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Effects of resistance exercise training on mass, strength,
and turnover of bone in growing rats

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Abstract To determine the effects of resistance exercise
on mass, strength and local turnover of bone, 50
Sprague Dawley rats, 8 weeks of age, were assigned
to five groups: a baseline control and two groups of
sedentary and exercising rats. The trunk of the rats
was kept upright during electrically stimulated jumping
exercise for 1 h every other day. In 4 weeks, the
trabecular mineralizing surface per bone surface (MS/
BS), bone formation rate per bone surface (BFR/BS)
and the compression load of the lumbar body in-
creased and the number of osteoclasts decreased, but
bone mineral density (BMD) and structure did not
increase. In the mid femur, the cross-sectional area,
the cortical bone area, the moment of inertia, the peri-
steoal MS/BS, BFR/BS and the bending load increased
in the exercise group. In 8 weeks, the increases in
BMD, structure and load values were significant in
both the lumbar and mid femur. At both 4 and
8 weeks, the MS/BS for the endocortical surface of
mid femur were not increased and mineral apposition
rate (MAR) remained reduced. These results show that
jumping exercise increases the mass and strength of
the lumbar vertebrae and mid femur by stimulating bone
formation and accelerates cortical drift by both in-
creasing periosteal bone formation and reducing the
endocortical MAR.

Key words Bone formation · Cortical drift ·
Jumping · Trunk upright position · Osteoclast

Introduction

A mechanical stimulus increases bone strength through
metabolic alterations in bone formation and resorption
(Chambers et al. 1993; Jagger et al. 1995; Fujimura
et al. 1997; Umemura et al. 1997). Short-term resist-
ance exercise increases bone turnover but not bone
mass in humans (Virtanen et al. 1993; Ashizawa et
al. 1997), while long-term exercise increases both bone
strength and mass (Menkes et al. 1993; Ryan et al.
1994).

In rodents aerobic exercises including swimming and
running are applied to study the long-term effects of
exercise on bone morphology and metabolism (Bourrin
et al. 1992; Yeh et al. 1993; Nordsletten et al. 1994;
Tuukkanen et al. 1994; Bourrin et al. 1995). The effects
of jumping induced by electrical stimulation of the floor
increase femoral cortical bone strength (Umemura
et al. 1997) and the trabecular bone mass of the pro-
ximal tibia (Westerlind et al. 1998). The effects of
jumping on the local turnover and mechanical prop-
erties of bone have not been studied. The direction or the
amount of mechanical stress on the skeleton is not
controllable during jumping exercise induced by elec-
trical stimulation (Umemura et al. 1997; Westerlind
et al. 1998).

Rat skeletons were loaded by fitting the animals
with jackets containing a metal bar. This bar also
served to keep their trunks upright while they jumped
(Tamaki et al. 1992). After confirming that the jumping
exercise with the load does not reduce the body weight
increase in growing rats, we applied this type of
training to 8-week-old rats. The purpose was to eval-
uate the effects of resistance exercise training on the
mass, strength and local turnover of the lumbar ver-
tebrae and mid femur.
Methods

Animals

Fifty male Sprague-Dawley rats, 5 weeks of age (Japan CLEA, Tokyo, Japan) were acclimated for 1 week at 22 ± 2 °C and 60% humidity. The light/dark cycle was 12 h with lights on from 7:00 to 19:00 hours. Exercise training was conducted between 7:00 and 8:00 hours every other day. All rats were housed individually in metal cages. Drinking water was available at all times and the amount of food taken was equalized among the groups by feeding at 8:00-9:00 hours and 20:00-21:00 hours. All rats were fed a commercial diet (Japan CLEA; Ca: 1200 mg/100 g; P: 1080 mg/100 g). In preliminary experiments, the body mass of the jumping rats increased but the amount of food intake and body mass were not as great as compared to values for the sedentary rats from the 5th week (data not shown). Thus, the food intake for the sedentary groups was adjusted to that of the exercising groups of the previous day. The body mass of the rats was measured weekly and all rats remained healthy. The protocol was approved by The University of Tsukuba’s Institutional Animal Care and Use Committee.

Grouping and periods of experimentation

The rats were divided into five groups of ten animals each. Group C was the control and sacrificed at the start. Groups 4S and 4T were the sedentary and the training groups which were sacrificed after 4 weeks and Groups 8S and 8T were the similar groups, sacrificed after 8 weeks.

Resistance training

Two groups of rats were trained (Fig. 1) with ten rats at the same time. The rat wore a leather jacket connected to 35-cm wood bar, the other end of which was attached to a fulcrum secured on a table. The jacketed rats rested in a sitting position with their hind legs on the floor, and jumped when their tail was electrically stimulated (10 V, 100 Hz, for 0.3 s) at 2-s intervals. Iron plates were loaded on the bar. The maximum power generated for jumping in rats (one repetition maximum: 1 RM) was defined as the mass of the minimum load of iron plates with which the rats were unable to jump following electrical stimulation, and this was measured biweekly. The mass of the iron plates on the bar was set at 70% of 1 RM of the weakest animal. The load in the initial 2 weeks was 0.7 kg and increased to reach 1.5 kg.

This exercise training regimen was started after 2 weeks of acclimation to the apparatus. For acclimation the animals, wearing a jacket, were fixed to the apparatus for 1 h every other day without electrical stimulation. The jumping exercise consisted of 10 sets of 15 repetitions a day. Each training session included resting periods. We chose the load, the number of repetitions, the length of the resting period and the duration of the experiments according to Tamaki et al. (1992).

Experimental design

Rats were sacrificed at 8:00 hours by exsanguination under ether anaesthesia. The 3rd, 4th and 5th lumbar vertebrae (L3, L4 and L5) and both femora were harvested. The L3, L4 and the right femur were immediately fixed with 4% paraformaldehyde in 0.1 M phosphate buffer containing 2% sucrose, and stored at 4 °C. The L5 and the left femur were stored at −80 °C until mechanically tested. Bone labelling of rats by a subcutaneous injection with calcein [8 mg/kg body mass (BM)] was performed 7 and 3 days before the sacrifice.

Fig. 1 Diagram illustrating the resistance exercise apparatus. The jacketed rats rested in the sitting position on their hind legs on the floor, jumping up when the tail was electrically stimulated at 2-s intervals

Bone mineral measurements

The vertebral body was isolated after removing the posterior elements and transverse processes. The bone mineral density (BMD, mg/cm²) and the bone mineral contents (BMC, mg) of the L5 vertebral body and the left femur were measured using DXA (DCS-3000, Aloka, Tokyo). The mineralization profile of the specimen was stored with the monitoring image, and the BMD and BMC values for the whole vertebral body and the mid diaphyseal region (12 mm in length) were also obtained.

Mechanical tests

Each L5 vertebral body specimen was fixed with a clamp at the base of the transverse processes in the holder of a diamond band saw (Exakt, Norderstedt, Germany). By removing the cranial and caudal ends of the specimens, the plano-parallel surfaces were obtained for compression testing. From each vertebral body, a central cylinder specimen with plano-parallel ends and a height of 3.5 mm was obtained (Mosekilde et al. 1993; Tanaka et al. 1996; Ohnishi et al. 1997). Mechanical testing of the L5 was carried out using a load tester (Tension UTA-1T, Orientec, Tokyo). The vertebral cylinder sample was placed centrally on the smooth surface of a steel disk (10 cm diameter). Cranio-caudal compression force was applied by a steel disk (1.8 cm in diameter).