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

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## 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

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

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

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

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

To fill in this gap we proposed in this study a new method of measuring both loading magnitude and frequency to calculate loading intensity using acceleration data. The need for such a method is supported by previous findings that different exercises could induce the change of loading magnitude and the shift of loading frequency (Cappozzo, 1982), both of which could have significant effect on bone adaptation (Burr et al., 2002). It would be very important to discern how loading magnitude and loading frequency are modulated in different exercise interventions and how this may be related to the different effects of exercises on bone health. However, these questions have not been investigated in previous studies due to the lack of methods that can examine the loading intensity in the frequency domain for exercises performed in a natural environment. Therefore, the main aim of this study was to develop such a new method that could quantitatively assess the gross loading intensity of common physical activity of locomotion in the natural environment by using accelerometers. The secondary aim was to examine whether the loading intensity calculated by this new method could reflect the frequency domain characteristics of loading in different activities.

## METHODS

### Participants

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

### Measure

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

### Research Design

The study was conducted as a within-subject design. Each participant performed eight different activities in the natural environment (workplace or at home): slow walking, walking at normal pace, fast walking, slow running, running at normal pace, fast running, walking up and walking down a standard flight of stairs. Walking and running activities were performed over a straight distance of 20 m. The variations of speed (slow, normal, and fast) in walking or running were controlled by participants with the supervision of the author (SK).

**Procedure**

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

**Data Analysis**

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

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

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

$$LI\_N = \sum_{f_i = 0.1}^{6Hz} \frac{(A_i \times f_i)}{g}$$

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

$$LM\_N = \sum_{f_i} \frac{A_i}{g}$$

where $LM\_N$ is the normalized loading magnitude ($g$).

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

## RESULTS

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

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

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

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

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

## What Does This Paper Add?

The quantitative assessment of physical activity and exercise is crucial for understanding and evaluating the effects of exercise programs on bone health. Previous studies found that both the magnitude and the frequency of mechanical loading are important for bone adaption. However, there is currently a lack of assessment methods that can quantify the influence of both loading magnitude and frequency in physical activities performed in natural environment. To fill in this gap, this study has developed a novel method to objectively measure loading intensity of everyday activities by using accelerometer. This method can provide new insight for the assessment of exercise intensity in relation to bone health. It has the potential to be developed into a tool to assess the therapeutic effects of exercise and to provide feedback for people to improve their levels of physical activity.

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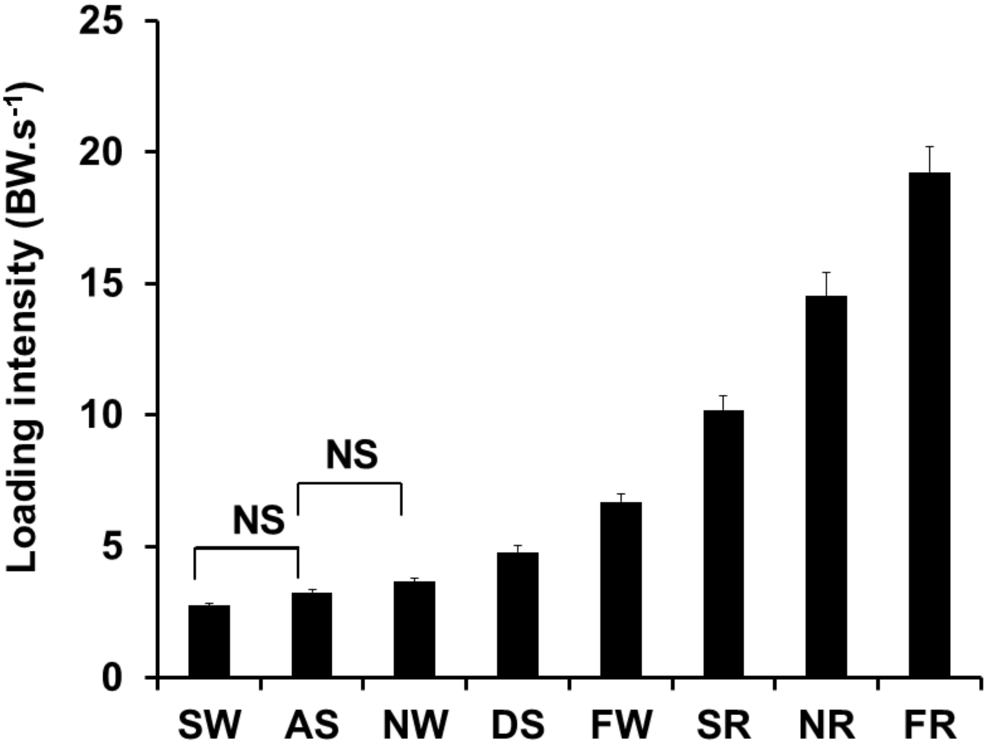

Figure 1. Mean loading intensity of eight different activities. Error bars indicate the standard error of means. NS=not significantly different; SW=slow walking; AS=ascending stairs; NW=normal walking; DS=descending stairs; FW=fast walking; SR=slow running; NR=normal running; FR=fast running.

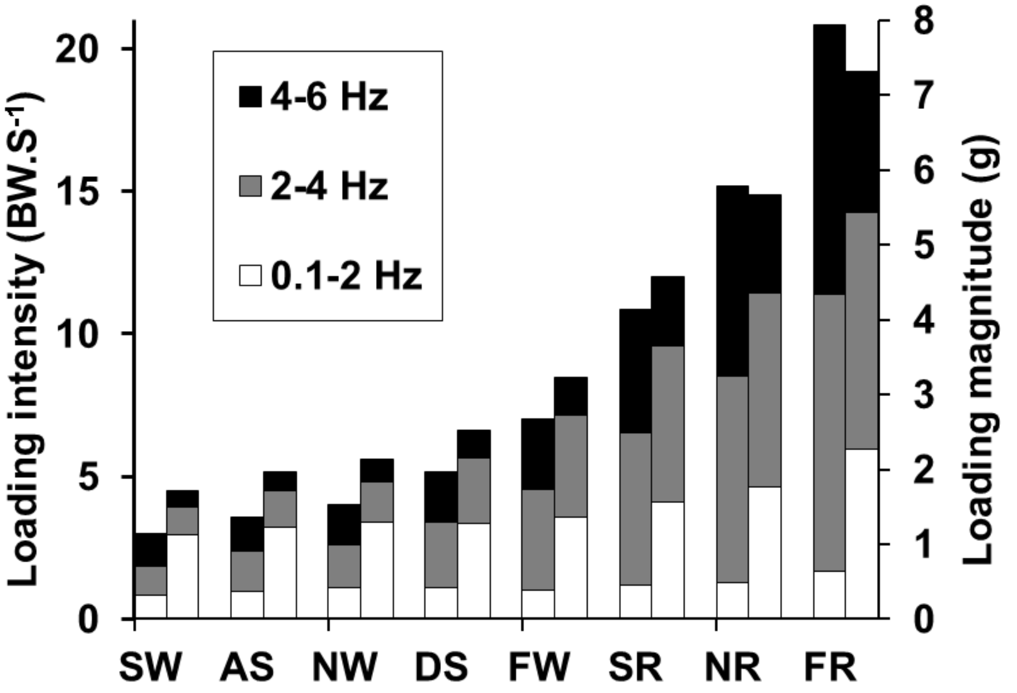

Figure 2. Distribution of normalized loading intensity and loading magnitude at three different frequency bands (0.1 – 2, 2 – 4 and 4 - 6 Hz) in different activities. For each activity the stacked column on the left represents loading intensity, and the stacked column on the right represents loading 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.