Bones benefits gained by jump training are preserved after detraining in young and adult rats

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Honda A, Sogo N, Nagasawa S, Kato T, Umemura Y. Bones benefits gained by jump training are preserved after detraining in young and adult rats. J Appl Physiol 105: 849–853, 2008. First published July 3, 2008; doi:10.1152/japplphysiol.00902.2007.—We investigated the osteogenic responses to jump training and subsequent detraining in young and adult male rats to test the following hypotheses: 1) jump training has skeletal benefits; 2) these skeletal benefits are preserved with subsequent detraining throughout bone morphometric changes; and 3) there are no differences between young and adult rats during detraining in terms of the maintenance of exercise-induced changes. Twelve-week-old (young) and 44-wk-old (adult) rats were divided into the following four groups: young-sedentary, young-exercised, adult-sedentary, and adult-exercised. The exercised groups performed jump training (height = 40 cm, 10 jumps/day, 5 days/wk) for 8 wk followed by 24 wk of being sedentary. Tibial bone mineral content and bone mineral density in vivo significantly increased with jump training, and the effects were maintained after detraining in both the young and adult exercised groups, although the benefits of training became somewhat diminished. After 24 wk of detraining, the beneficial effects of training on bone mass and strength were preserved and associated with morphometric changes, such as periosteal bone formation continues throughout life. However, periosteal bone formation in response to mechanical loading with age, is the effect of estrogen (10, 12, 19). In general, geometric adaptations are observed in males and females, or as perioseal perimeter, cortical area, and moment of inertia. There were no significant age-exercise interactions in such parameters, except for the perioseal perimeter. These results suggest that there are few differences in bone accommodation and maintenance by training and detraining between young and adult rats.

High-impact exercise, such as jump or resistance training, efficiently increases bone mass and strength (2). However, data regarding the effects of exercise with subsequent detraining are somewhat controversial.

In human studies, some researchers have reported that the benefits of physical training are lost or diminished after cessation of training or retirement from competition (5, 25). However, others have reported significantly increased bone mass or reduced fracture risk among former athletes compared with age-matched controls (15, 17).

In animal studies, some researchers have reported that extra bone mass and strength gained by running are lost when exercise is completely ceased, although the training effects are sometimes maintained for a while (8, 9, 18, 27). These studies suggest that continuous exercise is necessary to maintain exercise-induced bone benefits. However, the results of other previous studies suggest that residual bone mass and strength gained by exercise are maintained after detraining (4, 13, 21, 24, 26). These studies have further demonstrated an association between gains in bone mass or strength and increased cortical area or bone enlargement, which persist after detraining. Such morphometric changes may preserve bone mass and strength. Warden et al. (26) have demonstrated persistent loading effects throughout bone structural changes in female rats. They investigated the effects of only 7 wk of loading using an axial compression loading device and a subsequent 98-wk period of detraining on the ulna in growing female rats.

However, in all previous studies, except for Warden et al. (26), detraining periods were short, considering rat life span. Furthermore, it is unclear whether the effects of exercise on bone mass and strength might persist, regardless of age. If exercise induces morphometric changes, even in aged rats, effects on bone mass and strength might be preserved similarly to those in young rats. In addition, because Warden et al. used a nonphysiological (external) loading model under anesthesia, the results might be different when a physiological (training) model is applied.

Several studies have reported greater exercise-induced bone quantitative and morphometric improvements during growth (pre- or peripuberty) or in youth, compared with after growth (puberty) or adulthood (1, 9, 14, 16, 20). A remarkable cross-sectional expansion with age was observed in males (12, 19). It has been speculated that one of the reasons why different geographic adaptations are observed in males and females, or with age, is the effect of estrogen (10, 12, 19). In general, estrogen enhances endocortical bone formation and reduces periosteal bone formation in response to mechanical loading (19). In males with less estrogen exposure than females, periosteal bone formation continues throughout life. However, we have previously reported that high-impact jump training induces beneficial bone morphometric changes in young and adult female rats, regardless of estrogen levels (6, 7). In addition, we recognized the need to investigate the effects of jump training and longer detraining periods on male rats, as well as the importance of exercise during middle and old age, as well as in youth.

Thus, in the present study, we examine the possibility that 1) jump training has skeletal benefits in both young and adult male rats; 2) the skeletal benefits of jump training in both young and adult rats are preserved with subsequent detraining throughout bone morphometric changes; and 3) there are no
differences between young and adult rats during detraining in term of the maintenance of jump training-induced changes.

To test the above three hypotheses, we investigated osteogenic responses to high-impact jump training and subsequent detraining in male rats of different ages.

MATERIALS AND METHODS

Animals. Forty male Wistar rats, aged 10 wk, were obtained from Japan SLC (Hamamatsu, Japan). Rats were housed individually in standard cages under a constant temperature (22 ± 1°C). The light-dark cycle was 12:12 h. They were fed standard chow (CE-2; CLEA) and water ad libitum. Rats were divided into the following four groups: 1) young-sedentary (YS, n = 10), 2) young-exercised (YE, n = 10), 3) adult-sedentary (AS, n = 10), and 4) adult-exercised (AE, n = 10). The experiment started at 12 wk of age for the young groups and at 44 wk of age for the adult groups, and the experimental period was 32 wk (Fig. 1). Body weight was measured every week, and in vivo left tibial bone mineral content (BMC) and bone mineral density (BMD) were measured every 4 wk. At the end of the experiment, the rats were killed, and ex vivo bone parameters were measured every 4 wk. At the end of the experiment, the rats were killed, and ex vivo bone parameters were measured.

Training program. Rats in the sedentary groups were allowed to move freely in their cages for 32 wk. The exercised groups performed high-impact jump training (height = 40 cm, 10 jumps/day, 5 days/wk) for the first 8 wk, and then underwent a period of detraining for 24 wk of the same activity level as the sedentary groups. Rats in the exercised groups jumped from the bottom of a mat floor to grasp the top of a wooden box (40 cm in height) with their forepaw, and then climbed up to the top edge. This training procedure is described in detail in a previous study (23). Apart from the jumping protocol, rats in the sedentary groups were handled in the same way as the exercised groups.

Bone densitometry measurements in vivo. Every 4 wk, BMC and BMD of the left tibia, including the tibia and fibula, were measured by dual-energy X-ray absorptiometry (DXA) (DSC-600A; Aloka, Tokyo, Japan) under anesthesia with pentobarbital solution. The hip and knee joints were positioned at 90°, and the tibia was defined as the area between the knee joint and the ankle joint. Bone was monitored using an ultra-high-resolution mode in the prone position. The coefficient of variation of BMC and BMD was 2.7 and 1.8%, respectively, for one measurement. YS, young-sedentary (n = 10); AS, adult-sedentary (n = 8); AE, adult-exercised (n = 8).

RESULTS

Two rats in the AS group and two rats in the AE group died following anesthesia or disease. Data from these rats were omitted from results and statistical analysis.

Body weight. The adult groups had a significantly higher body weight than young groups. Exercise did not affect body weight (Table 1).

In vivo data. The adult groups had significantly greater BMC until 24 wk, as well as BMD until 20 wk, compared with the young groups, after which the differences disappeared. At pretraining, there were no significant exercise effects on BMC and BMD. However, significant training-induced increases were observed in BMC and BMD in both age groups, and BMC and BMD remained greater among the exercised groups compared with the sedentary groups throughout the experiment. These results demonstrate the maintenance of the beneficial effects of jump training after detraining, although the advantages of exercise somewhat diminished when training ceased (Figs. 2 and 3).

Ex vivo data. Data for two rats in the AS group and two rats in the AE group with regard to maximum breaking force were excluded due to technical errors in testing. Significant age effects were recognized in length, fat-free dry weight, medullary area, and BMC, with the parameters being significantly greater among the adult groups compared with the young groups. Exercise significantly increased all ex vivo parameters, except for BMD, and the exercised groups had significantly increased BMC and BMD. However, significant training-induced increases were observed in BMC and BMD in both age groups, and BMC and BMD remained greater among the exercised groups compared with the sedentary groups throughout the experiment. These results demonstrate the maintenance of the beneficial effects of jump training after detraining, although the advantages of exercise somewhat diminished when training ceased (Figs. 2 and 3).

Bone analysis ex vivo. After the left tibial length was measured with sliding calipers, mechanical testing was performed using a three-point bending system (TK-252C; Muromachi, Tokyo, Japan). The bone was placed on two supports separated by 16 mm, and the test was conducted at the midpoint of the tibia. The maximum mechanical load before breaking was recorded.

The right tibia was immersed in a solvent (2 volumes of chloroform combined with 1 volume of methanol) for 1 wk and then dried at 80°C for 24 h. After the fat-free dry weight was measured, whole BMC and BMD were obtained by DXA. The bone was positioned with the lateral surface of the diaphysis facing up and scanned. The coefficient of variation of BMC and BMD was 1.3 and 1.4%, respectively. Next, the bones were embedded in plastic resin and cut at the midshaft. A digitizing system was used to determine endosteal and periosteal perimeters, medullary and cortical areas, and the minimum and maximum moment of inertia.

Statistical analysis. Data are presented as means ± SD. A two-way (age × exercise) ANOVA using SPSS 12.0 J for Windows was used to examine the individual main effect and interaction between these factors for ex vivo data. Similarly, two-way ANOVA was used to calculate in vivo data and body weight at each time point. A significance level of P < 0.05 was used for all statistical tests.

Fig. 1. Experimental protocol. In vivo bone mineral content (BMC) and bone mineral density (BMD) using dual-energy X-ray absorptiometry (DXA) were measured every 4 wk. At the end of the experiment, the rats were killed, and ex vivo bone parameters were measured. YS, young-sedentary (n = 10); YE, young-exercised (n = 10); AS, adult-sedentary (n = 8); AE, adult-exercised (n = 8).
increased values compared with the sedentary groups. The observed increases in periosteal perimeter, cortical area, and moment of inertia indicated bone enlargement and morphometric changes. A significant interaction was observed in periosteal perimeter showing a greater increase in the AE than in YE relative to their respective sedentary groups (Table 2).

These results show that bone accommodation and maintenance by training and detraining are similar among young and adult rats.

**DISCUSSION**

In this study, high-impact jump training increased bone mass and strength, and these benefits gained by training were preserved for 6 mo of detraining in association with bone morphometric changes in young and adult rats. These results suggest that the effects of training and subsequent detraining on bone are not limited by age.

In vivo BMC and BMD increased in the exercised groups with jump training and remained greater than in the sedentary groups after detraining. However, on cessation of training, the increases of exercised groups compared with corresponding sedentary groups somewhat diminished (i.e., percent changes in BMC were 13.0% in young rats and 16.7% in adult rats after training, but final measurements of 5.1 and 8.9%, respectively, were obtained; similarly, BMD, increased by 11.9% in young rats and by 13.9% in adult rats after training, but these values were 7.6 and 5.0%, respectively, after detraining). This agrees with the study by Warden et al. (26), who reported that the bone quantities gained by exercise were lost after prolonged detraining.

Järvinen et al. (9) have observed different bone adaptive mechanisms to loading among young and adult rats, with young rats primarily demonstrating geometric changes (increase in bone size) and adult rats demonstrating increased bone density. However, the loss of exercise-induced bone benefits was not affected by age (9). A number of studies have reported greater exercise-induced bone quantitative increases and morphometric improvements during growth (pre- and peripuberty) than after growth (after puberty), and in youths compared with adults (1, 9, 14, 16). In the present study, jump training of only 10 jumps/day stimulated bone formation in young and adult rats, and exercise benefits were similarly maintained after detraining. Our data show that exercise “after puberty and in aging” is important for maintenance of bone health, in the same way that exercise is important “during growth or before puberty” in male rats.

Our data contradict the previous findings of Iwamoto et al. (8) and Wu et al. (27), who observed a loss of bone mass gained by running after short-term training cessation. In addition, our results differed slightly from those of Pajamäki et al. (18). In their studies of the femoral neck in male rats, running during growth was observed to significantly increase bone mass, strength, and cross-sectional area, which persisted for 14 wk after cessation of training. Thereafter, exercise-induced benefits were completely lost by 28 wk of detraining. However, we observed sustained benefits even after a 24-wk period of detraining, even though this is less than the 28-wk detraining period described in their study. Warden et al. (26) have also reported prolonged maintenance of training benefits on bone strength and structure in the ulna midshaft. This study and that by Warden et al. have commonly demonstrated bone morpho-

Table 1. **Body weight changes**

<table>
<thead>
<tr>
<th></th>
<th>YS</th>
<th>YE</th>
<th>AS</th>
<th>AE</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before training</td>
<td>375.0±12.6</td>
<td>375.6±11.9</td>
<td>572.1±41.7</td>
<td>578.6±41.1</td>
<td>Age effect*</td>
</tr>
<tr>
<td>After training</td>
<td>507.9±24.9</td>
<td>496.6±19.7</td>
<td>606.9±41.9</td>
<td>611.9±46.3</td>
<td>Age effect*</td>
</tr>
<tr>
<td>At end of experiment</td>
<td>571.1±23.8</td>
<td>593.5±28.7</td>
<td>628.3±41.7</td>
<td>636.5±57.9</td>
<td>Age effect*</td>
</tr>
</tbody>
</table>

Values are means ± SD. YS, young-sedentary (n = 10); YE, young-exercised (n = 10); AS, adult-sedentary (n = 8); AE, adult-exercised (n = 8). There were significant age effects at each time point. However, exercise did not affect body weight. *P < 0.01.

Fig. 2. Exercise-induced changes in BMC in vivo. Values represent means ± SD. BMC in the adult groups was significantly greater than that in the young groups [from preexercise (pre) to 20 wk, P < 0.01, and 24 wk, P < 0.05]. Exercise significantly increased BMC in young and adult rats, and exercised rats had significantly higher BMC compared with sedentary rats after detraining (from 4 wk to the last measurement; P < 0.01). A significant interaction between age and exercise was observed at pretraining (P < 0.05).

Fig. 3. Exercise-induced changes in BMD in vivo. Values represent means ± SD. The adult groups had significantly greater BMD compared with the young groups (from preexercise to 16 wk, P < 0.01, and 20 wk, P < 0.05), but these differences later disappeared. Exercise significantly increased BMD among both young and adult rats, and the training effects were maintained after 32 wk (from 4 to 32 wk; P < 0.01).
metric and structural changes by training and its maintenance. Unfortunately, we could not find evidence of increase or maintenance of cross-sectional and cortical area in other studies (8, 18, 27). A possible explanation for the differences observed among these studies might relate to the examination of different bone sites (i.e., the diaphysis vs. the meta/epiphysis), as well as different loading types and assessment methods (i.e., DXA, peripheral quantitative computed tomography, etc.). Fujie et al. (4) have reported different bone adaptations to training between the diaphysis and metaphysis. The jump training and axial compression loading device used by Warden et al. (26) provided large mechanical stress to the midshaft, and effects on the diaphysis might be more sustained than in the meta/epiphysis (24).

Other studies reporting the maintenance of training benefits have also observed maintenance of bone morphometric changes (i.e., increases and maintenance of cross-sectional and cortical areas), although they involve shorter detraining periods (4–15 wk) (4, 13, 21). Warden et al. (26) have reported the maintenance of bone strength, total cross-sectional area, and minimum moment of inertia at the midshaft in an exercised male rats of different ages. However, our results were in agreement with their study, indicating that exercise-induced benefits are maintained via morphometric and structural changes (i.e., increases and maintenance of cross-sectional and cortical areas), although they involve shorter detraining periods (8, 18, 27). A possible explanation for the differences in results might also provide important information.

In conclusion, our data indicate that high-impact jump training stimulates bone osteogenic responses in adult, as well as young, male rats. Moreover, the observed increases in bone mass and strength in the present study were preserved and were associated with bone morphometric changes in both young and adult rats, even after cessation of jump training. These results suggest that exercise training during adulthood, as well as youth, is very important for bone health. However, due to a number of problems, including the small sample size, relatively short duration of detraining, and methodological techniques used in this study, further research is necessary to confirm these findings.

### REFERENCES


### Table 2. *Ex vivo tibial bone parameters and cross-sectional analysis of bone at the tibial midshaft*  

<table>
<thead>
<tr>
<th>Parameter</th>
<th>YS</th>
<th>YE</th>
<th>AS</th>
<th>AE</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, mm</td>
<td>44.4±0.6</td>
<td>44.3±1.0</td>
<td>45.6±0.8</td>
<td>45.1±0.6</td>
<td>Age effect†</td>
</tr>
<tr>
<td>Fat-free dry weight, mg</td>
<td>637.1±32.0</td>
<td>669.5±37.2</td>
<td>678.9±37.9</td>
<td>728.4±50.2</td>
<td>Age effect†, exercise effect†</td>
</tr>
<tr>
<td>Maximum load, N</td>
<td>120.4±9.6</td>
<td>132.7±9.6</td>
<td>111.8±15.3</td>
<td>130.8±16.3</td>
<td>Exercise effect*</td>
</tr>
<tr>
<td>Endosteal perimeter, mm</td>
<td>6.50±0.37</td>
<td>6.76±0.67</td>
<td>6.63±0.43</td>
<td>7.27±0.63</td>
<td>Exercise effect*</td>
</tr>
<tr>
<td>Periosteal perimeter, mm</td>
<td>11.37±0.40</td>
<td>11.49±0.45</td>
<td>11.03±0.46</td>
<td>12.00±0.80</td>
<td>Exercise effect†, age-exercise interaction*</td>
</tr>
<tr>
<td>Medullary area, mm²</td>
<td>2.80±0.27</td>
<td>3.22±0.56</td>
<td>2.99±0.27</td>
<td>3.70±0.65</td>
<td>Age effect*, exercise effect*</td>
</tr>
<tr>
<td>Cortical area, mm²</td>
<td>4.78±0.35</td>
<td>5.13±0.38</td>
<td>4.68±0.35</td>
<td>5.27±0.60</td>
<td>Exercise effect†</td>
</tr>
<tr>
<td>I_{min}, mm^4</td>
<td>3.44±0.49</td>
<td>3.65±0.51</td>
<td>3.17±0.42</td>
<td>3.97±0.93</td>
<td>Exercise effect*</td>
</tr>
<tr>
<td>I_{max}, mm^4</td>
<td>5.86±0.62</td>
<td>7.12±0.82</td>
<td>5.83±0.78</td>
<td>8.51±1.81</td>
<td>Exercise effect†</td>
</tr>
<tr>
<td>BMC, mg</td>
<td>295.7±20.3</td>
<td>310.9±23.6</td>
<td>310.2±16.0</td>
<td>331.3±18.0</td>
<td>Age effect*, exercise effect*</td>
</tr>
<tr>
<td>BMD, mg/cm²</td>
<td>106.9±5.5</td>
<td>113.5±6.9</td>
<td>112.1±8.4</td>
<td>112.6±7.7</td>
<td></td>
</tr>
</tbody>
</table>

Values are means ± SD. Group designations are specified in Table 1. I_{min}, minimum cross-sectional moment of inertia; I_{max}, maximum cross-sectional moment of inertia; BMC, bone mineral content; BMD, bone mineral density. A sample number of 6 was used to determine maximum load in AS and AE groups. ∗P < 0.05; †P < 0.01.


