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# Treadmill Exercise Intensity and Its Effects on Cortical Bone in Horses of Various Ages

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ABSTRACT. The effects of treadmill exercise on mid-metacarpal bone mass and density were assessed by both noninvasive and invasive means in three groups of horses: *Group 1*—6 adult Standardbreds received a 13 week exercise programme which included intense interval training. A significant increase in ultrasound speed through the mid-metacarpus occurred by the end of training. However, no change in bone mineral content was detected. *Group 2*—9 two year old Standardbreds received either maximal, submaximal or no treadmill exercise. Ultrasound speed declined in all horses, but the least decline occurred in the maximally exercised animals and there was no change in bone mineral content. Microradiographs indicated decreasing bone porosity associated with the increasing levels of exercise. *Group 3*—12 yearling Thoroughbreds received either maximal or no treadmill exercise for 16 weeks. There were significant increases in ultrasound speed and bone mineral content of the mid-metacarpus associated with exercise. Microradiography and histomorphometry demonstrated reduced bone porosity and increased dorsal cortical thickness in the exercised horses. The results indicate that bone quality and quantity are affected by exercise intensity, as well as by the age of the horse. High intensity exercise in young horses resulted in reduction of intra-cortical remodelling activity and alteration in the cross-sectional morphology of the mid-metacarpus by modelling

*Key words*. Horses, exercise intensity; bone mass; ultrasound speed; microradiography; histomorphometry

## INTRODUCTION

The response of cortical bone to exercise varies according to the duration and intensity of training and the age of the animal.[2] The literature contains reports indicating a large variation in bone response from retardation of bone growth,[16] to increases in bone mass and density,[9,17] while some show no effect at all.[8] Exercise has also been shown to retard and even reverse the rate of involution and postmenopausal bone loss in humans.[15]

Studies on the effects of exercise on cortical bone of horses have generally been limited to a single age group and have often involved mature and non-athletic breeds of horses.[4,6,14] The studies on young horses have tended to concentrate on low intensity exercise, which has not produced dramatic effects.[3,11] The objective of this study was to investigate, by noninvasive means, the response of bone to exercise in horses of varying maturity. The extent of bone modelling and remodelling activity was also assessed by histomorphometry.

## MATERIALS AND METHODS

### *Experiment 1*

Six previously trained adult Standardbred horses, 4 females and 2 geldings aged 5–10 years, were trained on a high speed treadmill (Beltalong, Euroa, Vic.) for 13 weeks. The exercise consisted of interval-like training; the horses spent 4 weeks trotting at 4 m $s^{-1}$, and then 6 weeks of interval training at 8–10 m $s^{-1}$, and finally 3 weeks at 10 to 12 m $s^{-1}$. The incline of the treadwill was 3°.

### *Experiment 2*

Nine 2 year old Standardbred horses which had been broken in were given either no exercise ($n=3$, 3 females), submaximal exercise ($n=3$, 3 females) or maximal treadmill exercise ($n=3$, 1 female and 2 geldings). The maximally exercised horses were loaded periodically with weight (20 kg) on their backs. The submaximal exercise group trained for 17 weeks trotting at 4 m $s^{-1}$. The maximal exercise group spent 5 weeks trotting at 4 m $s^{-1}$, then 12 weeks interval training at speeds from 8 to 12 m $s^{-1}$. The treadwill incline was 3°.

### *Experiment 3*

Twelve unbroken yearling Thoroughbred horses were given either no exercise ($n=6$, 1 female and 5 males) or maximal exercise ($n=6$, 3 females and 3 males). Training consisted of 4 weeks trotting at 4 m $s^{-1}$ followed by 5 weeks sprint work at speeds of 8 to 12 m $s^{-1}$, followed by 5 weeks sprint work at 12 to 14.5 m $s^{-1}$. The incline of the treadmill was reduced from 3° to zero in the final 5 weeks of training to facilitate the higher speed exercise.

The horses in Experiments 1 and 2 were kept in a 10 acre paddock when not exercising. The horses in Experiment 3 were kept in small yards.

### *Noninvasive measurements of bone quality and quantity*

Each horse had the apparent ultrasound velocity ($C_a$ m $s^{-1}$) and the estimated transverse bone ultrasound velocity ($C_b$ m $s^{-1}$) through each mid-metacarpus[7] measured before, during, and in Experiment 1 after, the training programme. The bone mineral content (BMC g $cm^{-1}$) of the same mid-metacarpal site was also measured during this period by single photon absorptiometry.[7] By combining the data from the ultrasound velocity measurements and BMC, bone mineral density (BMC g $cm^{-3}$), compact bone density (CBD g $cm^{-3}$) and the bulk modulus (E GN $m^2$) of the bone were estimated.[7]

### *Invasive measurements of bone*

Microradiographs were taken of cross sections of cortical bone from the mid-metacarpus of all horses in Experiments 2 and 3. 100 µm slices of bone were cut from embedded and unembedded bone on a diamond coated internal hole saw (Leitz 1600, Wild Leitz, Wetzlar, West Germany). Microradiographs were taken of these sections in a Faxitron 804 machine using Kodak high resolution film. The films were then examined for areas of new bone production and the intracortical bone porosity was measured. The porosity was measured using a quantitative image analyser (Mop Videoplan, Kontron Bildanalyze, 8057 Eching-Munich, West Germany) attached to a transmitted light microscope (Zeiss, Oberkochen, West Germany). The porosity was calculated at the:

($\Sigma$ Area of all canals and resorption spaces/ Total area of field of view) $\times 100\%$.

Histomorphometry of cortical bone sections from near the mid-metacarpal site of the horses in Experiment 3 was also conducted. The histomorphometry facility was unavailable for Experiments 1 and 2. Intra-vital bone labels (oxytetracycline, 15 mg $kg^{-1}$ I.V.) were given 14 and 4 days before the horses were destroyed. Static morphometry measurements (Table 1) were taken from 5 µm sections of the dorsal cortex stained with either Toluidine blue or Goldner's trichrome. Quantitative image analysis of the bone sections was used to determine the bone volume and cellular details. Thicker (60 µm) adjacent sections of bone were viewed under fluorescent light to measure areas and amounts of active bone formation (i.e. "dynamic" parameters of Table 1). The combination of both sets of data allows bone formation rates, bone resorption rates and osteon remodelling periods to be calculated.

### *Standardised exercise tests*

In each experiment, at regular intervals, the heart rate response to a rapid incremental exercise programme was assessed. In Experi-

Table 1. *Histomorphometric parameters measured for cortical bone (modified from Anderson*[1]*)*

| *Static* | |
|---|---|
| Primary measurements | Derived measurements |
| Total area ($mm^2$) | % Area of mineralised bone |
| Area of all cavities ($mm^2$) | % Area of bone |
| Surface of all cavities (mm) | % Area of osteoid |
| Area of osteoid ($mm^2$) | Relative % area of osteoid |
| Surface of osteoid (mm) | % Area of resorption cavities |
| Mean width of osteoid (μm) | % Active surface of resorption cavities |
| Active surface of osteoid (mm) | Relative osteoclastic activity |
| No. of osteoblasts | % Surface of osteoid |
| Surface of resorption cavities (mm) | % Active surface of osteoid |
| Active surface of resorption cavities (mm) | Relative osteoblastic activity |
| No. of osteoclasts | % Inactive surface |
| *Dynamic* | |
| Intracortical measurement | Periosteal/endosteal measurement |
| Mean distance between double labels (μm) | % Surface with double labels |
| Mean wall thickness (μm) | % Surface with single labels |
| Appositional rate (μm $day^{-1}$) | % Surface with no labels |
| Mineralisation lag time (day) | Mean distance between double labels (μm) |
| Sigma formation (day) | Trabecular |
| Sigma formation and resorption (day) | |

ment 1 the test consisted of 2 min at 4 and 6 m $s^{-1}$, followed by 1 min at 7, 8, 9, 10 and 11 m $s^{-1}$. In Experiments 2 and 3 the test consisted of 2 min at 4 m $s^{-1}$ followed by 1 min at 5, 6, 7 and 8 m $s^{-1}$. From each test the speed at which a heart rate of 200 bpm ($V_{200}$) occurred was measured. Heart rate was monitored by a portable heart rate meter (PEH 100, Polar Electro Ky, Finland). Plasma lactate accumulation in response to the exercise test was also determined. Venous blood samples were collected, prior to and 2 min after the exercise test. The plasma was assayed for lactic acid concentration using a blood lactate kit (Sigma Diagnostics, St. Louis, MO) in Experiment 1. In the other experiments, a blood lactate kit (Boehringer, Mannheim, West Germany) was adapted for use on a multichannel automated colorimeter (Roche, Dee Why, NSW, Australia).

### *Statistics*

The results are presented as mean ± SD. Differences between two groups were tested for significance using a two sample Student's *t*-test, and differences between paired data within a group were analysed using a Student's *t*-test for paired data. Results were considered to be significant when $p \leqslant 0.05$.

## RESULTS

The maximal exercise required of the horses in these experiments resulted in all the horses galloping at their peak speeds. Most of the Standardbred horses cantered and galloped at speeds greater than 8 m $s^{-1}$.

In Experiment 1 only 4 of the 6 horses finished the entire training programme. One horse was retired due to a recurrence of a pre-existing tenosynovitis, the second devel-

Table 2. *Apparent ultrasound velocity* ($C_a$ *m* $s^{-1}$) *and estimated transverse bone ultrasound velocity* ($C_b$ *m* $s^{-1}$) *of the right mid-metacarpus* (*mean* ± *SD*) *at the start and after training of horses in Experiments 1, 2 and 3*

| | $C_a$ | | $C_b$ | |
|---|---|---|---|---|
| | Start of training | After training | Start of training | After training |
| Experiment 1 | | | | |
| | 2 867<br>±66.4 | 2 915<br>±63.0 | 3 236<br>±89.2 | 3 296<br>±79.3 |
| Experiment 2 | | | | |
| Controls | 2 780<br>±82 | 2 716<br>±111 | 3 166<br>±66 | 3 058<br>±120 |
| Submax. exercise | 2 820<br>±42 | 2 744<br>±30 | 3 201<br>±61 | 3 088<br>±32 |
| Maximal exercise | 2 780<br>±22 | 2 762<br>±16 | 3 163<br>±15 | 3 143<br>±22 |
| Experiment 3 | | | | |
| Controls | 2 724<br>±41 | 2 701<br>±42 | 3 145<br>±71 | 3 099<br>±57 |
| Maximal exercise | 2 780<br>±15 | 2 824<br>±37 | 3 174<br>±43 | 3 231<br>±72 |

oped a foot abscess and later had a severe bout of exertional myopathy. All the horses in Experiment 2 suffered from a severe upper respiratory tract infection (i.e. strangles) before the commencement of training. This seemed to influence the ultrasound velocity readings during the recuperation period. One horse in Experiment 3 developed bruised soles and a subsolar abscess during the period of maximal training (Weeks 10–12) and only exercised at submaximal levels during this period.

### *Experiment 1*

The ultrasound velocity through the mid-metacarpal shaft increased as training progressed, and was significantly higher at the end of training compared to pre-training values (Table 2). Bone mineral content, and consequently BMD, and CBD, did not alter due to training (Table 3). The transverse bulk modulus (E) increased from $19.4 \pm 1.11$ to $20.25 \pm 1.03$ GN $m^{-2}$ for the right metacarpus and $19.68 \pm 1.32$ to $20.4 \pm 1.34$ GN $m^{-2}$ for the left ($p < 0.05$ paired *t*-test).

### *Experiment 2*

All but 3 horses showed a reduction in ultrasound velocity through the mid-metacarpal site (Table 2). The greatest decrease occurred in the non-exercised group and the least in the maximally exercised group. There was no detectable change in BMC (Table 3) or E, over the period of investigation. The microradiographs from these horses showed non-significant differences in intra-cortical bone porosity commensurate with the level of exercise. The maximally exercised horses had the lowest bone porosity ($3.65 \pm 0.44\%$), while the non-exercised horses had the highest bone porosity ($4.62 \pm 0.14\%$). The submaximally exercised horses' bone porosity was between these two values ($3.86 \pm 0.45\%$). Subperiosteal new bone growth was only evident in the control and

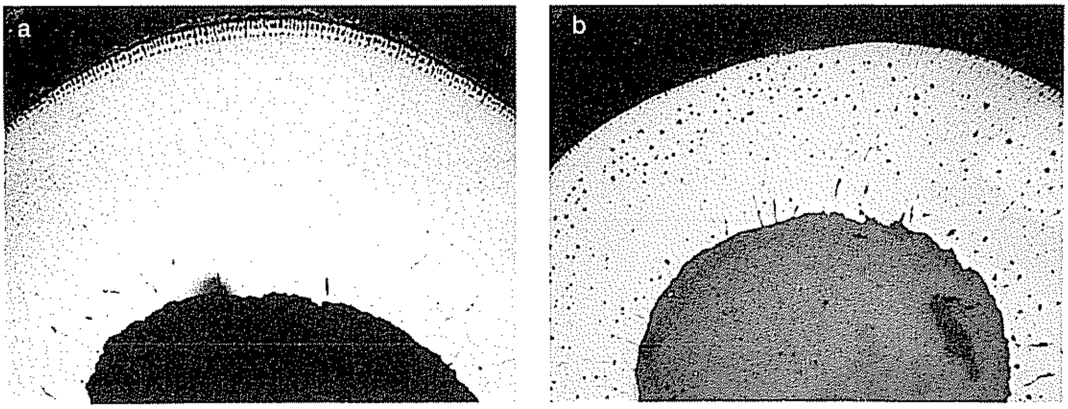

*Fig. 1* Microradiographs from the mid-shaft of the third metacarpus from: (*a*) an exercised horse, and (*b*) a non-exercised horse in Experiment 3.

submaximally exercised horses, and was not apparent in the maximally exercised horses.

*Experiment 3*

The ultrasound velocity through the mid-metacarpus had increased in the maximally exercised horses by the last week of training, whereas $C_a$ and $C_b$ had slightly decreased in the non-exercised horses (Table 2). Bone mineral content markedly increased in the exercised horses, and only marginally increased in the non-exercised horses (Table

Table 3. *Bone mineral content (BMC g cm$^{-1}$) and bone mineral density (BMD g cm$^{-3}$) of the left mid-metacarpus (mean ± SD) at the start and after training of horses in Experiments 1, 2 and 3*

| | BMC (g cm$^{-1}$) | | BMD (g cm$^{-3}$) | |
|---|---|---|---|---|
| | Start of training | After training | Start of training | After training |
| Experiment 1 | | | | |
| | 8.55 | 8.67 | 0.97 | 1.01 |
| | ±0.49 | ±0.72 | ±0.04 | ±0.03 |
| Experiment 2 | | | | |
| Controls | 6.49 | 6.55 | 0.94 | 0.91 |
| | ±1.12 | ±0.90 | ±0.01 | ±0.01 |
| Submax. exercise | 7.76 | 8.28 | 0.97 | 1.01 |
| | ±0.69 | ±0.29 | ±0.02 | ±0.05 |
| Maximal exercise | 6.67 | 6.76 | 1.03 | 0.96 |
| | ±0.65 | ±0.72 | ±0.13 | ±0.14 |
| Experiment 3 | | | | |
| Controls | 6.37 | 6.54 | 1.04 | 0.98 |
| | ±0.31 | ±0.56 | ±0.13 | ±0.06 |
| Maximal exercise | 6.87 | 7.84 | 0.99 | 1.14 |
| | ±0.56 | ±0.30 | ±0.05 | ±0.14 |

Table 4. *Static histomorphometric data (mean ± SD) from the dorsal cortex of the mid-shaft of the third metacarpus of horses in Experiment 3*

| | Dorsal cortex | |
|---|---|---|
| Measurement | Exercised ($n=6$) | Non-exercised ($n=6$) |
| Area of mineralised bone | $97.34 \pm 0.723^{a}$ | $94.45 \pm 2.07$ |
| Area of bone | $97.35 \pm 0.727^{a}$ | $94.95 \pm 1.74$ |
| Area of osteoid | $0.004 \pm 0.008^{b}$ | $0.497 \pm 0.358$ |
| Relative area of osteoid | $0.004 \pm 0.008^{b}$ | $0.529 \pm 0.386$ |
| Area of resorption cavities | $0.007 \pm 0.002$ | $0.453 \pm 0.321$ |
| Surface of resorption cavities | $0.075 \pm 0.183^{b}$ | $3.23 \pm 1.697$ |
| Active surface of resorption cavities (%) | 0 $-^{b}$ | $0.916 \pm 0.647$ |
| Relative osteoclastic activity | 0 – | $30.24 \pm 17.71$ |
| Surface of osteoid | $0.384 \pm 0.648^{b}$ | $11.81 \pm 7.64$ |
| Active surface of osteoid | $0.093 \pm 0.229^{b}$ | $7.55 \pm 5.64$ |
| Relative osteoblastic activity | $5.983 \pm 14.67$ | $52.17 \pm 30.06$ |
| Inactive surface | $99.54 \pm 0.16^{a}$ | $84.96 \pm 8.92$ |
| No. of osteoblasts (per 50 fields of view) | $1.17 \pm 2.86$ | $100.2 \pm 67$ |
| No. of osteoclasts (per 50 fields of view) | 0 – | $3 \pm 1.26$ |

[a] Significantly greater than the non-exercised group ($p<0.05$).
[b] Significantly less than the non-exercised group ($p<0.05$).

3). Bone mineral density increased in the exercised horses and slightly decreased in the non-exercised group (Table 3). The bulk modulus increased from 18.77 ± 1.24 to 19.8 ± 1.79 GN $m^{-2}$ in the left limb and from 18.75 ± 0.70 to 19.95 ± 1.34 GN $m^{-2}$ in the right limb ($p<0.05$ paired *t*-test) in the exercised horses and slightly decreased in the non-exercised.

The microradiographs indicated a significant difference in intra-cortical bone porosity at the end of training between the two groups (exercised 4.74 ± 0.73 vs. non-exercised 6.96 ± 1.43). Much greater subperiosteal osteogenesis was seen on the dorsal cortex of the exercised horses (Fig. 1 *a* and *b*). Histomorphometry revealed this same pattern, the exercised horses had a greater cortical bone volume and a larger percentage of inactive surfaces. The area of osteoid, length of active osteoid, osteoblast numbers, and also the areas, surfaces of osteoclastic resorption was much greater in the non-exercised horses (Tables 4 and 5).

The dorsal periosteal surface of the exercised group had the larger appositional rate, and was nearly totally active in all these horses at the end of training. The non-exercised horses had a smaller appositional rate and this was distributed more uniformly around the periosteum (Tables 6 and 7).

### *Standardised exercise tests*

Improvement in $V_{200}$ and plasma lactate accumulation (PLA) occurred in the younger horses that were exercised maximally (Table 8). The adult Standardbred horses did not significantly alter their $V_{200}$ or PLA during training, although they seemed more able to complete their exercise as training progressed. The $V_{200}$ of the two year old horses increased as training progressed. The improvement in the maximally exercised horses was significantly greater than in the submaximally exercised horses. PLA decreased significantly in the maximally exercised horses but not significantly in the sub-

Table 5. *Dynamic histomorphometric data (mean ± SD) from the dorsal cortex of the mid-shaft of the third metacarpus in Experiment 3*

| | Dorsal cortex | |
|---|---|---|
| Measurement | Exercised ($n=6$) | Non-exercised ($n=6$) |
| Mean distance between double labels (μm) | 14.47 | 14.96 ± 1.74 |
| Mean wall thickness (μm) | 72.39 ± 5.38 | 74.41 ± 7.37 |
| Appositional rate (μm day$^{-1}$) | 1.447 | 1.496 ± 0.174 |
| Mineralisation lag time (day) | – | 7.91 ± 2.02 |
| Sigma formation (day) | 43.33[a] | 50.22 ± 6.67 |
| Sigma resorption (day) | – | 13.75 ± 6.16 ($n=5$) |
| Sigma resorption and formation (day) | – | 64.84 ± 11.26 ($n=5$) |

[a] $n=1$ for this measurement.

maximally exercised horses. The young Thoroughbred horses showed a large increase in $V_{200}$ as a result of training and a significant reduction in PLA (Table 8).

## DISCUSSION

This study highlights some of the important factors involved in the bone's response to exercise; namely the age of the animal and

Table 6. *Percentage of surfaces on the mid-shaft of the third metacarpus exhibiting fluorescent labels of horses in Experiment 3*

| | | Periosteal surface | | | Endosteal surface | | | |
|---|---|---|---|---|---|---|---|---|
| Cortical site | Group of horses | % Double label | % Single label | % No label | % Double label | % Single label | % No label | Trabecular |
| Dorsal cortex | Exercise | 74.3 ± 34.3 | 25.7 ± 34.3 | 0 | 54.2 ± 45.2 | 5.8 ± 6.7 | 40 ± 39.1 | 0 |
| | Non-exercise | 46.8 ± 30.9 | 15.2 ± 21.8 | 38.0 ± 23.9 | 2.5 ± 6.1 | 5.8 ± 6.7 | 91.7 ± 11.7 | 3 |
| Palmar cortex | Exercise | 2.1 ± 5.1 | 7.9 ± 14.1 | 90.0 ± 15.8 | 3.3 ± 7.7 | 7.7 ± 12.0 | 91.0 ± 15.5 | 0 |
| | Non-exercise | 45.7 ± 31.9 | 18.4 ± 15.9 | 35.9 ± 34.6 | 16.0 ± 25.7 | 7.0 ± 9.2 | 77.0 ± 34.8 | 3 |
| Lateral cortex | Exercise | 43.3 ± 47.6 | 15.0 ± 23.4 | 41.7 ± 49.2 | 9.2 ± 14.3 | 2.1 ± 5.0 | 88.7 ± 17.6 | 0 |
| | Non-exercise | 41.7 ± 49.1 | 16.6 ± 25.8 | 41.7 ± 49.2 | 18.0 ± 40.28 | 3.8 ± 6.1 | 78.2 ± 39 | 3 |
| Medial cortex | Exercise | 12.2 ± 29.8 | 16.7 ± 16.6 | 71.2 ± 30.7 | 1.8 ± 2.9 | 5.7 ± 7.6 | 92.5 ± 10 | 0 |
| | Non-exercise | 36.5 ± 49.7 | 10.8 ± 17.4 | 52.7 ± 44.9 | 12.7 ± 16.1 | 7.7 ± 9.6 | 79.6 ± 19.4 | 3 |

Table 7. *Surface appositional rates ($\mu m\ day^{-1}$) of the mid-shaft of the third metacarpus of horses in Experiment 3 (mean ± SD)*

| Cortical site | Group of horses | Appositional rate ($\mu$m day$^{-1}$) |  |  |  |
|---|---|---|---|---|---|
|  |  | Periosteal surface |  | Endosteal surface |  |
| Dorsal cortex | Exercise | 1.561 ± 0.084* |  | 1.127 ± 0.141 | ($n=4$) |
|  | Non-exercise | 1.281 ± 0.190 |  | 1.921 | ($n=1$) |
| Palmar cortex | Exercise | 1.45 | ($n=1$) | 1.65 | ($n=1$) |
|  | Non-exercise | 2.48 ± 0.41 |  | 2.31 ± 1.44 | ($n=1$) |
| Lateral cortex | Exercise | 1.56 ± 0.12 | ($n=3$) | 1.73 ± 0.16 | ($n=3$) |
|  | Non-exercise | 1.46 ± 0.18 | ($n=3$) | 1.59 ± 0.08 | ($n=2$) |
| Medial cortex | Exercise | 1.92 ± 0.38 | ($n=2$) | 2.29 ± 0.14 | ($n=2$) |
|  | Non-exercise | 2.14 ± 0.59 | ($n=3$) | 1.80 ± 0.17 | ($n=3$) |

* Significantly greater than non-exercise group $p < 0.05$.

the intensity of the exercise programme. Intense treadmill exercise (i.e. < 12 m s$^{-1}$ on a 3° slope) resulted in only a marginal increase in bone density of the metacarpal cortex in adult horses. A similar level of exercise intensity in two year old horses failed to produce a significant improvement in bone density. The absence of an effect in these ani-

Table 8. *$V_{200}$ (bpm) and plasma lactate accumulation (PLA mmol $l^{-1}$) at the start and after training of horses (mean ± SD) in Experiments 1, 2 and 3*

|  | $V_{200}$ |  | PLA |  |
|---|---|---|---|---|
|  | Start of training | After training | Start of training | After training |
| Experiment 1 |  |  |  |  |
|  | 9.51<br>± 1.32 | 9.40<br>± 1.48 | 15.21<br>± 3.86 | 15.43<br>± 6.37 |
| Experiment 2 |  |  |  |  |
| Submaximal exercise | 6.66<br>± 0.54 | 7.41<br>± 0.58 | 6.57<br>± 2.11 | 6.14<br>± 1.67 |
| Maximal exercise | 7.13<br>± 0.35 | 9.02<br>± 0.44 | 4.0<br>± 0.89 | 2.57<br>± 0.40 |
| Experiment 3 |  |  |  |  |
|  | 6.86<br>± 0.90 | 8.86<br>± 1.60 | 6.015<br>± 2.52 | 2.34<br>± 0.05 |

mals was presumably related to their previous training experience. This inference was corroborated by the fact that fast exercise in young untrained horses markedly improved bone density and dramatically altered the distribution of bone mass in the metacarpal cortex. There were two processes involved in this change in bone structure. First, there was an alteration through intracortical remodelling and, secondly, an alteration by periosteal and endosteal modelling.

It is well known that all these changes in bone are strain dependent and this can involve the magnitude, distribution and rate of strain.[10] Intra-cortical remodelling may be inhibited above a minimum or threshold level of strain; in humans this level is thought to be 300 $\mu$ strain.[5] Research on the isolated avain ulna has demonstrated that new surface bone growth is linearly proportional to strain magnitude above 1 000 $\mu$ strain.[13] In these experiments the strain magnitude was not measured. However, studies by Nunamaker[12] have demonstrated that very high strains occur on the dorsal metacarpal cortex in galloping horses and that the highest are recorded in young horses. It is important to bear in mind that the response of bone to training on a track may differ somewhat as the bone will be subjected to wide variations in stress. Consequently, strain will be increased due to variation in the track surface and the centripetal forces that occur whilst running on the curve.

The data presented here indicate that little improvement in bone density can be expected in previously trained two year old and adult horses maximally exercised on a treadmill. In contrast bone density and distribution of bone mass can be greatly altered by exercise at speeds up to 14 m $s^{-1}$. This improvement in bone can be achieved without significant injury to the limbs or bones involved. The ultimate objective of this research is to develop controlled programmes of fast work to improve bone quality in the early stages of training and limit the effects of exercise-induced injuries.

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