry³⁵, which is achievable through light and moderate physical activity. In addition
269 increased loading frequency has been associated with increased bone formation³⁶, 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.^{26,37,38} Previous work by Kelley et al.²⁷, 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.⁹⁻¹¹ 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.²⁷
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.¹⁴

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.³⁹ 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.^{14,40,41} 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,^{26,37,38} 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 body⁴² 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.,³⁷ 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.^{26,37,38} 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,³² or bone strength.⁴³

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,¹⁹⁻²¹ 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,^{21,30} 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.²¹ 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.²²

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.⁴⁴ 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 Test⁴⁵ 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.⁴²

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

430 **References**

- 431 1. WHO. Obesity and Overweight Fact Sheet No.311 2015.
432 www.who.int/mediacentre/factsheets/fs311/en/ Accessed 12/08/2015.
- 433 2. Allison DB, Downey M, Atkinson RL, et al. Obesity as a disease: A white paper on
434 evidence and arguments commissioned by the Council of The Obesity Society.
435 *Obesity*. 2008;16:1161-1177. doi: 10.1038/oby.2008.231.
- 436 3. Scheers T, Philippaerts R, Lefevre J. Patterns of physical activity and sedentary behavior in
437 normal-weight, overweight and obese adults, as measured with a portable
438 armband device and an electronic diary. *Clin Nutr*. 2012;31:756-764. doi:
439 10.1016/j.clnu.2012.04.011.
- 440 4. Shaw KA, Gennat HC, O'Rourke P, Del Mar C. Exercise for overweight or obesity.
441 *Cochrane Database of Systematic Reviews*. 2006(4):Art No.: CD003817. doi:
442 10.1002/14651858.CD003817.pub3.

- 443 5. Bell JA, Hamer M, van Hees VT, Singh-Manous A, Kivimaki M, Sabia S. Healthy obesity
444 and objective physical activity. *Am J Clin Nutr.* 2015;102:268-275. doi:
445 10.3945/ajcn.115.110924.
- 446 6. Hansen BH, Holme I, Anderssen SA, Kolle E. Patterns of objectively measured physical
447 activity in normal weight, overweight, and obese individuals (20–85 Years): A
448 cross-sectional study. *PLoS One.* 2013;8(1):e53044. doi:
449 10.1371/journal.pone.0053044.
- 450 7. Felson DT, Zhang Y, Hannan MT, Anderson JJ. Effects of weight and body mass index on
451 bone mineral density in men and women: The framingham study. *J Bone
452 Miner Res.* 1993;8(5):567-573. doi: 10.1002/jbmr.5650080507.
- 453 8. Shapses SA, Riedt CS. Bone, body weight, and weight reduction: What are the concerns? *J
454 Nutr.* 2006;136:1453-1456.
- 455 9. Shapses SA, Sukumar D. Bone metabolism in obesity and weight loss. *Annu Rev Nutr.*
456 2012;32:287-309. doi: 10.1146/annurev.nutr.012809.104655.
- 457 10. Sjøgaard AJ, Holvik K, Omsland TK, et al. Abdominal obesity increases the risk of hip
458 fracture. A population-based study of 43,000 women and men aged 60-79
459 years followed for 8 years. Cohort of Norway. *Journal of International
460 Medicine.* 2015;277(3):306-317. doi: 10.1111/joim.12230.
- 461 11. Zhao L, Jiang H, Papasian CJ, et al. Correlation of obesity and osteoporosis: Effect of fat
462 mass on the determination of osteoporosis. *J Bone Miner Res.* 2008;23(1):17-
463 29. doi: 10.1359/JBMR.070813.
- 464 12. Zhao L, Liu Y, Liu P, Hamilton J, Recker R, Deng H. Relationship of obesity with
465 osteoporosis. *The Journal of Clinical Endocrinology & Metabolism.*
466 2007;92(5):1640-1646. doi: 10.1210/jc.2006-0572.
- 467 13. Guadalupe-Grau A, Fuentes T, Guerra B, Calbet JAL. Exercise and bone mass in adults.
468 *Sports Med.* 2009;39(6):439-468.
- 469 14. Turner CH, Robling AG. Designing exercise regimens to increase bone strength. *Exercise
470 and Sport Science Reviews.* 2003;31(1):45-50.
- 471 15. Turner CH. Three rules for bone adaptation to mechanical stimuli. *Bone.* 1998;23(5):399-
472 407.

- 473 16. David V, Martin A, Lafage-Proust M, et al. Mechanical loading down-regulates
474 peroxisome proliferator-activated receptor γ in bone marrow stromal cells and
475 favors osteoblastogenesis at the expense of adipogenesis. *Endocrinology*.
476 2007;148(5):2553-2562. doi: 10.1210/en.2006-1704.
- 477 17. Robling AG, Turner CH. Mechanical signaling for bone modeling and remodeling. *Crit*
478 *Rev Eukaryot Gene Expr*. 2009;19(4):319-338.
- 479 18. Foley S, Quinn S, Jones G. Pedometer determined ambulatory activity and bone mass: A
480 population-based longitudinal study in older adults. *Osteoporos Int*.
481 2010;21:1809-1816. doi: 10.1007/s00198-009-1137-1.
- 482 19. Wee J, Sng BYJ, Chen L, Lim CT, Sungh G, De SD. The relationship between body mass
483 index and physical activity levels in relation to bone mineral density in
484 premenopausal and postmenopausal women. *Archives of Osteoporosis*.
485 2013;8(1-2):162. doi: 10.1007/s11657-013-0162-z.
- 486 20. Saravi FD, Sayegh F. Bone mineral density and body composition of adult
487 premenopausal women with three levels of physical activity. *Journal of*
488 *Osteoporosis*. 2013.
- 489 21. Langsetmo L, Hitchcock CL, Kingwell EJ, et al. Physical Activity, Body Mass Index and
490 Bone Mineral Density — Associations in a Prospective Population-based
491 Cohort of Women and Men: The Canadian Multicentre Osteoporosis Study
492 (CaMos). *Bone*. 2012;50(1):401-408. doi: 10.1016/j.bone.2011.11.009.
- 493 22. Lee PH, Macfarlane DJ, Lam TH, Stewart SM. Validity of the international physical
494 activity questionnaire short form (IPAQ-SF): A systematic review.
495 *International Journal of Behavioural Nutrition and Physical Activity*.
496 2011;8:115. doi: 10.1186/1479-5868-8-115.
- 497 23. Prince SA, Adamo KB, Hamel ME, Hardt J, Gorber SC, Tremblay M. A comparison of
498 direct versus self-report measures for assessing physical activity in adults: a
499 systematic review. *International Journal of Behavioral Nutrition and Physical*
500 *Activity*. 2008;5:56. doi: 10.1186/1479-5868-5-56.
- 501 24. Abel MG, Peritore N, Shapiro R, Mullineaux DR, Rodriguez K, Hannon JC. A
502 comprehensive evaluation of motion sensor step-counting error. *Applied*
503 *Physiology, Nutrition and Metabolism*. 2011;36:166-170. doi: 10.1139/H10-
504 095.

- 505 25. Crouter SE, Schneider PL, Bassett DR. Spring-levered versus piezo-electric pedometer
506 accuracy in overweight and obese adults. *Med Sci Sports Exerc.*
507 2005;37(10):1673-1679. doi: 10.1249/01.mss.0000181677.36658.a8.
- 508 26. Chahal J, Lee R, Luo J. Loading dose of physical activity is related to muscle strength
509 and bone density in middle-aged women. *Bone.* 2014;67:41-45. doi:
510 10.1016/j.bone.2014.06.029.
- 511 27. Kelley S, Hopkinson G, Strike S, Luo J, Lee R. An accelerometry-based approach to
512 assess loading intensity of physical activity on bone. *Res Q Exerc Sport.*
513 2014;85:245-250. doi: 10.1080/02701367.2014.897680.
- 514 28. Reeves S, Huber JW, Halsey LG, Villegas-Montes M, Elgumati J, Smith T. A cross-over
515 experiment to investigate possible mechanisms for lower BMIs in people who
516 habitually eat breakfast. *Eur J Clin Nutr.* 2015;69:632-637. doi:
517 10.1038/ejcn.2014.269.
- 518 29. Craig L, Marshall A, Sjöström M, et al. International Physical Activity Questionnaire: 12-
519 country reliability and validity. *Med Sci Sports Exerc.* 2003;35(8):1381-1395.
- 520 30. IPAQ. Guidelines for data processing and analysis of the International Physical Activity
521 Questionnaire (IPAQ) – short and long forms. 2005.
522 <https://sites.google.com/site/theipaq/scoring-protocol>. Accessed 24/06/2013.
- 523 31. Halsey LG, Huber JW, Low T, Ibeawuchi C, Woodruff P, Reeves S. Does consuming
524 breakfast influence activity levels? An experiment into the effect of breakfast
525 consumption on eating habits and energy expenditure. *Public Health Nutr.*
526 2011;15(2):238-245. doi: 10.1017/S136898001100111X.
- 527 32. Weeks BK, Beck BR. The BPAQ: A bone-specific physical activity assessment
528 instrument. *Osteoporos Int.* 2008;19:1567-1577. doi: 10.1007/s00198-008-
529 0606-2.
- 530 33. Cohen J. *Statistical Power Analysis for the Behavioral Sciences.* 2nd ed. Hillsdale, NJ:
531 Lawrence Earlbaum Associates; 1988.
- 532 34. Cappozzo A. Low frequency self-generated vibration during ambulation in normal men. *J*
533 *Biomech.* 1982;15(8):599-609.
- 534 35. Vainionpää A, Korpelainen R, Sievänen H, Vihriälä E, Leppäluoto J, Jämsä T. Effect of
535 impact exercise and its intensity on bone geometry at weight-bearing tibia and
536 femur. *Bone.* 2007;40:604-611. doi: 10.1016/j.bone.2006.10.005.

- 537 36. Hsieh Y, Turner CH. Effects of loading frequency on mechanically induced bone
538 formation. *J Bone Miner Res.* 2001;16(5):918-924.
- 539 37. Jämsä T, Vainionpää A, Korpelainen R, Leppäluoto J. Effect of daily physical activity on
540 proximal femur. *Clinical Biomechanics.* 2006;21:1-7. doi:
541 10.1016/j.clinbiomech.2005.10.003.
- 542 38. Vainionpää A, Korpelainen R, Vihriälä E, Rinta-Paavola A, Leppäluoto J, Jämsä T.
543 Intensity of exercise is associated with bone density change in premenopausal
544 women. *Osteoporos Int.* 2006;17:455-463. doi: 10.1007/s00198-005-0005-x.
- 545 39. Tobias JH, Gould V, Brunton L, et al. Physical activity and bone: may the force be with
546 you. *Front Endocrinol (Lausanne).* 2014;5.
547 <http://journal.frontiersin.org/article/10.3389/fendo.2014.00020/full>.
- 548 40. Umemura Y, Ishiko T, Yamauchi T, Kurono M, Mashiko S. Five jumps a day increase
549 bone mass and breaking force in rats. *J Bone Miner Res.* 1997;12:1480-1485.
- 550 41. Robling AG, Burr DB, Turner CH. Recovery periods restore mechanosensitivity to
551 dynamically loaded bone. *J Exp Biol.* 2001;204:3389-3399.
- 552 42. Smeathers JE. Transient vibrations caused by heel strike. *Proceedings of the Institute of*
553 *Mechanical Engineering Part H.* 1989;203:181-186.
- 554 43. Farr JN, Lee VR, Blew RM, Lohman TG, Going SB. Quantifying bone-relevant activity
555 and its relation to bone strength in girls. *Med Sci Sports Exerc.*
556 2011;43(3):476-483. doi: 10.1249/MSS.0b013e3181eeb2f2.
- 557 44. Ward DS, Evenson KR, Vaughn A, Brown Rodgers A, Troiano RP. Accelerometer use in
558 physical activity: Best practices and research recommendations. *Med Sci*
559 *Sports Exerc.* 2005;37(11S):S582-S588. doi:
560 10.1249/01.mss.0000185292.71933.91.
- 561 45. Grubbs FE. Procedures for detecting outlying observations in samples. *Technometrics.*
562 1969;11(1):1-21.
563

Table 1 Participant demographics (mean \pm SD).

Group	n	Sex	Age (y)	Height (m)	Body Mass (kg)	BMI (kg·m ⁻²)
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				
IPAQ-SF Data						
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
Pedometer Data						
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.

