Acceleration-Based Study of Optimum Exercise for Human Weight-Bearing Bones Enhancement

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Abstract

Physical activity is known to enhance the mechanical competence of bones. However, previous related studies provide little information regarding the optimum exercises for the prevention of osteoporosis in the lumbar region, including the hip joints. Physical activities can be evaluated by simultaneously collecting acceleration data from accelerometers worn on different parts of the body. We attached three triaxial accelerometers to the ankle, knee, and lumbar points of 20 young women subjects in order to perform acceleration measurements while walking (a flat surface and a stairway) and jumping rope. The acceleration at the lumbar point while walking a flat surface, ascending stairs, and descending stairs were 1.96 ± 0.28, 1.92 ± 0.29, and 2.88 ± 0.66 G, respectively. On the other hand, jumping rope provided an acceleration of 5.4 G at the lumbar point. This value is higher than the threshold acceleration necessary to induce an osteogenic response in the lumbar region of young subjects, namely 3.5 G. Descending stairs provided the second-highest intensity of acceleration in the lumbar region; however, it also produced excess impact acceleration at the ankle and knee points. Jumping rope, in contrast, provided sufficient intensity of acceleration in the lumbar region, but the acceleration imparted to the ankle and knee points remained at a tolerable level. Moreover, correlation analyses of the acceleration at the ankle, knee, and lumbar points during each physical activity showed that the knee joints solely regulated the strong landing impact force while the subjects were descending the flight of stairs. In comparison, while jumping rope, the ankle and hip joints regulated the large landing impact force cooperatively, without overloading themselves. Our results suggest that jumping rope can provide sufficient acceleration to induce an osteogenic response in the lumbar region without causing an overload to any joints. Thus, jumping rope is one of the most optimum exercises for bone mineral gain in the proximal femur and lumbar vertebrae regions in young subjects. ©2010 Jpn. Soc. Biol. Sci. Space; Article ID: 102402006

Keywords: Acceleration; Osteoporosis prevention; Physical activity; Jumping rope; Walking

Introduction

Bone is a rigid organ but not a stationary tissue. It is constantly being remodeled through breaking down by osteoclastic absorption and rebuilding by osteoblastic formation. These processes enable the bone to restructure itself in response to daily mechanical stress. This self-restructuring of bones has been referred to as the mechanostat theory which claims that bone is added where it is needed and removed from where it is not (Frost, 1987).

Space flight, bed rest, and immobilization are well known causes that induce bone loss. The rate of bone loss in the skeleton is related to the level of normal bio-mechanical stress and strain to which the bone is subjected. Space flight tends to affect the weight-bearing bones (tibia, femur, and vertebrae), where all the daily gravitational mechanical stress acts, more than the non-weight-bearing bones (radius and ulna) (for a review see Carmeliet et al., 2001). Development of site-specific bone loss in weight-bearing bones has also been found in post-menopausal osteoporosis. Therefore, from the young to the elderly, the beneficial effects of mechanical loading on weight-bearing bones are well known. In young people, high-impact exercise has positive effects on bone enhancement of the peak bone mass attained (Mosley et al., 1997; Courteix et al., 1998; Judex and Zernicke, 2000). In addition, there is overwhelming experimental and clinical evidence that osteogenic response of bone to mechanical stimuli is threshold-
driven (Mosley et al., 1997; Hsieh et al., 2001; Borer et al., 2007). Therefore, it is very important to precisely measure the load acting on weight-bearing bones during exercise, and to investigate the quantitative threshold level of an osteogenic response.

We have recently developed a new accelerometer-based physical activity monitoring instrument, which permits precise measurement of the magnitude of acceleration during exercise at the distal (ankle and knee) and proximal (lumbar) points of the body (Kitamura et al., 2009). Our instrument has the advantage of high sampling rate in acceleration recording, including acceleration during impact. Using this instrument, we have quantified load acceleration at each point of weight-bearing bone during activities, such as, walking or jumping. We have also discussed potential exercises that have positive effects on bone enhancement or suppress osteoclastic bone absorption.

Materials and Methods

Subjects

Twenty healthy female students (Age: 21.2 ± 0.7 years, BMI: 20.9 ± 1.3 kg/m²) who had no history of neurological disorders or musculoskeletal pathology were employed as volunteers. Each subject gave a written informed consent prior to participation in this study, which was approved by the Kanazawa University Human Research Ethics Committee.

Acceleration measurement system

The accelerometer-based physical activity monitoring instrument consists of three triaxial (X-, Y-, and Z-axes) accelerometers (Microstone, MA3-20Ac, MA3-10Ac, and MA3-4Ac, Japan), a 16-bit analog-to-digital converter board (CONTEC ADA16-32/2(CB)/F, Japan), and a data logger (SHARP PC-MM1-H5W, Japan). The frequency characteristic of three triaxial accelerometers is 0.8–1000 Hz and their sensing ranges are ±20 G (MA3-20Ac), ±10 G (MA3-10Ac), and ±4 G (MA3-4Ac). The data logger accumulates nine output signals from the three triaxial accelerometers at time intervals of 1 ms.

Each subject wore a data logger and accelerometers were placed on the surface of the left shank of the body 3 cm proximal to the lateral malleolus (ankle point), left lateral aspect of the thigh 2 cm proximal to the lateral epicondyle of femur (knee point), and vertebral column on the Jacoby’s line (lumbar point) (Fig. 1A). Two sport gears and a medical support belt were used to firmly fix the three accelerometers to the body surface at the ankle, knee, and lumbar points, respectively.

Physical activities

Acceleration measurements were performed while the subject was walking along a flat corridor, ascending and descending a stairway, and jumping rope. For a walking along the corridor, we measured acceleration at 3, 4, and 5 km/h to examine the effect of walking speed.
on loading acceleration. For stair walking, we measured loading acceleration when a subject was ascending or descending the stairs with a speed of 100 steps/min. The stairway consisted of 25 steps, and each step was 62 cm in depth, 15 cm in height, and had a 13.6° slope. During acceleration measurement for jumping rope, the subjects were requested to perform two-footed 5 cm vertical jumps 25 times in a row.

**Data processing**

For each activity, an acceleration signal of 20 consecutive steps in the direction of each of the three axes was applied to measure the magnitude of loaded acceleration (Fig. 1B). The top and bottom peak points of the acceleration wave were automatically recognized with respect to each step, and the amplitude between both peaks was measured as the magnitude of loaded acceleration value in each direction using a signal processing software (KISSEI COMTEC, BIMUTAS II, Japan) (Fig. 2A–C). Then, a scalar of the resultant acceleration vector, obtained by adding the three vectors in X-, Y-, and Z-axes, can be obtained from the following equation:

$$ A = \sqrt{(Ax)^2 + (Ay)^2 + (Az)^2} $$

Where, $A$ is the scalar of resultant acceleration vector, and $Ax$, $Ay$, and $Az$ are the scalar quantities of the acceleration vector, which are measured using the three triaxial accelerometers in the X-, Y-, and Z-axes, respectively. This scalar of the resultant acceleration vector shows the actual magnitude of loading acceleration at each point of measurement.

**Statistical analysis**

Values have been presented as means ± standard deviation. The two groups were compared using a paired t-test. The statistical significance among the groups of pairwise comparisons was assessed using a one-way ANOVA followed by a Bonferroni’s test. We have also performed regression analysis of the acceleration intensity between the points of acceleration measurement to understand the efficiency of impact transmission through the joint between two analyzed points. The significance level for all statistical tests was set at 0.05.

**Results**

**Acceleration measurement during activities**

Figure 3 shows the magnitude of accelerations at the ankle, knee, and lumbar points while walking at 3, 4, and 5 km/h. Collision between the shoe and ground gives rise to landing impact on the foot, and this impact is transferred through the body. Then, the transfer of

**Fig. 2.** (A) Top and (B) bottom peaks points of acceleration waves were automatically recognized with respect to each step of walking using signal processing software. A top peak point was identified by the software as the maximum value in the area where those values are bigger than the specified set level. Similarly, a bottom peak point was identified as the minimum value in the area where those values are lower than the specified set level. (C) Amplitude between the top and bottom peaks measured as magnitude of impact acceleration value in each direction.
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Impact from the ankle to lumbar reduced. In addition, the peak acceleration measured at each point significantly increased with the increase in walking speed. The magnitude of loaded peak accelerations at the ankle, knee, and lumbar points for ascending and descending stairs are shown in Figure 4. Descending stairs had a significant impact on the human body, especially the ankle, as compared to ascending the stairs. Figure 5 represents the magnitude of loaded peak accelerations at the ankle, knee, and lumbar points during jumping rope. Jumping rope induced a relatively large acceleration at the lumbar point as compared to the other activities.

Mean and standard deviation values of peak accelerations at the ankle, knee, and lumbar points in each activity are shown in Table 1. The largest peak acceleration of 20.30 ± 5.03 G at the ankle point was measured while descending the stairs. The largest peak acceleration of 10.29 ± 1.97 G at the knee point was also found while descending the stairs. However, the largest acceleration of 5.40 ± 1.69 G at the lumbar point was observed while jumping rope.

Correlation analysis of acceleration values at three points along the body

We have performed correlation analyses of the acceleration values at three points along the body for each exercise to evaluate the regulation of landing impact-transfer through the knee and hip joints (Table 2). In the correlation analyses of accelerations at the ankle, knee, and lumbar points for the measurement of walking at 5 km/h, a significant correlation (p < 0.01) was found between the ankle and knee points, but no correlation was found between the ankle and lumbar points or between the knee and lumbar points (Table 2A). In the measurements for ascending the stairs, a significant correlation was found between the ankle and knee points (p < 0.01), and between the ankle and lumbar points (p < 0.01), and also between the knee and lumbar points (p < 0.05) (Table 2B). In the measurements for descending the stairs, a significant correlation (p < 0.01) was found between the knee and lumbar points, but no correlation was found between the ankle and knee points or the ankle and lumbar points (Table 2C). In the measurements for jumping rope, a significant correlation (p < 0.01) was found between the ankle and knee points, but no

<p>| Table 1 Magnitude of peak acceleration of resultant vector from AP(X)-, ML(Y)-, and VT(Z)-axis acceleration at the ankle, knee, and lumbar points during each exercise. Values are represented in mean ± one standard deviation. |
|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Kinds of exercise</th>
<th>Ankle</th>
<th>Knee</th>
<th>Lumbar</th>
<th>Ankle</th>
<th>Knee</th>
<th>Lumbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 Walking (km/h)</td>
<td>5.90 ± 1.09</td>
<td>4.58 ± 0.57</td>
<td>1.18 ± 0.21</td>
<td>3.0 Walking (km/h)</td>
<td>8.87 ± 1.35</td>
<td>6.88 ± 0.89</td>
</tr>
<tr>
<td>4.0 Ascending stairs</td>
<td>12.26 ± 3.03</td>
<td>8.38 ± 2.17</td>
<td>1.92 ± 0.29</td>
<td>4.0 Ascending stairs</td>
<td>20.30 ± 5.03</td>
<td>10.29 ± 1.97</td>
</tr>
<tr>
<td>5.0 Descending stairs</td>
<td>5.90 ± 1.09</td>
<td>4.58 ± 0.57</td>
<td>1.18 ± 0.21</td>
<td>5.0 Descending stairs</td>
<td>8.87 ± 1.35</td>
<td>6.88 ± 0.89</td>
</tr>
</tbody>
</table>

* Each acceleration in the table is scalar value of resultant vector from x-, y-, and z-axes acceleration vectors.
correlation was found between the ankle and lumbar points or between the knee and lumbar points (Table 2D).

<table>
<thead>
<tr>
<th></th>
<th>Ankle</th>
<th>Knee</th>
<th>Lumbar</th>
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<tbody>
<tr>
<td>Ankle</td>
<td>1.38×10⁻⁴</td>
<td>N.S.</td>
<td></td>
</tr>
<tr>
<td>Knee</td>
<td>1.38×10⁻⁴</td>
<td>N.S.</td>
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**Discussion**

In most studies (MacKelvie et al., 2001; Petit et al., 2002; Iuliano-Burns et al., 2003; Mackelvie et al., 2003; Mckay et al., 2005) conducted on the effects of exercise on bone mineral accrual in boys and girls, the intensity of exercise has been indicated in the ground reaction force (GRF), which is the reaction to the force the body exerts on the ground. In these studies, bone mineral content (BMC) and/or bone mineral density (BMD) in the proximal femur or lumbar spine significantly increased for GRF intensity ranging from 3.5 to 8.8 times body weight. Intensity of GRF is expressed in the form of multiples of body weight, which corresponds to acceleration in G at the gravity point of the human body, consequently a

![Fig. 5](image_url). Intensities of measured peak accelerations at the ankle, knee, and lumbar points during jumping rope. **: p < 0.01, using one-way ANOVA plus Bonferroni’s test; N.S.: not significant.

![Fig. 6](image_url). Comparison of loaded acceleration for each activity at (A) the ankle, (B) knee, and (C) lumbar joints. *: p < 0.05, **: p < 0.01, using one-way ANOVA plus Bonferroni’s test.
GRF value can be directly converted to its equivalent acceleration value at the lumbar point during any activity. Therefore, the results of these studies involving long-term young human in vivo experiments, suggested that an acceleration magnitude of more than 3.5G is necessary for yielded increment in BMC or BMD in the weight-bearing bones of the young subjects. In other words, 3.5G is the threshold acceleration for osteogenic response of bone in young human to mechanical stimuli.

Osteoporosis is a systemic, skeletal disease characterized by low bone density and micro-architectural deterioration of bone tissue, with a consequent increase in bone fractures (Kanis et al., 1994). In particular, the femoral neck fracture is difficult to treat. Moreover, there is a risk of being bedridden and subsequent dementia in the elderly (Kitamura et al., 1998). Thus, osteoporosis is a critical disease in aging society. We need more emphasis on preventive measures to offset osteoporosis in the femoral neck and lumbar spine regions. Since bone mass increases during childhood and puberty, consolidates during young adulthood, and declines with age (Matkovic et al., 1994; Heaney et al., 2000), one major preventive strategy is the maximization of peak bone mass in the young. The present results indicate that jumping rope can provide enough acceleration, which exceeds 3.5G, to the lumbar and proximal femur regions without excess impact on the ankle and knee (Figure 6). Therefore, jumping rope is one of the most effective measures for weight-bearing bones enhancement in young subjects.

Our previous studies (Suzuki et al., 2007; Suzuki et al., 2008) using teleost scale as a bone model showed that osteoclastic activity significantly decreased to less than 2G under dynamic (vibration-driven) and static (centrifugally driven) acceleration loading. These results suggest that an acceleration of even 2G or less in the lumbar region caused by walking shows probability of suppressing bone absorption. In the elderly, reduction in musculoskeletal strength, neurological motor control capability, and sense of balance makes it difficult for them to do high-impact exercise. Therefore, another strategy to prevent osteoporosis is to minimize loss of bone mass in the elderly, i.e., an appropriate measure for the elderly might be not to increase osteoblastic activity involving high-impact exercise but to suppress bone absorption performing activities with 2G or less acceleration, such as, walking.

During locomotion or jumping, when the feet strike the ground, an impact force is generated that causes a shock wave through the whole body from the foot to the head. However, the human body mainly depends almost completely on joint kinematics and muscular activity to regulate harmful shock wave transmission (Laforce et al., 1996). In the present study, we have performed correlation analyses of loading acceleration at the ankle, knee, and lumbar points in each activity to attempt an explanation of the capability of impact regulation in each joint. If the transmission of a shock wave through the joint is maintained, there must be a statistically significant relationship between the acceleration values of the lower and upper points. On the other hand, if no statistically significant relationship is found, the implication would be that the impact force was attenuated by the joint...
kinematics. In the case of walking at 5 km/h, a statistically significant relationship was found between the impact accelerations of the ankle and knee points. However, there was no statistically significant relationship between the impact accelerations of the ankle and lumbar points or the knee and lumbar points (Table 2A). These results suggest that the impact force produced by foot landing was attenuated at the hip joint. In the case of ascending the stairs, a statistically significant relationship was found between impact accelerations at the ankle and knee points. However, in the relationship between the impact acceleration of the ankle and knee points or the ankle and lumbar points, there was no statistically significant relationship (Table 2C). These results suggest that our body mainly depends on knee joint kinematics and muscular activity to regulate shock wave transmission during descending the stairs. In the case of jumping rope, a statistically significant relationship was found between impact accelerations at the ankle and knee points. However, in the relationship between the impact acceleration of the ankle and lumbar points or the knee and lumbar points, there was no statistically significant relationship (Table 2D). These results suggest that the impact force, passing through the ankle point, was transmitted through the knee joint and attenuated at the hip joint. In the present study, we have not measured the impact acceleration at the foot. As a result, we could not analyze the contribution of the ankle joint to impact force regulation. However, our body uses the ankle joint to regulate impact force when the foot touches the ground at the toe. On the other hand, the ankle joint regulation does not work when the foot touches the ground at the heel. Therefore, this ankle joint regulation and our findings from the linear regression analyses are summarized in Figure 7. When we are walking over a flat place, our body is mainly using the hip joints to regulate the landing impact force. When we are ascending stairs, the ankle joints mainly regulate landing impact force. When we are descending the stairs, knee joints solely bear to regulate the large landing impact force. When we are jumping rope, the ankle and hip joints coordinate to regulate the large landing impact force.

Conclusion

We have quantified acceleration at each point of weight-bearing bone along the body during activities, such as, walking and jumping rope. The results of the present study indicated that jumping rope can provide enough acceleration more than 3.5G, which is necessary for yielded increment in BMC or BMD in the weight baring bones of the young subjects, to the lumbar and proximal femur regions without excess impact on the ankle and knee. Thus, jumping rope is one of the most optimum exercises for mineral gain in the proximal femur and lumbar vertebrae regions in the young. In addition, our results also suggest that frequent walking might be a possible activity to minimize a loss of bone mass in the elderly.

Acknowledgments

This study was supported in part by grants to Kitamura, K. (Grant-in-Aid for Scientific Research (C) No. 21500681) sponsored by the Japan Society for the Promotion of Science, and to Suzuki, N. (Grant-in-Aid for Space Utilization) sponsored by the Japan Aerospace Exploration Agency.

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