



UWL REPOSITORY

repository.uwl.ac.uk

An accelerometry-based approach to assess loading intensity of physical activity on bone

Kelley, Sarah, Hopkinson, Georgina, Strike, Siobhan, Luo, Jin ORCID logoORCID:

<https://orcid.org/0000-0001-5451-9535> and Lee, Raymond (2014) An accelerometry-based approach to assess loading intensity of physical activity on bone. *Research Quarterly for Exercise and Sport*, 85 (2). pp. 245-250. ISSN 0270-1367

<http://dx.doi.org/10.1080/02701367.2014.897680>

This is the Accepted Version of the final output.

UWL repository link: <https://repository.uwl.ac.uk/id/eprint/6902/>

Alternative formats: If you require this document in an alternative format, please contact: open.research@uwl.ac.uk

Copyright:

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy: If you believe that this document breaches copyright, please contact us at open.research@uwl.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.

Rights Retention Statement:

LOADING INTENSITY ASSESSED BY ACCELEROMETRY

1 **An Accelerometry Based Approach To Assess Loading Intensity Of Physical Activity On Bone**

2

3

Sarah Kelley, Georgina Hopkinson, Siobhan Strike, Jin Luo, and Raymond Lee

4

Department of Life Sciences, University of Roehampton, London, UK

5

6

7

8 Correspondence:

9 Dr. Jin Luo

10 Department of Life Sciences

11 University of Roehampton

12 Holybourne Avenue

13 London SW15 4JD

14 UK

15 Tel: +44 (020) 83923000 ext 4699

16 Fax: +44(020) 83923610

17 Email: Jin.Luo@roehampton.ac.uk

18

19

LOADING INTENSITY ASSESSED BY ACCELEROMETRY

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22

ABSTRACT

Purpose: The purpose was to develop a new method for assessing the potential bone loading intensities of different locomotion activities by using accelerometers. **Method:** 30 participants (women: N = 19; men: N = 11), average age of 40 years (range: 22-81 years), performed eight activities (three self selected speeds of walking, three self selected speeds of running, ascending and descending stairs) in the workplace or at home, while wearing an accelerometer. The loading intensity for each activity was calculated from measured acceleration by a new method that considers both loading magnitude and frequency. A one- way repeated-measures ANOVA was employed to examine whether type of activity had any significant influence on the loading intensity. **Results:** The eight activities showed different loading intensities ($p < .001$). Running had higher loading intensity than walking and ascending or descending stairs ($p < .05$). The higher the speed of walking or running, the higher the loading intensity ($p < .05$). The increase of loading intensity in different activities was induced by both the increase of loading magnitude and the shift of loading frequency. **Conclusions:** This study developed a new method to measure loading intensity of physical activity on bone by using an accelerometer. This method can provide new insight for the assessment of exercise intensity in relation to bone health.

Key words: Natural environment; Loading magnitude; Loading frequency; Motion sensors

LOADING INTENSITY ASSESSED BY ACCELEROMETRY

1 An Accelerometry Based Approach To Assess Loading Intensity Of Physical Activity On Bone

2

3 The primary function of the bones is to provide support and muscle attachment to allow
4 effective locomotion. To fulfill this function bones need to be stiff and strong. The mechanical
5 property of a bone is determined by its mass, the distribution of the bone mass, and the quality of the
6 bone along with the material properties of the bone tissue. As a result of ageing, bone mass and bone
7 quality are reduced, resulting in weaker bone strength and stiffness. This loss of bone mass and
8 quality may eventually lead to the development of osteoporosis (Frost, 1997).

9 Bone is a living organ. Its mechanical property is regulated through two processes: bone
10 modeling in which bone mass and strength are increased; and bone remodeling in which bone mass
11 and strength are conserved or reduced (Frost, 1997). According to the ‘mechanostat theory’ the
12 functioning of these two processes are controlled by the bone strain induced by mechanical stress
13 placed upon the bone, along with other factors such as hormones (Frost, 1997). As physical activity
14 places the bones under stress, it can potentially lead to changes in bone mass, bone structure, and bone
15 strength by influencing the modeling and remodeling processes. To maintain the health of bone,
16 regular moderate to vigorous weight bearing activity, as well as high impact activity, are
17 recommended (Vuori, 2001). However, it is still unclear as to the exact frequency, intensity and
18 duration of exercise that is required for optimal effect on the health of bone. In order to understand and
19 evaluate the therapeutic effects of exercise programs it is essential to quantify the biomechanical
20 profiles of physical activities in order to identify the mechanical parameters that are most clinically
21 beneficial. For instance, osteogenic index (OI) has been adopted as a measure to quantitatively assess
22 bone loading in exercises (Turner & Robling, 2003). The development of OI was based on previous
23 experimental studies on bone adaptation to mechanical stimuli (Burr, Robling, & Turner, 2002). The
24 findings of these studies showed that there were three important factors that can determine bone
25 adaptation: loading magnitude, loading rate (frequency), and duration of loading. These three factors
26 were therefore incorporated into a mathematical formula to calculate OI, in which loading magnitude
27 was multiplied by loading frequency to represent the intensity of loading for an exercise (Turner &
28 Robling, 2003).

LOADING INTENSITY ASSESSED BY ACCELEROMETRY

1 Currently the loading intensities of exercises on bone are often assessed in the laboratory using
2 a force platform to measure ground reaction force, which were then used to calculate loading intensity
3 (Rantalainen et al., 2011). Although many researchers have used this force platform method to assess
4 the loading intensities, its limitations are evident: the exercise movements are performed in a
5 laboratory rather than a natural environment and the types of physical activities that can be assessed
6 are also limited to the time when the body is in contact with the force platform. To overcome these
7 limitations, it is warranted to develop a new assessment strategy that can be used in a natural
8 environment.

9 In recent years accelerometers have increasingly been used to assess mechanical loading in
10 physical activities (Ahola, Korpelainen, Vainionpaa, & Jamsa, 2010; Liikavainio et al., 2007;
11 Rowlands & Stiles, 2012). With the advantages of small size and weight, and the ability to provide
12 reliable measurement in natural environment (Liikavainio et al., 2007), accelerometers enable the
13 assessment of loading to be performed outside from the laboratory. To calculate loading intensity most
14 studies used acceleration parameters that are correlated with the magnitude of the peak ground
15 reaction force, such as peak acceleration (Ahola et al., 2010; Jamsa, Vainionpaa, Korpelainen,
16 Vihriala, & Leppaluoto, 2006) and acceleration counts (Rowlands & Stiles, 2012). Some studies used
17 acceleration parameters that are related to loading rate (frequency), such as the slop of the acceleration
18 signal (Heikkinen, Vihriala, Vainionpaa, Korpelainen, & Jamsa, 2007). However, to the authors'
19 knowledge there has been no study to date that includes both loading magnitude and frequency in the
20 calculation of loading intensity from acceleration data.

21 To fill in this gap we proposed in this study a new method of measuring both loading magnitude
22 and frequency to calculate loading intensity using acceleration data. The need for such a method is
23 supported by previous findings that different exercises could induce the change of loading magnitude
24 and the shift of loading frequency (Cappozzo, 1982), both of which could have significant effect on
25 bone adaptation (Burr et al., 2002). It would be very important to discern how loading magnitude and
26 loading frequency are modulated in different exercise interventions and how this may be related to the
27 different effects of exercises on bone health. However, these questions have not been investigated in
28 previous studies due to the lack of methods that can examine the loading intensity in the frequency

LOADING INTENSITY ASSESSED BY ACCELEROMETRY

1 domain for exercises performed in a natural environment. Therefore, the main aim of this study was to
2 develop such a new method that could quantitatively assess the gross loading intensity of common
3 physical activity of locomotion in the natural environment by using accelerometers. The secondary
4 aim was to examine whether the loading intensity calculated by this new method could reflect the
5 frequency domain characteristics of loading in different activities.

6

7

METHODS

8 **Participants**

9 Thirty participants (women: N=19; men: N=11) with average age of 40 years (range: 22-81
10 years) were recruited through personal contacts. The average weight and height of participants were
11 75 kg (range: 41-108 kg) and 1.69 m (range: 1.56-1.88 m) respectively. Inclusion criteria were that
12 they were free of any musculoskeletal injury or disability and were physically fit and able to
13 participate in the study. The study was approved by the University's ethical committee. Written
14 informed consent was obtained from all participants.

15 **Measure**

16 Acceleration was measured by an MSR three-axis accelerometer (model 145B, MSR
17 Electronics GmbH, Switzerland; size 39 x 23 x 72 mm; weight 16 g) that was securely attached by
18 double sided medical tape onto the skin of lower back at the level L5. This location was chosen due to
19 its proximity to the center of mass so that an overall loading intensity of the whole body could be
20 measured. The sampling frequency for the accelerometer was set at 50 Hz. The validity of MSR
21 accelerometers has been investigated in a previous field study which compared MSR with another
22 device (Actiwatch Spectrum, Philips Respironics, Amsterdam, NL) for the monitoring of sleep-wake
23 activity at high altitude. The results of that study showed that the acceleration measured by MSR was
24 highly correlated ($R=0.98$, $P<0.001$) with that by Actiwatch Spectrumh (Nussbaumer-Ochsner,
25 Schuepfer, Siebenmann, Maggiorini, & Bloch, 2011).

26 **Research Design**

27 The study was conducted as a within-subject design. Each participant performed eight different
28 activities in the natural environment (workplace or at home): slow walking, walking at normal pace,

LOADING INTENSITY ASSESSED BY ACCELEROMETRY

1 fast walking, slow running, running at normal pace, fast running, walking up and walking down a
2 standard flight of stairs. Walking and running activities were performed over a straight distance of 20
3 m. The variations of speed (slow, normal, and fast) in walking or running were controlled by
4 participants with the supervision of the author (SK).

5 **Procedure**

6 After accelerometer had been attached to the lower back, participants performed each activity
7 once. They first performed walking at their normal pace for 20 m. They then walked back to the
8 starting point at a slower pace before they walked as fast as they could for 20m. The same process was
9 then repeated on each participant to perform normal, slow and fast running. They then walked
10 normally up a standard flight of stairs consisting of around 15 steps of normal height and then return
11 back down again.

12 **Data Analysis**

13 The recorded acceleration data was acquired by a personal computer using the MSR software
14 (MSR 4.16). The raw data were then imported into MATLAB (version 7.10.0, R2010b; The
15 Mathworks, Inc, Massachusetts, U.S.A.). The resultant acceleration was computed. A length of four
16 seconds of resultant acceleration data from each movement was selected, which was then filtered
17 using a Butterworth bandpass filter (0.1 to 6 Hz) to remove the static gravitational acceleration and
18 noise. As the skin mounted accelerometer also measures the vibration signal transmitted from bone to
19 skin surface, the transmissibility of skin and soft tissues can influence the reliability of bone
20 acceleration measurement. The natural frequency of the skin and soft tissues covering lumbar spine
21 has been measured to be around 10 Hz (Smeathers, 1989). It was thus suggested that bone
22 accelerations can only be reliably measured on the skin at this location for frequency up to around 5
23 Hz (Smeathers, 1989). Therefore a cut-off frequency of 6 Hz was employed in this study to filter the
24 acceleration signals. Fast Fourier transformation was performed on the 4 seconds acceleration data to
25 obtain its Fourier series in frequency domain. As discussed before, the loading intensity of a physical
26 activity can be determined by the integration of the product of loading magnitude (the product of the
27 body mass and measured acceleration) and loading frequency (Turner & Robling, 2003). Hence,

LOADING INTENSITY ASSESSED BY ACCELEROMETRY

$$1 \quad LI = \sum_{f_i=0.1}^{6\text{Hz}} (M \times A_i) \times f_i$$

2 where LI is the loading intensity ($\text{N}\cdot\text{s}^{-1}$), f_i is the i th frequency in the Fourier series (Hz), M is the body
 3 mass (kg) of the participant, and A_i is the acceleration (m/s^2) at frequency f_i . The loading intensity was
 4 then normalized with respect to body weight (BW) as to allow comparison between different
 5 participants:

$$6 \quad LI_N = \sum_{f_i=0.1}^{6\text{Hz}} \frac{(A_i \times f_i)}{g}$$

7 where LI_N is the normalized loading intensity ($\text{BW}\cdot\text{s}^{-1}$) and g is the gravitational acceleration
 8 ($9.81\text{m}/\text{s}^2$). In order to further examine the distribution of loading intensities in the frequency domain
 9 (our secondary aim), the normalized loading intensity was calculated over three frequency bands: 0.1
 10 to 2, 2 to 4 and 4 to 6 Hz. The normalized loading magnitude was also calculated over each of the
 11 three frequency bands:

$$12 \quad LM_N = \sum_{f_i} \frac{A_i}{g}$$

13 where LM_N is the normalized loading magnitude (g).

14 A one-way repeated-measures ANOVA was employed to examine whether activity had any
 15 significant influence on the total normalized loading intensity from 0.1 to 6 Hz. Two-way repeated-
 16 measures ANOVAs were employed to examine the influence of activity on the normalized loading
 17 intensity and loading magnitude across the three frequency bands. Where a significant main effect or
 18 interaction effect was found, post-hoc paired comparison (with Bonferroni adjustment) was used to
 19 identify where the difference arose. Effect size was calculated as partial eta squared (η^2). SPSS
 20 (version 17.0, Inc, Chicago, IL) was used for statistical analysis. Significance was accepted at $p < .05$.

21

22

RESULTS

23 Four older participants more than 73 years old could not achieve the fast running trial. Two of
 24 them either could not use the stairs or did not live in accommodation that provided stairs. Therefore
 25 the repeated measure ANOVA was performed on data from 26 participants.

LOADING INTENSITY ASSESSED BY ACCELEROMETRY

1 As seen from Figure 1, different activities were found to have different loading intensities,
2 $F(7,175) = 162.0$, $p < .001$, partial $\eta^2 = .87$. Running had higher loading intensities than walking,
3 ascending or descending stairs, $p < .05$. The higher the speed of walking or running, the higher the
4 loading intensity, $p < .05$.

5 Loading intensity was significantly different among the three frequency bands, $F(2,350) =$
6 311.0 , $p < .001$, partial $\eta^2 = .93$, and across eight activities, $F(7,350) = 157.7$, $p < .001$, partial $\eta^2 = .86$.
7 There was a significant interaction effect between activity and frequency band on loading intensity,
8 $F(14,350) = 95.6$, $p < .001$, partial $\eta^2 = .79$. Loading magnitude was also significantly different among
9 the three frequency bands, $F(2,350) = 551.8$, $p < .001$, partial $\eta^2 = .96$, and across eight activities,
10 $F(7,350) = 165.0$, $p < .001$, partial $\eta^2 = .87$. There was a significant interaction effect between activity
11 and frequency band on loading magnitude, $F(14,350) = 76.7$, $p < .001$, partial $\eta^2 = .75$. These
12 interaction effects can be clearly seen from Figure 2: the contribution of high frequency band (2-4 Hz
13 and 4-6 Hz) to the total loading intensity and loading magnitude became larger with the increase of
14 walking and running speed. For example, compared with slow running, loading intensity in the three
15 frequency bands (0.1-2 Hz, 2-4 Hz and 4-6 Hz) increased by 10%, 35%, and 55% respectively in
16 normal running, and by 43%, 82%, and 118% respectively in fast running. Loading magnitude
17 showed the similar trend. However, compared with slow running, loading magnitude in the three
18 frequency bands increased by 13%, 23%, and 42% respectively in normal running, and by 46%, 52%,
19 and 102% respectively in fast running. It can be clearly seen that the amount of the increase in loading
20 magnitude in the two high frequency bands in normal running and fast running was not enough to
21 account for the increase of loading intensity in these two frequency bands (2-4 Hz: 23% vs. 35% in
22 normal running and 52% vs. 82% in fast running; 4-6 Hz: 42% vs. 55% in normal running and 102%
23 vs. 118% in fast running). It is likely that apart from the increase of loading magnitude, a shift towards
24 higher loading frequency within each of the two high frequency bands (2-4 Hz and 4-6 Hz) would also
25 have contributed to the increase of loading intensity. These results demonstrated that the increase of
26 loading intensity with the speed of walking or running was driven by both the increase of loading
27 magnitude and the shift of loading frequency.

LOADING INTENSITY ASSESSED BY ACCELEROMETRY

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28

DISCUSSION

The current study has developed a new method using accelerometers to assess loading intensity of physical activities. This method can be applied in a natural environment, and can assess the influence of both the magnitude and frequency of loading, which are two important factors that determine bone adaptation. As indicated in previous studies, the magnitude of internal loading determines the amount of strain imposed on the bone, which has been found to be proportional to the amount of bone formation (Rubin & Lanyon, 1984). The frequency of loading is also a very important parameter. Animal experiments demonstrated that bone formation is stimulated more effectively by loading applied at higher frequencies (Burr et al., 2002). In humans it was also found that dynamic exercises involving higher frequency mechanical loading are more effective to increase bone mineral density (Stengel et al., 2005). Different physical activities could induce different loading magnitudes and at the same time also induce different loading characteristics in the frequency domain (Cappozzo, 1982). As a consequence the change of loading intensity is the result of the interaction between loading magnitude and loading frequency, rather than either of these of two factors acting alone. This was clearly shown in our results that the change of loading magnitude with the running speed could not fully explain the change of loading intensity in the two high frequency bands (2-4 Hz and 4-6 Hz), which suggest that the shift of loading frequency within these two frequency bands must have contributed to the change of loading intensity. These results suggested that the new method developed in this study could provide a powerful tool to assess how exercise interventions can change loading intensity by modulating loading magnitude and loading frequency.

Previous studies have used either a subjective rating or an objective measurement method to quantify loading intensity. The subjective rating method involves assigning an arbitrary number (e.g. 1 or 2) to each physical activity as its loading intensity (Dolan, Williams, Ainsworth, & Shaw, 2006). On the other hand, objective measurement method requires ground reaction force (Rantalainen et al., 2011) or acceleration (Ahola et al., 2010) to be recorded by a force platform or an accelerometer, which could be used to calculate loading intensity. To the authors' knowledge, only one study (Rantalainen et al., 2011) has calculated loading intensity using both loading magnitude and frequency

LOADING INTENSITY ASSESSED BY ACCELEROMETRY

1 as suggested by Turner and Robling's OI (Turner & Robling, 2003). However, that study used force
2 platform which limited its application in a natural environment.

3 One limitation of the current study is the location of the accelerometer at lower back. Although
4 this location was chosen to provide an overall loading intensity measurement of the whole body due to
5 its proximity to the center of mass, it cannot provide accurate loading intensity measurement on
6 specific bones of other parts of the body such as femur and tibia. Previous studies have demonstrated
7 that impact accelerations at foot resulted from the contact with ground may be attenuated or amplified
8 during its transmission through human body (Smeathers, 1989), suggesting that loading on specific
9 bones can be assessed more accurately by attaching accelerometers to the location that is close to the
10 target skeletal site. However, the new method developed in this study can be easily applied to other
11 accelerometer locations where loading intensity measurement on specific bone (e.g. femur, tibia) is
12 needed. The current study filtered acceleration data at the cut-off frequency of 6 Hz to ensure the
13 reliable measurement of bone acceleration. Although this may be appropriate for the purpose of this
14 study as movement frequency at center of mass was found to be in the range of 0.3 to 3.5 Hz in most
15 daily physical activities (Mathie, Coster, Lovell, & Celler, 2004), it has its limitations as human gait
16 frequency content at other parts of the body can reach 9.8 Hz (Angeloni, Riley, & Krebs, 1994). To
17 solve this problem, a new method has been developed recently by our group to correct the artifacts
18 from skin movement so that bone acceleration higher than 6 Hz can also be measured reliably by skin-
19 mounted accelerometers (Morgado Ramirez, Strike, & Lee, 2013). Finally, it should also be pointed
20 out that although the osteogenic effect may be enhanced by increasing speed of walking or running,
21 we do not know if this could lead to a loss of body balance control and increase risks of falls.
22 However, this possibility is outside the scope of the current study and should be examined in future
23 work.

24

25 **What Does This Paper Add?**

26 The quantitative assessment of physical activity and exercise is crucial for understanding and
27 evaluating the effects of exercise programs on bone health. Previous studies found that both the
28 magnitude and the frequency of mechanical loading are important for bone adaptation. However, there

LOADING INTENSITY ASSESSED BY ACCELEROMETRY

1 is currently a lack of assessment methods that can quantify the influence of both loading magnitude
2 and frequency in physical activities performed in natural environment. To fill in this gap, this study
3 has developed a novel method to objectively measure loading intensity of everyday activities by using
4 accelerometer. This method can provide new insight for the assessment of exercise intensity in relation
5 to bone health. It has the potential to be developed into a tool to assess the therapeutic effects of
6 exercise and to provide feedback for people to improve their levels of physical activity.

7

8

LOADING INTENSITY ASSESSED BY ACCELEROMETRY

REFERENCES

- 1
2 Ahola, R., Korpelainen, R., Vainionpaa, A., & Jamsa, T. (2010). Daily impact score in long-term
3 acceleration measurements of exercise. *Journal of Biomechanics*, 43(10), 1960-1964. doi:
4 10.1016/j.jbiomech.2010.03.021
- 5 Angeloni, C., Riley, P. O., & Krebs, D. E. (1994). Frequency content of whole body gait kinematic
6 data. *IEEE Transaction on Rehabilitation Engineering*, 2(1), 40-46.
- 7 Burr, D. B., Robling, A. G., & Turner, C. H. (2002). Effects of biomechanical stress on bones in
8 animals. *Bone*, 30(5), 781-786. doi: S875632820200707X [pii]
- 9 Cappozzo, A. (1982). Low frequency self-generated vibration during ambulation in normal men.
10 *Journal of Biomechanics*, 15(8), 599-609.
- 11 Dolan, S. H., Williams, D. P., Ainsworth, B. E., & Shaw, J. M. (2006). Development and
12 reproducibility of the bone loading history questionnaire. *Medicine and Science in Sports and*
13 *Exercise*, 38(6), 1121-1131. doi: 10.1249/01.mss.0000222841.96885.a8
- 14 Frost, H. M. (1997). On our age-related bone loss: insights from a new paradigm. *Journal of Bone and*
15 *Mineral Research*, 12(10), 1539-1546. doi: 10.1359/jbmr.1997.12.10.1539
- 16 Heikkinen, R., Vihriala, E., Vainionpaa, A., Korpelainen, R., & Jamsa, T. (2007). Acceleration slope
17 of exercise-induced impacts is a determinant of changes in bone density. *Journal of*
18 *Biomechanics*, 40(13), 2967-2974. doi:10.1016/j.jbiomech.2007.02.003
- 19 Jamsa, T., Vainionpaa, A., Korpelainen, R., Vihriala, E., & Leppaluoto, J. (2006). Effect of daily
20 physical activity on proximal femur. *Clinical Biomechanics (Bristol, Avon)*, 21(1), 1-7. doi:
21 S0268-0033(05)00236-6 [pii]10.1016/j.clinbiomech.2005.10.003
- 22 Liikavainio, T., Bragge, T., Hakkarainen, M., Jurvelin, J. S., Karjalainen, P. A., & Arokoski, J. P.
23 (2007). Reproducibility of loading measurements with skin-mounted accelerometers during
24 walking. *Archives of Physical Medicine and Rehabilitation*, 88(7), 907-915. doi: S0003-
25 9993(07)00260-2 [pii]10.1016/j.apmr.2007.03.031
- 26 Mathie, M. J., Coster, A. C., Lovell, N. H., & Celler, B. G. (2004). Accelerometry: Providing an
27 integrated, practical method for long-term, ambulatory monitoring of human movement.
28 *Physiological Measurement*, 25(2), R1-20.

LOADING INTENSITY ASSESSED BY ACCELEROMETRY

- 1 Morgado Ramirez, D. Z., Strike, S., & Lee, R. Y. (2013). Measurement of transmission of vibration
2 through the human spine using skin-mounted inertial sensors. *Medical Engineering and*
3 *Physics*. doi: S1350-4533(13)00007-6 [pii]10.1016/j.medengphy.2012.12.013
- 4 Nussbaumer-Ochsner, Y., Schuepfer, N., Siebenmann, C., Maggiorini, M., & Bloch, K.E. (2011).
5 High altitude sleep disturbances monitored by actigraphy and polysomnography. *High*
6 *Altitude Medicine & Biology*, 12(3), 229-236. doi: DOI: 10.1089/ham.2010.1073
- 7 Rantalainen, T., Hoffren, M., Linnamo, V., Heinonen, A., Komi, P. V., Avela, J., & Nindl, B. C.
8 (2011). Three-month bilateral hopping intervention is ineffective in initiating bone biomarker
9 response in healthy elderly men. *European Journal of Applied Physiology*, 111(9), 2155-2162.
10 doi: 10.1007/s00421-011-1849-8
- 11 Rowlands, A. V., & Stiles, V. H. (2012). Accelerometer counts and raw acceleration output in relation
12 to mechanical loading. *Journal of Biomechanics*, 45(3), 448-454. doi: S0021-290(11)00769-X
13 [pii]10.1016/j.jbiomech.2011.12.006
- 14 Rubin, C. T., & Lanyon, L. E. (1984). Regulation of bone formation by applied dynamic loads.
15 *Journal of Bone and Joint Surgery American Volume*, 66(3), 397-402.
- 16 Smeathers, J. E. (1989). Transient vibrations caused by heel strike. *Proceedings of the Institute of*
17 *Mechanical Engineering Part H*, 203(4), 181-186.
- 18 Stengel, S. V., Kemmler, W., Pintag, R., Beeskow, C., Weineck, J., Lauber, D., . . . Engelke, K.
19 (2005). Power training is more effective than strength training for maintaining bone mineral
20 density in postmenopausal women. *Journal of Applied Physiology*, 99(1), 181-188. doi:
21 01260.2004 [pii]10.1152/jappphysiol.01260.2004
- 22 Turner, C. H., & Robling, A. G. (2003). Designing exercise regimens to increase bone strength.
23 *Exercise and Sport Sciences Reviews*, 31(1), 45-50.
- 24 Vuori, I. M. (2001). Dose-response of physical activity and low back pain, osteoarthritis, and
25 osteoporosis. *Medicine and Science in Sports and Exercise*, 33(6 Suppl), S551-586; discussion
26 609-610.
27

LOADING INTENSITY ASSESSED BY ACCELEROMETRY

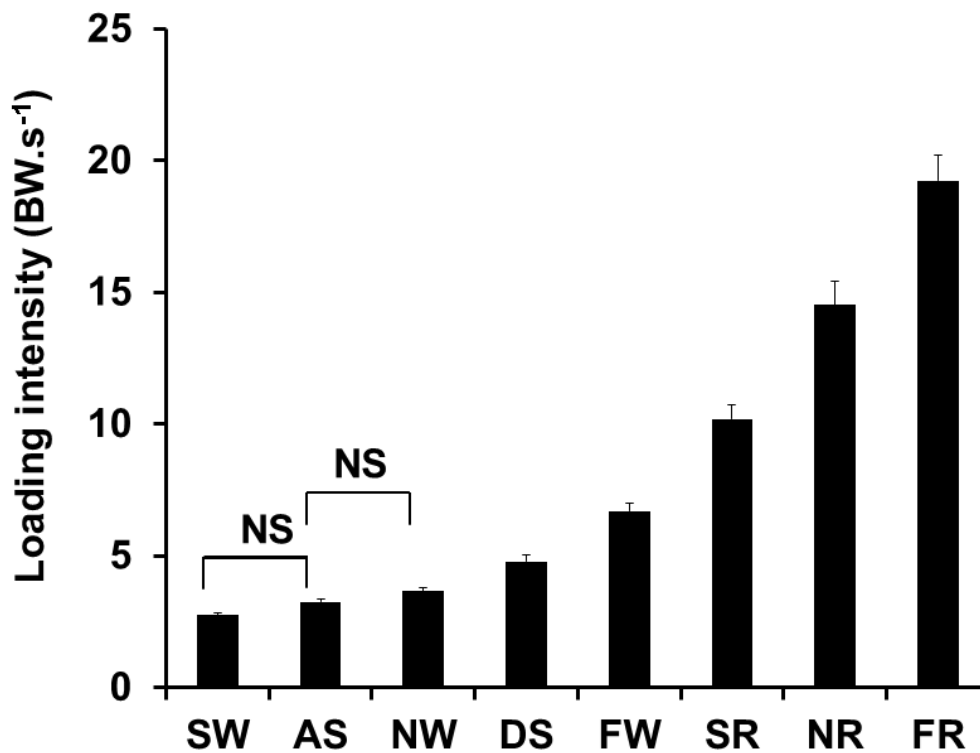


Figure 1. Mean loading intensity of eight different activities. Error bars indicate the standard error of means. NS=not significantly different; SW=slow walking; AS=ascending stairs; NW=normal walking; DS=descending stairs; FW=fast walking; SR=slow running; NR=normal running; FR=fast running.

LOADING INTENSITY ASSESSED BY ACCELEROMETRY

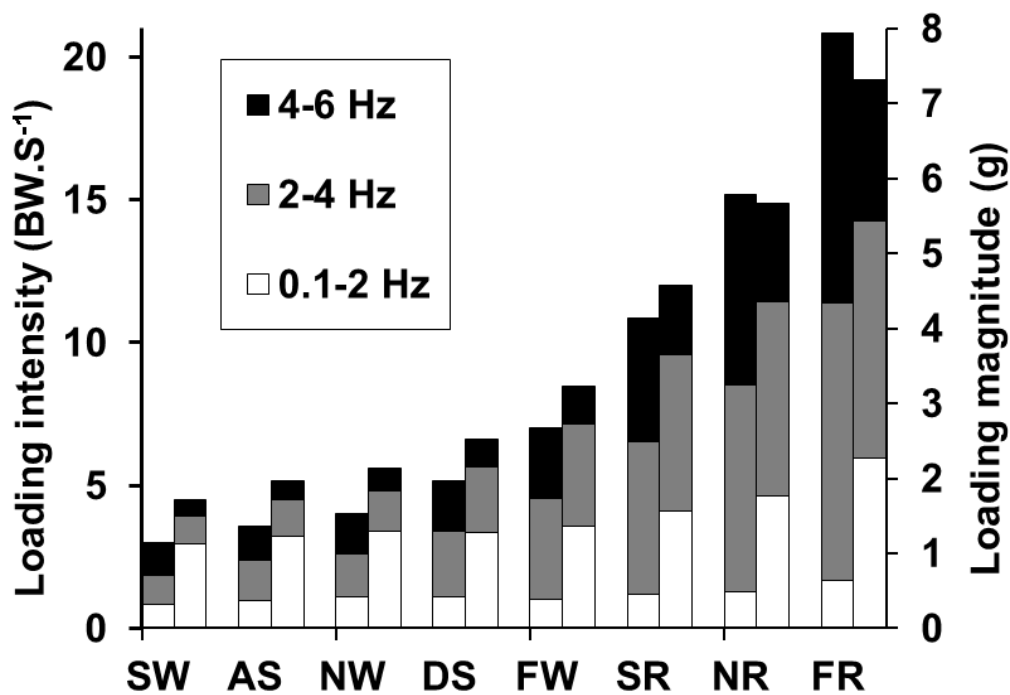


Figure 2. Distribution of normalized loading intensity and loading magnitude at three different frequency bands (0.1 – 2, 2 – 4 and 4 - 6 Hz) in different activities. For each activity the stacked column on the left represents loading intensity, and the stacked column on the right represents loading magnitude. SW=slow walking; AS=ascending stairs; NW=normal walking; DS=descending stairs; FW=fast walking; SR=slow running; NR=normal running; FR=fast running.