Exercise-induced strain and strain rate in the distal radius

Z. Földhazy, A. Arndt, C. Milgrom, A. Finestone, I. Ekenman

From Huddinge University Hospital, Stockholm, Sweden

Strains applied to bone can stimulate its development and adaptation. High strains and rates of strain are thought to be osteogenic, but the specific dose response relationship is not known. In vivo human strain measurements have been performed in the tibia to try to identify optimal bone strengthening exercises for this bone, but no measurements have been performed in the distal radial metaphysis, the most frequent site of osteoporotic fractures. Using a strain gauged bone staple, in vivo dorsal metaphyseal radial strains and rates of strain were measured in ten female patients during activities of daily living, standard exercises and falls on extended hands. Push-ups and falling resulted in the largest strain rates (18 582 to 45 954 µε/s). On the basis of their high strain and/or strain rates these or variations of these exercises may be appropriate for distal radial metaphyseal bone strengthening.

The incidence of fractures caused by osteoporosis is increasing and the distal radius is the most frequent site for such fractures.1 The majority of fractures of the distal radius are related to osteoporosis, caused by low energy trauma and frequently characterised by comminution of the dorsal cortex. A yearly incidence of distal radial fractures of 264/100 000 has been reported in Minnesota,2 and 365/100 000 in Helsinki, Finland.3 The age incidence curve has two peaks2 with the highest occurring predominantly amongst elderly women and an earlier considerably smaller peak mainly comprised of younger men secondary to high-energy trauma. While the financial burden of fractures of the distal radius on the health care system is not as great as that of fractures of the hip, it is nonetheless a significant problem, especially when considering that approximately 20% of cases have chronic symptoms and a functional deficit.5

Animal studies have shown that the skeleton adapts to mechanical stimuli.6-8 Human studies have also established relationships in older individuals9 between physical activity and bone quality in the weight-bearing skeleton and in the upper extremity in female volleyball players.10 In order to get an osteogenic response from strain in the skeleton it has been stated that high strain rates11,12 and high strain magnitudes13 are essential. Relatively simple activities such as jumping exercises and running result in high strains and strain rates in the weight-bearing skeleton as measured in vivo in the human tibia.14 To our knowledge no corresponding data on the upper extremity exist.

The aim of this study was to identify exercises that might strengthen the distal radial metaphysis in the female population on the basis of in vivo measurements.

Methods

Pilot testing. Prior to the in vivo experiment cadaver dissections were performed to determine the safest site for the application of strain-gauged bone staples to the dorsal surface of the distal radial metaphysis. This was determined to be just proximal to Lister’s tubercle, between the second and third tendon compartments.

A site specific calibration between the strain-gauged staple and a surface mounted strain gauge was performed on two cadaver bones at this site. A strain-gauged staple was mounted to a depth of 4 mm using an impactor. In the middle of the staple a uniaxial strain gauge was glued to the bone (uniaxial strain gauge, model CEA-06-125UN-350, with gauge length 6.99 mm and width 3.05 mm, and gauge grid length 3.18 mm and width 2.54 mm, Measurements Group Inc., Raleigh, North Carolina). The ends of the bones were potted. Five bending trials (0.5 Hz) were performed at a low strain...
range, about 400 µε, and at a higher strain range of 1000 µε for each bone. The raw signals were amplified and recorded with an IOTECH, Daqbook/112 12-bit acquisition system (Iotech Inc., Cleveland, Ohio) with enhanced parallel port and then processed with DaqBook DaqBoard Series 5.02 software (Iotech Inc.) on a PC notebook. The slope \( k \), in the linear regression \( y = kx + b \) between the surface and staple mounted strain gauges was calculated to determine the calibration factor between staple recordings and bone surface deformation. The value for \( k \) was 12.8 for the first specimen and 13.6 for the second specimen and the mean (13.2) was used in this study. The correlation coefficient \( (r) \) between surface and staple strain was 0.98 for both specimens.

**Instrumented staple technique.** Two strain gauges (types EA-06-031DE-350 and EA-06-031EC-350, Measurements Group Inc) were mounted perpendicular to each other on the underneath bridge surface of a 16 mm x 15 mm titanium staple with a staple bridge thickness of 1.0 mm (3M, St. Paul, Minnesota). This configuration facilitated the registration of uniaxial strain in the longitudinal direction of the bone. After local anaesthetic a 2 to 3 cm skin incision was made just proximal to Lister's tubercle on the dorsal aspect of the left distal radius. A guide was used to drill two holes through the cortex and the staple was inserted to a depth of 4 mm in the pre-drilled holes with the aid of an insertion tool. Staples were positioned between the second and third tendon compartments in an axial orientation (Fig. 1). Standard radiographs were used to check the position. Strain gauge signal quality was determined in the operating theatre prior to the beginning of the experimental protocol. The signal was amplified by a strain gauge conditioner (2120A, Measurements Group Inc), sampled at 1000 Hz and filtered with standard analog data collection software (Bioware, Kistler, Winterthur, Switzerland). The strain gauge signal was filtered with a digital 4 Hz low pass, dual pass Butterworth filter in all exercises except the two falling exercises for which a 100 Hz cutoff frequency was chosen. Analysis of the filtered data was conducted with Origin software (Microcal, Northampton, Massachusetts). The single maximum peaks for compression and tension strains were recorded for each trial. Means of a number of tests were calculated from the slope of the linear portion of the strain signal prior to the chosen maximum compression rate was calculated from the slope of the linear portion of the calibration factor between staple recordings and bone surface deformation. The value for \( k \) was 12.8 for the first specimen and 13.6 for the second specimen and the mean (13.2) was used in this study. The correlation coefficient \( (r) \) between surface and staple strain was 0.98 for both specimens.

**Experimental protocol.** Ethical approval for this study was obtained from the Huddinge University Hospital Research Ethical Committee. The patients were informed of the details of the experiment and the risks involved prior to participation.

Ten healthy pre- and post-menopausal female patients were recruited. The patients were chosen to reflect the target group for eventual bone strengthening exercises. The mean age was 47 years (34 to 60), with a mean weight of 63.5 kg (55 to 95) and a mean height of 165 cm (158 to 172). The patients’ descriptions of their levels of activity ranged from one being an aerobics instructor to largely sedentary lifestyles. One patient had suffered a slightly displaced fracture of the left distal radius about 30 years prior to the study, but no complications had occurred and her wrist function was normal. Bone mineral density (BMD) was determined using dual energy X-ray absorptiometry (DEXA) at the distal radius and total body (head, arms, legs, trunk, ribs, pelvis and spine). The patients were familiarised with the activities to be performed during the experiment prior to insertion of the staple. Two ten-second trials were recorded for all exercises except the falls. The qualitatively better recording was chosen for analysis.

Activity details are described below:
1) Arm-curl: biceps curl with 7 kg weight while sitting on a chair with the elbow supported against the torso; 2) Chin-up: on an iron bar, hands in supination and lifting their own body-weight and if possible raising the chin over the bar; 3) Fall, standing: forward fall from upright standing, landing on both extended hands. For safety and confidence a wide belt was fastened about the waist and an assistant standing behind the patient held a rope attached to this. Patients could choose to what extent the belt restrained the fall; 4) Fall, kneeling: forward fall from kneeling, landing on both extended hands. Again with the belt, although no patients required support during these less dynamic falls; 5) Push-ups: kneeling push-ups with palms on the floor; 6) Stirring: stirring a pot of heavy dough with a wooden ladle; 7) Typing: on a standard computer keyboard; 8) Vacuuming: vacuuming a loose rug with the possibility of the vacuum cleaner catching on a crease; 9) Wrist-curl, ext: wrist curl to extension with 2 kg weight while sitting with the forearm pronated and the elbow flexed to approximately 90° and the thigh acting as a support for the lower arm; 10) Wrist-
curl, flex: wrist curl to flexion with 2 kg weight while sitting with the forearm supinated and the elbow flexed to approximately 90° with the thigh acting as a support for the lower arm (Table I).

After completion of the experiment (maximum of two hours after insertion of the staple), the staple was removed and the incision sutured. After the experiment transverse computer tomography (CT) slices were obtained from all subjects at the level of the distal staple leg and at the mid-staple position from six subjects (Fig. 2). Total transverse area, total cortical area and dorsal cortical thickness between Lister’s tubercle and the dorsal ulnar aspect of the radius were derived with standard CT software (Siemens, Munchen, Germany).

Statistical analysis. Repeated measurements analysis was used to analyse the data and perform statistical comparisons in order to test for differences between the different exercise results. The Friedman two-way analysis of variance by ranks was used as the data was not normally distributed. The Wilcoxon signed-rank test for location was used to test the different exercise results pairwise, after a significant result by use of the Friedman test. The Spearman rank correlation coefficient was used in order to test hypotheses about independence between variables. Descriptive statistics and graphical methods were also used to characterise the data.

The study employs multiple hypothesis testing, where each hypothesis was analysed separately and the existence of patterns in and the consistency of the results were considered in the analysis. Results were considered statistically significant at \( p \leq 0.05 \).

Results

Complete data sets were obtained for all patients. All experienced some swelling and tenderness at the surgical site for the first few days after the removal of the staple. By two weeks all were asymptomatic and able to return to their normal activities. There were no complications related to the experiment. The Friedman test run on compression, tension and strain rate values separately was significant (\( p < 0.0001 \)) for all three modalities. The maximum compression strain was significantly greater for the falling and push-up exercises than for all other activities with the only exceptions being falling from the knees compared with arm-curl and wrist-curl in flexion. Some significant differences were also seen between the exercises with lower amplitudes. For example maximum compression in vacuuming was significantly greater than measured in chin-ups and typing (Fig. 3; Table II).

Maximum tension strain in the chin-up exercise was significantly greater than in arm-curls, fall from kneeling, push-ups, stirring and typing. Tension in the wrist-curls towards extension was also significantly greater than in typing. The dorsal distal radius was under constant compression strain in the push-up exercise, i.e. no tension strains were recorded at any time during the push-ups and

**Table I. Activities (by number)**

<table>
<thead>
<tr>
<th>No.</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Arm (biceps) curl with 7 kg weight</td>
</tr>
<tr>
<td>2</td>
<td>Chin-up hanging on a iron bar (hands in supination)</td>
</tr>
<tr>
<td>3</td>
<td>Fall forward from standing, landing on extended hands</td>
</tr>
<tr>
<td>4</td>
<td>Fall forward from kneeling, landing on extended hands</td>
</tr>
<tr>
<td>5</td>
<td>Push ups on knees</td>
</tr>
<tr>
<td>6</td>
<td>Stirring a pot of dough with a wooden ladle</td>
</tr>
<tr>
<td>7</td>
<td>Type writing</td>
</tr>
<tr>
<td>8</td>
<td>Vacuuming a carpet</td>
</tr>
<tr>
<td>9</td>
<td>Wrist curl in extension with 2 kg weight</td>
</tr>
<tr>
<td>10</td>
<td>Wrist curl in flexion with 2 kg weight</td>
</tr>
</tbody>
</table>

Fig. 2

Transverse CT of the distal arm at the mid-staple level. The radius is on the left and the ulna on the right. Cortical parameter determination is illustrated; the arrow indicates the measurement location of the cortical thickness, the black outline indicates the cortical area and the external outline marks the perimeter of the complete radial cross-sectional area.

Fig. 3

Box plots of the compression strains for the ten activities as shown in Table I.
the difference between minimum and maximum compression was approximately 2300 µε (Fig. 4; Table III).

Median values for strain rate were 45 954 µε/s after falling from standing and 18 582 µε/s from kneeling. The strain rates for the falling exercises were significantly higher than for the other exercises. Strain rate during vacuuming was significantly greater than in the chin-up, typing and both wrist-curl activities (Fig. 5; Table IV).

No consistent significant correlations or even consistent trends were found between the total transverse radial area, the radial cortex area, the dorsal cortical thickness, patient’s age or the local BMD and the radius deformation results.

Discussion

In this study an attempt was made to quantify in vivo strain and strain rate at the distal radius, a common site of fracture in patients with osteoporosis. Previous in vivo human bone strain studies have been performed in the tibia and second metatarsal. In the current study measurements were made while performing simple strengthening exercises, standard household activities and during protected dynamic falls. The objective was to determine the applicability of these activities for bone strengthening training. Higher levels of compression strain and compression strain rate were measured in some exercises in comparison with data from the mid-tibia, but not higher than those recorded from the second metatarsal. The metaphyseal bone of the distal radius is presumably exposed to primarily axial compression, whereas bending of the diaphyseal bone causes lower compressions in the mid-tibia. High strains reported on the dorsal surface of the second metatarsal can be explained by bending moments resulting from high forces (body-weight) acting upon a relatively thin, long bone. The fact that generally lower levels of tension strain were recorded in our experiment than previously in the mid-tibia may be similarly explained by bending of the tibia causing tension while a bending effect of similar magnitude probably does not occur in metaphyseal bone.

There are several interesting consistencies in our results. In the chin-up exercise where the subjects were hanging by their arms we measured the highest tension and only very low compression. The fact that some compression arose indicated that forces resulting from lower arm muscle contraction exceeded the effect of body-weight and compressed the radius. This effect occurred in spite of the fact that most of the patients did not manage to pull up their body-weight and perform a proper chin-up. Conversely, in the push-up exercise where the bodyweight was constantly supported on the wrists only varying degrees of relatively high compression were measured. Due to the less dynamic nature of push-ups, these strains were lower than for falling, and the spread of results was also relatively low. While vacuuming the head of the vacuum cleaner frequently became caught in the folds of the carpet, and required some effort to disengage it; this explains the fairly high strain rate and spread of values during this activity.

Animal studies have shown that dynamic loading of bone must exceed a threshold of approximately 1000 µε in order to initiate an osteogenic response and that the extent of this response correlates to strain magnitude. The rate at which the strain changes also seems to be of major importance. An increased osteogenic response has been reported for strain rates from 13 000 µε/s to 100 000 µε/s, and in one case at strain rates of up to 316 000 µε/s in young roosters. As few as four cycles of activity a day have an osteogenic effect and this increases up to 36 cycles a day although it has been reported that there is no significant difference in osteogenic response between ten and 100 cycles a day. Bone cells rapidly desensitise to mechanical stimulus and therefore loading cycles are best administered in separate bouts for maximum effect. Furthermore, the mechanical properties of bone improve more than the corresponding rise in DEXA results, which should be consid-
ered when interpreting results of relatively discrete bone mineral density improvements after physical intervention.

In pre-menopausal women high impact intervention programmes have a positive influence on bone quality in the weight-bearing skeleton.24,25 This is doubtful in post-menopausal women according to some studies.9,25 Kohrt, Ehsani and Birge26 compared the effects of ground reaction exercises with joint reaction exercises (weight lifting, rowing) in post-menopausal women for 11 months. They found a positive effect in both exercise groups on bone mineral density at several sites with the exception of the wrist. Of their wrist loading exercises (arm-curls, overhead press and triceps extension) only the arm curls corresponded to the free weight exercises in our study. The absence of response in the distal radius might be due to insufficient local loading.

In contrast to earlier studies a strong anabolic effect on sheep trabecular bone from a high frequency (30 Hz), low magnitude (approximately 5 \(\mu\)ε) impact combination has recently been described.27-29 If similar results were also demonstrated in human studies they could have implications on osteoporosis intervention programmes. In view of this the exercises in our study with the lowest amplitudes would appear most relevant for dose response information on local strain, i.e. typing, stirring and possibly wrist-curls, although these still produced far higher amplitudes at lower frequencies than described in the above-mentioned literature.

The present study has several limitations. The strain measurements were made using strain-gauged bone staples and not surface bonded strain gauges. Since the strain-gauged bone staples were inserted to a depth of 4 mm within the bone of the distal radius they may also reflect internal strains within the bone and not only surface strains. The strain and strain rate measurements may have been affected by variation in the precise location and orientation of the staple insertion between subjects. Differences in bone quality and size between patients may also have contributed to differences in measurements. Because this

| Table II. Pairwise p values regarding maximal compression strain. Bold values indicate significant differences (p ≤ 0.05). |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | < 0.01 | 0.03 | 0.38 | 0.01 | 0.14 | 0.09 | 0.51 | 0.16 | 0.96 |
| 2 | < 0.01 | < 0.01 | < 0.01 | 0.57 | 0.88 | 0.02 | 0.89 | 0.04 |
| 3 | 0.04 | 0.37 | < 0.01 | < 0.01 | 0.02 | 0.03 | 0.02 |
| 4 | 0.24 | 0.01 | < 0.01 | 0.02 | 0.03 | 0.06 |
| 5 | < 0.01 | < 0.01 | < 0.01 | 0.02 | < 0.01 |
| 6 | 0.68 | 0.07 | 0.48 | 0.07 |
| 7 | 0.01 | 0.78 | 0.17 |
| 8 | 0.26 | 0.73 |
| 9 | 0.40 |

| Table III. Pairwise p values regarding maximal compression strain rate. Bold values indicate significant differences (p ≤ 0.05) |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | 0.01 | 0.77 | 0.28 | < 0.01 | 0.09 | 0.11 | 0.96 | 0.57 | 0.79 |
| 2 | 0.14 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | 0.24 | 0.07 | 0.24 |
| 3 | 0.09 | 0.02 | 0.21 | 0.14 | 0.77 | 0.50 | 0.59 |
| 4 | 0.03 | 0.20 | 0.72 | 0.28 | 0.16 | 0.51 |
| 5 | < 0.01 | < 0.01 | < 0.01 | 0.02 | < 0.01 |
| 6 | 0.20 | 0.24 | 0.21 | 0.72 |
| 7 | 0.11 | 0.05 | 0.24 |
| 8 | 0.57 | 0.65 |
| 9 | 0.88 |

| Table IV. Pairwise p values regarding maximal compression strain rate. Bold values indicate significant differences (p ≤ 0.05) |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | 0.64 | 0.02 | < 0.01 | 0.95 | 0.33 | 0.24 | 0.17 | 0.57 | 0.51 |
| 2 | 0.01 | < 0.01 | 0.38 | 0.09 | 0.44 | 0.01 | 0.33 | 0.88 |
| 3 | 0.17 | 0.01 | < 0.01 | < 0.01 | < 0.01 | 0.02 | 0.02 | 0.01 |
| 4 | 0.01 | < 0.01 | < 0.01 | < 0.01 | 0.04 | 0.02 | < 0.01 |
| 5 | 0.65 | 0.24 | 0.11 | 0.02 | 0.24 |
| 6 | 0.05 | 0.20 | 0.02 | 0.06 |
| 7 | 0.01 | 0.89 | 0.72 |
| 8 | 0.03 | 0.01 |
| 9 | 0.26 |
study compared intra-subject differences between activities, these factors should be minimised. Another limitation of this study was the variation in the execution of the exercises depending on the patients’ physical condition. There was considerable variation especially in the execution of the standing falling, kneeling falling and chin-ups. While some could raise their chins over the bar during the chin-ups, some could hardly raise their body-weight. Several were hesitant about falling forwards onto their hands, especially from a standing position. Although the security belt around the patients’ waists gave some confidence, it may also have increased the variability in the execution of the falls. These factors, combined with difficulties in positioning and orientating the CT images relative to the site of the staple, might explain the absolute absence of correlation between radiological data, BMD and deformation data.

The observation that controlled falls had the highest wrist strain and strain rates in this study indicate that of all the activities studied they have the highest osteogenic potential for the wrist. These activities are, however, problematic for the wrist. These activities, mechanisms, and relationship with estrogen of the mechanically adaptive process in bone. J Bone Miner Res 1996;10:1544-9.

References