ACCELEROMETER-BASED LONG-TERM MONITORING OF PHYSICAL EXERCISE

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Abstract: The incidence of osteoporotic fractures is increasing and has become one of the major health problems in developed countries. High-impact physical activities have been suggested to be effective in improving proximal femur bone mineral density (BMD). However, there has been no method to evaluate the optimal quality and quantity of exercise. Recently, we have studied the accelerometric method for quantification of physical activity. The method was applied in a population-based randomized intervention study of premenopausal women to evaluate the effect of the intensity of impact exercise on bone. The method appeared to be feasible for long-term monitoring of physical exercise and the device was well accepted. It was able to quantify the main impact characteristics. During the intervention study, it was able to record the intensity level of physical activity. Increased physical activity resulted in increased BMD at most weight-bearing measurement sites. Significant relationships between physical activity data and different bone parameters were found. The study showed that the quantity and quality of exercise can be monitored with the accelerometer-based physical activity monitor. The method could be useful in optimizing exercise for prevention of osteoporosis.

Introduction

The incidence of osteoporotic fractures is increasing and fractures have become one of the major health problems in developed countries. The ageing of the population will further increase the health hazards and economic costs due to this problem. Hip fracture is the most serious osteoporotic fracture with high related mortality. Although therapeutic effects of medical treatment have been shown [1], there is a need for preventive strategies at the population level. High-impact physical activities have been suggested to be effective in improving proximal femur bone mineral density (BMD) [2,3]. However, there has been no method to evaluate the optimal quality and quantity of exercise. Thus, we aimed to find a suitable method for monitoring skeletal exercise.

There are some specific requirements for monitoring exercise with respect to bone health. Bone adaptation is a function of mechanical loading, and the response of bone to mechanical stimuli is known to be threshold driven [4,5]. Thus, the method has to be able to measure the intensity of mechanical loading. In addition, bone response is very slow, from months to years, and long-term monitoring is needed.

The existing measurement methods are not applicable for monitoring bone exercise. Direct measurement of strains and stresses with strain gauges or pressure sensors is invasive and can only be used in experimental studies. Measurement of ground reaction forces (GRF) with a force plate is widely used in gait analysis and sport and exercise studies. However, the method is limited to a fixed place and time. Heart rate monitor can be applied for assessing the cardiovascular exertion during exercise, but it is not able to measure mechanical loading. Pedometers are used to record the number of steps. However, their threshold is adjusted for walking and they do not measure the intensity of impacts.

Recently, we have studied the accelerometric method for quantification of physical activity [6,7]. We applied the method in a population-based randomized intervention study in premenopausal women [8] to evaluate the effect of the intensity of impact exercise on bone [9-11]. Here we overview the method and its feasibility in long-term monitoring of exercise.

Materials and Methods

Accelerometric measurement can be considered as an indirect method for recording the intensity of impact loading (Fig. 1). In our study, we used an accelerometer worn at waist level, close to the right iliac crest, to have an estimate for the local loading at the hip.

First we studied the reliability of the accelerometer-based method using a three-dimensional prototype [6]. Briefly, the device consisted of three accelerometers (SCA-320, VTI Technologies, Finland),

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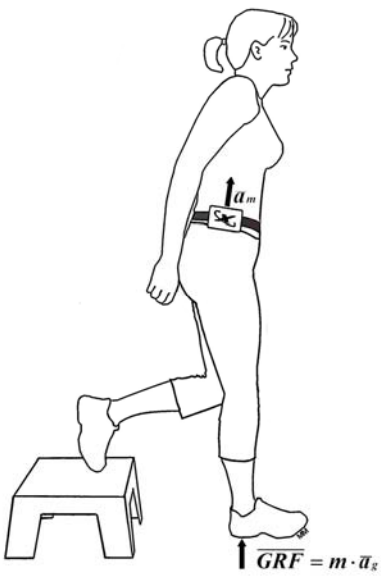

Figure 1: Accelerometric measurement of the local intensity of impact loading at the hip. [10]

connected orthogonally, and a data logger (Tattletale Model 8v2 Data Logger, Onset Computer Corp., USA) with a sampling rate of 400 Hz. A data reduction method was adopted to maintain the principal characteristics of each acceleration peak. The average peak amplitude error of the device was less than 2 % when compared with a reference sensor on a vibration tester [6].

Next, we performed a pilot study with 10 women (age 20–58 years, BMI 19.1-29.7 kg/m^2) to validate the method and to estimate typical vertical acceleration levels attained in different exercise patterns, using the prototype. The acceleration of gravity (1 g) was subtracted, so that a value of zero corresponded to standing (= zero impact). The peak impact acceleration was predominantly obtained immediately after the heel contact (Fig. 2).

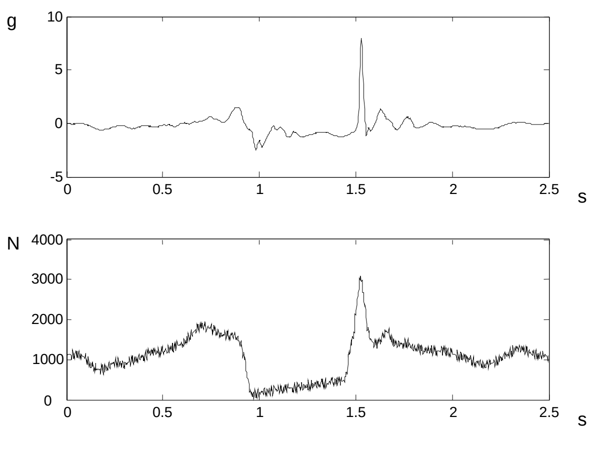

Figure 2: Accelerometric signal (upper) and ground reaction force (lower) during a jump. [10]

The reproducibility error, given as the root-mean-square coefficient of variation (CV_{RMS}), was 4.0 %. The peak acceleration values had a high correlation (*R* = 0.989; n = 572 recordings) with the values obtained simultaneously using a standard optical motion analysis system (MacReflex, Qualisys Ab, Sweden), operating at a rate of 100 frames/s (Fig. 3) [7], showing that the method reliably measures the local acceleration at the hip. The acceleration values also had a significant correlation with the GRF (*R* = 0.735 for the peak acceleration values, *R* = 0.937 for the area under the acceleration peaks; n = 462 recordings), measured with a force plate (Kistler 9287A with a Kistler 9865C charge amplifier, Kistler Instrumente AG, Switzerland), when the acceleration values were multiplied by body weight [9].

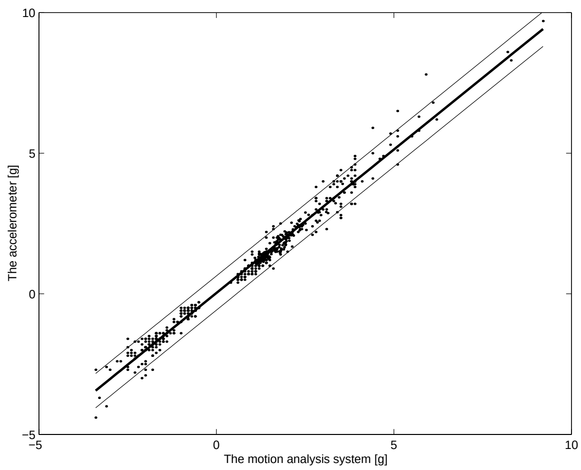

Figure 3: Relationship between the accelerometric method and motion analysis. Regression line and the 95% prediction limits; *R* = 0.989; n = 572. [7]

The average peak vertical acceleration levels were 0.8 g, 3.2 g and 4.2 g in walking at 5 km/h, running at 9 km/h and running at 13 km/h, respectively. The average peak values for aerobic stepping, lateral jumping, counter-movement jumps, jumps without counter-movement, and drop jumps from 40 cm were 1.2 g, 2.0 g, 4.4 g, 4.6 g and 5.6 g, respectively. [9]

Finally, the method was applied in a population-based randomized intervention study of premenopausal women [8] to evaluate the effect of the intensity of impact exercise on bone [9-11]. In this part of the study, we used a one-dimensional accelerometer-based body movement monitor (Newtest Ltd., Oulu, Finland) [12] to record the vertical peak acceleration values of impacts in long-term, the number of impacts at different acceleration levels describing the intensity of exercise. The monitor was worn on a belt close to the right iliac crest. The continuous recording time was several weeks. The physical activity monitor was validated against the prototype [6] in simultaneous measurements during exercise training, showing a high correlation between the activity monitor and the prototype (*R* = 0.971; n = 41 subjects) [9].

The intervention study consisted originally of 120 premenopausal women (age 35-40 years) [8]. For the individual quantification of their daily physical activity, all subjects were asked to carry the monitor at their waist daily, during all waking hours, for 12 months. The monitor recorded the data at the sampling rate of 400 samples per second, filtered, pre-analyzed and classified the impact peaks according to peak acceleration. The classified data were transferred to a server computer approximately every second week. The daily number of impacts was analyzed at 33 acceleration levels from 0.3 to 9.9 g, 0 corresponding to standing (the acceleration of gravity subtracted). The individual daily average number of impacts at each acceleration level was calculated for the analysis. The relationship between the physical activity data and different bone parameters, measured by dual-energy X-ray absorptiometry (DXA) (Hologic Delphi QDR, Bedford, Massachusetts, USA), computed tomography (CT) (Siemens Somatom Emotion, Munich, Germany) with the Geanie 2.1 bone analysis software (Bonalyse Ltd., Jyväskylä, Finland), peripheral DXA (Osteometer DTX200, Roedovre, Denmark) and quantitative ultrasound (QUS) (Hologic Sahara, Bedford, Massachusetts, USA) was evaluated. All measurements were performed at the beginning and at the end of the 12-month intervention.

The individual daily average number of impacts at 33 acceleration levels was defined. The average daily numbers were normalized relative to the corresponding mean values of the controls. Pearson's correlation coefficients were used to study the association between the relative number of acceleration peaks at each level and the percentage BMD changes. The study groups were pooled for correlation analysis. The data were analyzed using the SPSS statistical package (ver. 11.5 for Windows, SPPS Inc. Chicago, Illinois, USA

Results

The validation studies showed that the accelerometric measurement of local acceleration at the waist is highly reproducible and accurate when compared to the optical movement analysis or ground force measurements [6,7,9]. The method appeared to be feas-

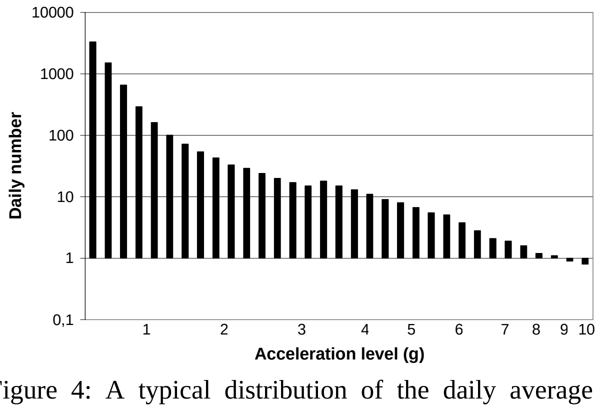

Figure 4: A typical distribution of the daily average number of impacts at different acceleration levels.

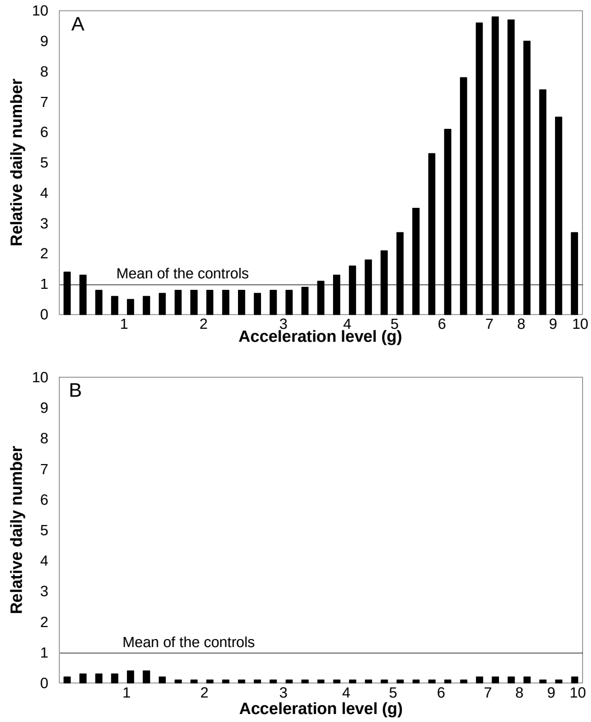

Figure 5: Distribution of the daily average number of impacts, normalized relative to the mean values of the control subjects. (A) An example of a very active person with high relative number of impacts at higher acceleration levels, while her number of impacts at lower levels is normal. (B) A physically inactive person with low relative number of impacts at all levels.

ible for long-term monitoring of physical exercise in a population-based randomized cohort of women, where it was able to record the intensity level of exercise. (Figures 4,5).

The device was moderately well accepted. Relevant physical activity data was available from 64 out of 80 subjects who completed the original intervention study, representing a compliance of 80 %. The monitor was able to quantify the main impact characteristics. A total of ca. 150 million impacts were recorded during the study.

The significant relationships between physical activity data and different bone parameters were presented in more detail elsewhere [9-11]. Briefly, physical activity that induced acceleration levels exceeding 3.9 g correlated positively with the BMD change in the hip area [9]. Significant association was also found between the cross-sectional geometry of the femur and tibia as defined by CT, even at the lower accelerations of 1.1 g upwards [11]. Ultrasound speed-of-sound (SOS) at the calcaneus correlated with physical activity at 1.1-2.4 g [9].

Discussion

We presented here the feasibility of accelerometer-based measurement in long-term quantification of physical activity. It was able to reliably quantify the

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main impact characteristics and to record the intensity level of exercise in a population-based cohort of women. The device was moderately well accepted, suggesting that the method might be suitable for use in normal daily life.

We used here continuous long-term accelerometer-based monitoring of physical activity. There are several methods of analyzing accelerometric data; for example root-mean-square average, power spectrum integral and acceleration count have been used as measures of activity [13-16]. The daily number of vertical acceleration peaks at different acceleration levels was used here to assess the intensity of exercise in more detail.

We found that the highest acceleration at the vertical direction was related to the heel strike, which is in good agreement with previous studies [14-15]. The acceleration level of impacts was found to correlate with ground reaction force during different exercise patterns. This confirms the use of the accelerometric method as an estimate of mechanical loading.

In previous intervention studies, the assessment of exercise intensity has been based on the ground reaction forces of model performances. The intensity of exercise has been suggested to be defined by the loads applied to the bone [17]. Our findings are complementary to previous results, giving information on the acceleration levels for exercise. Here, low- or moderate-intensity impact training below the acceleration level of 4 g was not equally effective for the proximal femur BMD as high-impact exercise including accelerations of 4 g or more. We have reported net accelerations, where zero impact was adjusted to 0 g. Thus, the total loading affecting the bone is still 1 g higher when the acceleration of gravity is included. However, any comparison of the results of the previous studies with our data is difficult due to different methods for assessing the intensity of exercise. We used an accelerometric sensor that was attached on the subject, and the recordings can not be compared directly to ground reaction forces. Anyway, the moving sensor may give even more accurate local loading estimates than GRF measurements do. Here the monitor was worn on a belt close to the right iliac crest to have an estimate for the loading at the hip.

The association between physical activity and changes in BMD and bone geometry was found to be dependent on the acceleration level of impacts. Thus, the method might be useful for optimizing exercise for prevention of osteoporosis.

Conclusions

The accelerometer-based method seems to be a feasible method for long-term monitoring of physical exercise. The quantity and quality of bone exercise can be monitored with the accelerometer-based physical activity monitor, and the method could be useful for optimizing exercise for prevention of osteoporosis.

Acknowledgements

We acknowledge Ms Minna Tervo for her dedication and hard work in supervising the training of the subjects during the intervention study. We thank Dr. Pentti Nieminen, for statistical advice, and Mikko Määttä for assistance with figures. The study was financially supported by the National Technology Agency of Finland; Newtest Ltd., Oulu, Finland; CCC Group, Oulunsalo, Finland; Fastrax Ltd., Vantaa, Finland; the Juho Vainio Foundation; the Research Foundation of the Institutes of Sports; and the Finnish Foundation for Sports Research.

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