In vivo strain measurements to evaluate the strengthening potential of exercises on the tibial bone

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Mechanical loading during physical activity produces strains within bones. It is thought that these forces provide the stimulus for the adaptation of bone. Tibial strains and rates of strain were measured in vivo in six subjects during running, stationary bicycling, leg presses and stepping and were compared with those of walking, an activity which has been found to have only a minimal effect on bone mass.

Running had a statistically significant higher principal tension, compression and shear strain and strain rates than walking. Stationary bicycling had significantly lower tension and shear strains than walking. If bone strains and/or strain rates higher than walking are needed for tibial bone strengthening, then running is an effective strengthening exercise for tibial bone.


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Much of the mass participation in regular exercises for physical fitness is motivated by the perception that it enhances physical well-being. Specific regimes are usually chosen according to a combination of fitness goals and personal factors. Because of increasing concern about osteoporosis, bone strengthening has become a major pre-occupation, but the optimal exercise activities to achieve this have not yet been defined.

An accepted tenet of bone biology is that under normal circumstances there is a close relationship between the structure of bone and its particular function. This adaptive ability is maximum in growing bone and markedly decreases with ageing. Mechanical loading during physical activity produces strains within bones. It is thought that these strains and strain rates provide the stimulus for the structural adaptation of bones. Neither the threshold level and duration of activity nor the strain and strain rate needed to cause bone to alter its composition have been well defined.

An important step in the understanding of which exercise activities may best stimulate an increase in bone strength is the measurement of the strains and strain rates which they produce. Few assessments of bone strains during physical activity in man have been made in vivo. The tibia is the easiest site for such evaluation. Many of the exercises which are currently popular appear to generate bone strains and strain rates which are lower than walking, an activity which has been shown to have only a minimal effect on bone mass. To test this hypothesis we have measured the tibial strains and strain rates in vivo in six subjects during common exercises for physical fitness.

Subjects and Methods

We recruited six subjects, four men aged 37, 39, 45 and 52 years and two women aged 27 and 33 years, to have measurements of tibial strain in vivo. One had previously had such assessments using a rosette strain gauge bonded to the medial aspect of the mid-diaphysis of his tibia. All subjects received explanations of the goals, risks and benefits of their participation in the experiment and gave their informed consent. The experimental protocol was approved by the Human Rights Committee of the Hadassah University Hospital, Jerusalem, Israel and the Ministry of Health of Israel. All the subjects were healthy with no previous history of medical problems. Three of the men were recreational runners, averaging 6 to 15 km per week, and one of the women was a recreational skier.

In vivo strain measurements. We used strain-gauged staples (SGS) made from bone staples 16 × 15 mm in size
(3M Health Care, St Paul, Minnesota) with a Micro-Measurements EA-06-031DE-350 strain gauge (Measurements Group Inc, Raleigh, North Carolina) bonded to the undersurface. Three SGS were inserted percutaneously in a 30° rosette pattern in the medial aspect of the mid-diaphysis of the tibia.

Operative procedure. We implanted the SGS on each of the subjects on an outpatient basis in the morning. They were removed on the same day after completion of the collection of data. Prophylactic intravenous cefonicide was given before each implantation.

The right leg was prepared and draped at the level of the mid-shaft of the tibia to facilitate placement of the SGS on the medial aspect. The exact level of the mid-diaphysis and the midpoint of the flat medial surface of the tibia were determined. An alignment block for the insertion of the staples was then placed centred at this point and the site of the six entrance holes for three staples marked. Local anaesthesia was given at these six points by injection of 2.5 ml of 1% lidocaine and 2.5 ml of 0.25% marcaine into the skin, subcutaneous tissue and the periosteum of the tibia. Surgical stab wounds were made in the skin and subcutaneous tissue at each of the points and using the alignment jig and a depth-limiting device the six entrance sites for the staples were drilled for 4 mm into the tibial cortex with a 1.2 mm drill. The three SGS were inserted into the tibia using a specially made inserter-impacter which allows the staple to be driven into the predrilled hole to a depth of 4 mm within the cortex. A gauze dressing was placed loosely over the staples.

Strain-gauge measurements. Each SGS was wired as a 1/4 Wheatstone bridge. The exiting wires of the strain gauge were connected to a portable four-channel amplifier. The conditioned amplifier signals were recorded on an FM analogue cassette recorder (TEAC HR10; TEAC Corp, Tokyo, Japan). The amplifier and the cassette recorder were carried in a standard Israeli army multipouch backpack. Playback was by a separate unit (TEAC MR40; TEAC Corp, Tokyo, Japan). The exit wires of the strain gauge were connected to a portable four-channel amplifier. The exiting wires of the strain gauge were recorded on an FM cassette recorder (TEAC HR10; TEAC Corp, Tokyo, Japan). The amplifier and the cassette recorder were carried in a standard Israeli army multipouch backpack. The conditioned amplifier signals were recorded on an FM analogue cassette recorder (TEAC HR10; TEAC Corp, Tokyo, Japan). The amplifier and the cassette recorder were carried in a standard Israeli army multipouch backpack. Playback was by a separate unit (TEAC MR40; TEAC Corp) connected to a PC and digitised at 400 Hz.

All the subjects wore Nike Air Max shoes for the experiment. Measurements of tibial strain were made in a random order for each subject as follows: 1) while running on a cinder track at a rate of 17 km/hr set by a pacer; 2) during walking on a treadmill at 5 km/hr; 3) while riding an exercise bicycle at 60 cycles/s, power setting 100W (Lumex Inc, Ronkokoma, New York); 4) while using a stepmaster, aerobic mode speed 4, for 5 minutes (Universal Gym Equipment Inc, Cedar Rapids, Iowa); and 5) during leg presses (Sportal Squat Machine; Unisport Ltd, Petah Tikvah, Israel).

Analysis of data. The data from the three SGS were processed using a custom-written computer program running under Windows (Microsoft, California) which takes the digitised amplified signal outputs of the three gauges, filters them, makes baseline corrections and derives the peak principal compression and tension strains and their axis, the peak engineering shear strains and the strain rates. The angle of the maximum principal compression strain to the long axis of the tibia was calculated.

Statistical analysis. The data were analysed using the Statistical Analysis System (SAS, Cary, North Carolina). For each of the exercise activities the principal compression, tension and shear strains and rates were calculated on the basis of five steps or cycles. For each of the individual exercises the major outcome variables were the maximum principal strains and strain rates. We tested whether the mean of each of the major outcomes differed between the exercises using repeated-measures ANOVA (analysis of variance) with alpha set to 0.05.

Results

The values for the principal compression, tension and shear strains and strain rates during walking on a treadmill wearing running shoes at 5 km/hr measured by the rosette SGS were within the range of ±10% of the values previously measured for one subject using a rosette strain gauge directly bonded to the tibia at the same site.

There was no statistical difference in the principal tension, compression and shear strains between walking, performing leg presses or using the stepmaster (Fig. 1). These were significantly higher during running than those during walking and those in tension and shear were significantly lower in stationary bicycling than in walking. There was no statistically significant difference between the angle of the maximum principal compression to the long axis of the tibia for the different exercises.

The maximum tension strain rates during walking were significantly higher when performing leg presses, using the stepmaster or stationary bicycling (Fig. 2). There was no statistically significant difference between tension strain rates during walking and running.

The maximum compression and shear strain rates during walking were significantly higher than those while performing stationary bicycling and leg presses. Running had higher compression and shear strain rates than the other exercises.

Discussion

There is evidence that there is a dose-response relationship between physical loading and the mechanical competence of bone. This is based primarily on studies using animal models. Assessment of a possible dose-response relationship between physical loading and mechanical competence in human bone first requires a knowledge of the strains and strain rates which occur during specific exercises at specific skeletal sites.

Only one study has been reported of measurements of bone strain in vivo during vigorous activities and this was limited to one subject during activities simulating military basic training. In our study, strains were measured at the
same tibial site as in that of Burr et al, using a rosette composed of three SGS instead of a regular strain gauge. One subject participated in both studies and there was a close correlation between the values for the principal strains and strain rates for walking on a treadmill for both techniques.

Walking has been found to have only a minimal effect on bone mass. Cavanaugh and Cann measured the effect of a one-year programme of brisk walking on spinal trabecular bone density in postmenopausal women. The decrease in spinal bone density was similar for both the brisk walkers and the control group at a follow-up of one year. In postmenopausal women the strain and strain rate of walking are below the range which generally stimulates bone strengthening. Any exercise activity in which the strain and strain rates are the same or lower than those of walking would not be expected to stimulate bone strengthening. Therefore walking was used as a standard of comparison for the other exercises evaluated in our study. Bone density changes in response to exercise were not measured.

On the basis of the principal strain measurements in this experiment, only running has a higher potential than walking to influence adaptive remodelling to strengthen the midshaft of the tibia. Exercises which change the strain distribution are likely to be potent osteogenic stimuli. Lanyon proposed the hypothesis of error strain distribution. According to this the more unusual the strain distribution the more potent is its osteogenic potential. In our experiment we found no statistically significant difference between the angle of the maximum principal compression to the long axis of the tibia for the different exercises. This lack of difference can be explained by the fact that all of these exercises are repetitious activities done principally in the frontal plane. According to Lanyon’s hypothesis they would therefore have low osteogenic potentials on the basis of their strain distributions.

Rubin and Lanyon, using preparations of isolated turkey wings, found that bone hypertrophy was proportional to strain magnitude. Turner et al, in a four-point bending model in the rat tibia, found that a loading threshold above
1050 microstrains activated bone formation. Above this threshold there was a linear increase in formation on the endocortical surface. Animal studies have shown that the response of immature and mature bone to strain environment is very different. Rubin\textsuperscript{20} loaded the functionally isolated ulna of young and old turkeys for 300 cycles/s at 3000 microstrains for eight weeks. The geometrical properties of the young bones increased significantly after the loading period because of the increased periosteal mineralisation. The old turkeys showed no increase in their geometrical properties and an absence of periosteal labelling, but did show greater mean thickness of the osteonal wall. In our study strain measurements were made on mature adults only. Adolescents may have different strain environments than adults during the same exercise activities.

Strain rate may also play a role in influencing the adaptive remodelling response in bone. If this is so, then of the exercises measured in our study only running has a higher potential than walking to influence adaptive remodelling in bone. If this is so, then of the exercises measured in our study only running can be an effective strengthening exercise for tibial bone.

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If bone strains and/or strain rates higher than walking are needed for bone strengthening, then of the exercises mentioned in our study only running can be an effective strengthening exercise for tibial bone.

References