Variations of bone structure in horses involved in sport have been studied for the past 30 years. The interest in this field is related to the fact that this variation can lead to the development of specific pathological changes that can end the athletic career of a horse. Changes in thickness of the dorsal cortex of the third metacarpal bone have been studied, especially in young Thoroughbreds. The architectural arrangement of bone tissue is related to the general functional requirement of the particular skeletal elements. Bone strain patterns can be altered in the event of persistent change in the normal pattern of loading. This change in strain distribution can initiate a redistribution of bone through a modelling response to alter the architecture of the bone. Changes in the shape of the bone may be the dominant adaptation to loading soon after birth.

Objectives—To evaluate changes in the cortical bone of the proximal phalanx of the forelimbs of Thoroughbreds in response to training.

Animals—Twenty-seven 2-year-old Thoroughbreds (20 females, 2 males, and 5 geldings).

Procedures—Horses were principally in training for races in a straight line and in a clockwise direction. Lateromedial and dorsopalmar radiographic views of each metacarpophalangeal joint were obtained before the horses started training and 1 year after starting exercise and racing. Width of the dorsal, palmar, lateral, and medial cortex and the width and thickness of the medulla were measured. Ratios (rather than absolute values) were used to remove the effect of differences in bone size among horses.

Results—10 horses were lost from the study. Radiographs were obtained for 17 horses 1 year after starting training (9 horses raced in a clockwise direction, and 8 raced in clockwise and counterclockwise directions). There was no difference between the cortical bone in the right and left forelimbs at the start of the study. After training for 1 year, the palmar cortex in the right forelimb was significantly thicker than that in the left forelimb.

Conclusions and Clinical Relevance—The strain patterns, biomechanics of rapid exercise, and type of training most probably determined differences in the adaptive responses of the proximal phalanx. The data reported here can be used in the evaluation of weight-bearing distribution along the proximal phalanx and evaluation of the relationship between exercise and bone remodelling of the proximal phalanx. (Am J Vet Res 2011;72:1482–1488)

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Abbreviations

DCP  Dorsal cortex of the proximal phalanx
GRF  Ground reaction force
LCP  Lateral cortex of the proximal phalanx
MCP  Medial cortex of the proximal phalanx
MPD  Width of the medulla of the proximal phalanx on the dorsopalmar radiographic view
MPL  Width of the medulla of the proximal phalanx on the lateromedial radiographic view
P1  Proximal phalanx
PCP  Palmar cortex of the proximal phalanx
RI  Second ratio index
Rld  Second ratio index of the dorsal cortex
Rlp  Second ratio index of the lateral cortex
Rpm  Second ratio index of the medial cortex
Rpp  Second ratio index of the palmar cortex
Z  First ratio index
Zd  First ratio index of the dorsal cortex
Zl  First ratio index of the lateral cortex
Zm  First ratio index of the medial cortex
Zp  First ratio index of the palmar cortex

and changes in the shape of the bone might be the best indicator of increased mechanical integrity.

Adaptation in cortical bone commonly refers to changes in structure or material organization in re-
sponse to loading conditions outside the physiologic stress and strain range, distribution, and duration or regional differences in structural or material organization that are influenced strongly by functional stimuli during physiologic development within or between bones. Adaptations are also considered to be biomechanically relevant variations in organization of cortical bone material that result from modelling and remodeling processes during skeletal development; these processes can be influenced by nonheritable stimuli, such as regional variations in microdamage.

Adaptation of the architecture of bone is the predominant response to exercise in young animals. The relative thickness of the cortices reflects the loading patterns of a particular bone. In young Thoroughbreds, the dorsal cortex of the third metacarpal bone increases in thickness in response to high-speed exercise, and this thickening is significantly related to the amount of time in training. Race training increases the diameter of medial and lateral cortices as well as the width of dorsopalmar and lateromedial cortices. These changes can be measured via radiography, which has been used to assess the change in shape of the third metacarpal bone in response to training. Results of a study designed to define the limitation and the amount of accuracy for this technique indicate an acceptable degree of accuracy can be obtained by appropriate alignment of a limb, cassette, and radiography machine.

To the best of our knowledge, there is no report of modification of P1 in response to training. The purpose of the study reported here was to determine whether radiographic measurements of the shape of P1 could be used to detect changes during a training program. A second objective was to identify change in bone shape in P1 of young Thoroughbreds during race training. Our hypothesis was that the cortices of P1 would change in response to a 1-year period of race training.

Materials and Methods

Animals—Between January 2006 and March 2007, 27 Thoroughbreds (20 females, 2 males, and 5 geldings) were enrolled in the study. Horses were 2 years old and in commercial race training at 2 racing stables. Informed consent was obtained from owners prior to participation of horses in the study. The study was conducted in accordance with guidelines reviewed and approved by the Institutional Animal Care and Use Committee of the University of Perugia.

Horses were examined radiographically before their first exposure to high-speed exercise and approximately 1 year later. The exercise program, including the distance traveled clockwise and counterclockwise during training and races, was recorded for each horse.

Radiography—Standard lateromedial and dorsopalmar views of the right and left forelimb metacarpophalangeal joint ( fetlock joint) were obtained at a distance of 80 cm by use of a standard portable radiography machine and cassettes with a rare-earth screen. Radiographic images considered unsuitable for measurements were excluded from the study.

Radiographic measurements—Measurements were performed twice by 2 investigators. Measurements of the radiographs were manually performed by use of a plastic ruler; measurements were accurate to within 0.1 mm. Several variables were measured, which included the MPD and MPL (distance between the endosteal surfaces of the 2 cortices for the respective radiographic view), LCP (distance between the periosteal surface and endosteal surface of the lateral cortex), MCP (distance between the periosteal surface and endosteal surface of the medial cortex), DCP (distance between the periosteal surface and endosteal surface of the dorsal cortex), and PCP (distance between the periosteal surface and endosteal surface of the palmar cortex).

On the dorsopalmar radiographic view, LCP, MCP, and MPD were measured at a point 5 cm distal to the center of the articular surface of P1 along a line perpendicular to the longitudinal axis of the bone (Figure 1). Ratios, rather than absolute values, were used to remove the effect of differences in bone size between horses. The Z is a measure of the tendency of the exam-
ined cortex to increase relative to the medulla, whereas the RI yields a measure of the tendency for bone to be deposited preferentially onto the cortex. Ratios were calculated as follows:

\[
Z_{pm} = \frac{MCP}{MPD}
\]

\[
Z_{pl} = \frac{LCP}{MPD}
\]

\[
RI_{pl} = \frac{(LCP + MCP)/MPD}{(MCP/LCP)}
\]

\[
RI_{pm} = \frac{(LCP + MCP)/MPD}{(LCP/MCP)}
\]

On the lateromedial radiographic view, DCP, PCP, and MPL were measured at a point 4 cm distal to the center of the articular surface of P1 along a line perpendicular to the longitudinal axis of the bone (Figure 2). Ratios were calculated as follows:

\[
Z_{pd} = \frac{DCP}{MPL}
\]

\[
Z_{pp} = \frac{PCP}{MPL}
\]

\[
RI_{pd} = \frac{((DCP + PCP)/MPL) \times (DCP/PCP)}{((DCP + PCP)/MPL) \times (PCP/DCP)}
\]

\[
RI_{pp} = \frac{((DCP + PCP)/MPL) \times (DCP/PCP)}{((DCP + PCP)/MPL) \times (PCP/DCP)}
\]

Statistical analysis—A paired Student t test was used for analysis of the data for each investigator to assess repeatability of the method. The differences between the means of the data for the 2 investigators were analyzed with a 2-sample Student t test to assess reproducibility of the method.

Differences between the ratios calculated for the left and right forelimbs before and after the training period were tested by use of a paired or Welch 2-sample Student t test to assess reproducibility for the accuracy of the method (Table 1).

The Zpl, Zpm, Zpd, RIpl, RIpm, and RIpd did not differ significantly between the right and left forelimb before and after the beginning of the training period (Table 2). Similarly, these variables did not differ significantly in each forelimb before and after the training period (Table 3). There was not a significant difference in Zpp or RIpp between the right and left forelimb before the training period or in each forelimb before and after the training period, whereas there were significant differences in Zpp \((P = 0.04)\) and RIpp \((P = 0.05)\) between the right and left forelimb after the training period.

**Results**

Ten horses were lost from the study (6 horses changed training centers, 3 horses developed musculoskeletal injuries, and 1 horse was excluded because its athletic use changed and it was trained for eventing rather than racing). The remaining 17 horses (9 at the first stable and 8 at the second stable) were evaluated before and after training and racing for 1 year. The 9 horses (7 females, 1 male, and 1 gelding) at the first stable were trained in a straight line and in a clockwise direction 4 d/wk. The 8 horses (7 females and 1 gelding) at the second stable were also trained in a straight line and in a clockwise direction 4 d/wk and in a counterclockwise direction 2 d/wk; training in a counterclockwise direction was not performed at high speed (gallop). None of the horses included in the study had clinical signs of soreness of the dorsal aspect of the metacarpal region (ie, sore shins) during training.

The 9 horses at the first stable raced at distances of 1,200 to 2,400 m. Eight race starts in 3 females were for distances of 1,200 m, and 83 starts for all 9 horses were for distances > 1,200 m; all races were run in a clockwise direction. The 8 horses at the second stable raced at distances of 1,000 to 3,000 m. Seventeen starts in 2 females were for distances of 1,000 to 1,200 m, and 107 starts in all 8 horses were for distances of > 1,200 m. Of the 124 races, 107 were run in a clockwise direction and 17 were run in a counterclockwise direction.

Results for the 2 investigators were analyzed. Statistical analysis confirmed repeatability and reproducibility for the accuracy of the method (Table 1).

The Zpl, Zpm, Zpd, RIpl, RIpm, and RIpd did not differ significantly between the right and left forelimb before and after the beginning of the training period (Table 2). Similarly, these variables did not differ significantly in each forelimb before and after the training period (Table 3). There was not a significant difference in Zpp or RIpp between the right and left forelimb before the training period or in each forelimb between before and after the training period, whereas there were significant differences in Zpp \((P = 0.04)\) and RIpp \((P = 0.05)\) between the right and left forelimb after the training period.
Table 2—Values for ratios between the left and right forelimbs of Thoroughbreds before and after a 1-year period of race training.

<table>
<thead>
<tr>
<th>Forelimb and time</th>
<th>Variable</th>
<th>Rpl</th>
<th>Zpl</th>
<th>Rlp</th>
<th>Zlp</th>
<th>Rpp</th>
<th>Zpp</th>
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<tbody>
<tr>
<td>Before training</td>
<td>No. of horses</td>
<td>13*</td>
<td>13*</td>
<td>13*</td>
<td>13*</td>
<td>14†</td>
<td>14†</td>
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<tr>
<td></td>
<td>Mean</td>
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<td>0.23</td>
<td>0.48</td>
<td>0.23</td>
<td>0.95</td>
<td>0.39</td>
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<tr>
<td></td>
<td>SD</td>
<td>0.13</td>
<td>0.054</td>
<td>0.104</td>
<td>0.044</td>
<td>0.161</td>
<td>0.064</td>
</tr>
<tr>
<td></td>
<td>Pvalue‡</td>
<td>0.39</td>
<td>0.13</td>
<td>0.47</td>
<td>0.06</td>
<td>0.45</td>
<td>0.51</td>
</tr>
<tr>
<td>Right</td>
<td>No. of horses</td>
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<td>15*</td>
<td>15*</td>
<td>15*</td>
<td>131</td>
<td>131</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>0.47</td>
<td>0.23</td>
<td>0.48</td>
<td>0.23</td>
<td>0.95</td>
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<tr>
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<td>13*</td>
<td>13*</td>
<td>13*</td>
<td>13*</td>
<td>14†</td>
<td>14†</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>0.49</td>
<td>0.23</td>
<td>0.47</td>
<td>0.22</td>
<td>1.03</td>
<td>0.39</td>
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<tr>
<td></td>
<td>SD</td>
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<td>0.104</td>
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<td>0.064</td>
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<tr>
<td></td>
<td>Pvalue‡</td>
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<td>0.13</td>
<td>0.47</td>
<td>0.06</td>
<td>0.45</td>
<td>0.51</td>
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<tr>
<td>After training</td>
<td>No. of horses</td>
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<td>15*</td>
<td>15*</td>
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<td>0.47</td>
<td>0.06</td>
<td>0.45</td>
<td>0.51</td>
</tr>
</tbody>
</table>

See Table 2 for key.

The LCP and MCP did not change significantly over time. No significant difference was detected between the left and right forelimbs before or after the training period. There was no significant difference of the dorsal cortex of P1 between the left and right forelimbs. The palmar cortex was significantly thicker in the right forelimb than in the left forelimb after the training period. There was not a significant difference between the left and right forelimbs at the beginning of the study, but changes developed during training. Radiographic geometric variation of equine long bones has been determined.2 The geometric proprieties of total bone and cortical bone and the width of the medullary canal and trabecular bone were evaluated by measuring radiographs of the humerus, radius, third metacarpal bone, femur, tibia, and third metatarsal bone in a population of horses. The greatest variation between bones of the left and right limbs was observed in the metaphyseal region, areas with bone protuberances, and regions with prominent bone superimposition.2 In humans, a dominant right hand is often larger than the contralateral left hand, but there is an inherent tendency for the right metacarpal bone to have more bone than the left metacarpal bone regardless of hand dominance, which suggests that the tendency for a larger size of the right hand in right-handed people could be attributable to an underlying asymmetry in the process of growth rather than purely an effect of differences in use.17 Asymmetry in the length of the third metacarpal bone in Thoroughbreds has been described, with the right metacarpal bone being longer than the left in 76% of Thoroughbreds.18 Asymmetric gene expression has been described, and this asymme-

Discussion

An index reported in earlier studies4,16 was adapted for use in the study reported here. During radiographic examinations, the cassettes were kept as close to the limb as possible to minimize the penumbra and also to optimize the magnification and quality of the radiographic images. There is little variation in measurement ratios as the distance between the cassette and limb increases, but the quality of the radiograph deteriorates.16 To obtain optimum measurements of bone shape, imperfect radiographic images were excluded from the study. Results of the statistical analysis used to assess the repeatability and reproducibility of the method revealed that the radiographic technique could also be used for measurement of P1.

Contrary to our hypothesis, there was no change induced by the training in all of the cortices analyzed. Instead, analysis of the results revealed that the palmar cortex was thicker in the right forelimb than in the left forelimb after the training period. There was not a significant difference between the left and right forelimbs at the beginning of the study, but changes developed during training. Radiographic geometric variation of equine long bones has been determined.2 The geometric proprieties of total bone and cortical bone and the width of the medullary canal and trabecular bone were evaluated by measuring radiographs of the humerus, radius, third metacarpal bone, femur, tibia, and third metatarsal bone in a population of horses. The greatest variation between bones of the left and right limbs was observed in the metaphyseal region, areas with bone protuberances, and regions with prominent bone superimposition.2 In humans, a dominant right hand is often larger than the contralateral left hand, but there is an inherent tendency for the right metacarpal bone to have more bone than the left metacarpal bone regardless of hand dominance, which suggests that the tendency for a larger size of the right hand in right-handed people could be attributable to an underlying asymmetry in the process of growth rather than purely an effect of differences in use.17 Asymmetry in the length of the third metacarpal bone in Thoroughbreds has been described, with the right metacarpal bone being longer than the left in 76% of Thoroughbreds.18 Asymmetric gene expression has been described, and this asymme-
try might be the root cause of skeletal asymmetry in many classes of animals, including horses.19

It is likely that the increased load and speed of exercise played a major role in the horses of the present study. The subchondral bone in the palmar aspect of the metacarpal condyles is denser (more bone tissue per unit of volume) than that in the dorsal regions.20 There is evidence that this difference is more marked in animals that have undergone intense training.20 The pattern of force acting on the distal articular surface of the third metacarpal bone can be resolved into 2 components transmitted through P1 and the proximal sesamoid bone.21 Downward forces on the condyles, produced by the weight of a horse, are opposed by P1 and the suspensory apparatus. Hypertension of the fetlock joint during high-speed locomotion increases the proportion of load borne by the suspensory apparatus, and the resulting forces are transmitted via the proximal sesamoid bones to the palmar aspect of the condyles.20 These forces, which increase with high-speed exercise, are responsible for the denser subchondral bone in the palmar aspect than in the dorsal aspect of the condyles.20 The stress acting on P1 from the distal condyles of the third metacarpal bone is approximately 14.62 kN (10.8 MN\(\cdot\)m\(^{-2}\)).20

Anatomic congruity between the articular surfaces of the third metacarpal bone and P1 is good. At low loads, the contact area typically is located slightly palmar to the center of the joint surface. When the load increases, the contact area of the proximal articular surface of P1 initially enlarges circumferentially and then enlarges mainly in the dorsal, lateral, and medial directions. The dorsal articular margin becomes involved only at extremely high loads.22 Several studies7,18,23,24 have been conducted to investigate differences in the strain patterns between the left and right forelimbs when a horse turns, and some changes were detected between the leading and trailing limbs and, consequently, between clockwise and counterclockwise races. Authors in 1 study7 investigated whether there was an association between the increased thickness and signs of soreness of the dorsal aspect of the metacarpal region in young Thoroughbreds during training for racing, but they did not investigate whether there was a difference in thickness of the dorsal cortex between the left and right metacarpus. In another study7 of horses raced in clockwise and counterclockwise directions, investigators found that the longer bones had thicker dorsal cortices, but the mean thickness of the dorsal cortex was similar in left and right limbs. It has been found that the strain on the dorsal surface of the third metacarpal bone is higher in the nonleading (or trailing) limb (left forelimb for a right-lead gallop and right forelimb for a left-lead gallop) and increases when a horse turns.23 In contrast, the leading forelimb of a racehorse receives the most vertical GRF in both a straight line and in a turn.23,24 The peak principal compressive strain on the dorsal cortex of the third metacarpal bone appears to be associated with deceleration of the limb immediately following impact,23 whereas strains acting on the digit, and hence P1, are associated with vertical GRF which is associated with loading during the stance phase.23 It has been determined in Thoroughbreds in training that the lead limb has a higher vertical landing velocity for the hoof than does the nonlead limb, which has a higher horizontal landing velocity for the hoof.26 In the period of horizontal braking and overextension of the fetlock joint, the proximal interphalangeal joint (pastern joint) axis becomes almost horizontal at high speed. The suspensory apparatus, which consists of the suspensory ligament and the distal sesamoidean ligaments (straight and oblique), resists the overextension of the fetlock joint by acting on the palmar surface of the third metacarpal bone and the phalanges23; in particular, the oblique distal sesamoidean ligaments insert on the palmar surface of P1. Despite the fact that compressive forces acting on the fetlock joint can potentially be transmitted to the hoof through the palmar aspect of the phalanges, to our knowledge, there are no data in the literature about the strain pattern of the dorsal, palmar, lateral, and medial surfaces of P1. In the present study, horses were trained and raced principally in a clockwise direction, and this condition could explain the greater thickness of the PCP in the right forelimb, compared with the thickness of the PCP in the left forelimb. In fact, although racehorses change leads ≥8 times/mile to avoid excessive muscular fatigue as a result of asymmetric work of the limbs, they prefer to canter or gallop with the leading limb inside the curve (ie, the right-lead gallop in these horses, with the sequence of footfalls being left hind limb, right hind limb, left forelimb, and right forelimb).27

Direct contact of the palmar part of the proximal articular surface of P1 occurs under loading conditions during the propulsion phase of the stride and during asymmetric weight bearing.27 Active bone modeling and remodeling processes are responsible for reorganization of the tissue to create the enhanced anisotropy as animals mature, which is a response to changes in strain pattern associated with different amounts of exercise and as a simple turnover to replacing old parts with new.21 A number of studies1,4,20,28–30 have been conducted to examine the association between functional strain and various architectural features of equine cortical bone. However, to our knowledge, there has not been a study of cortical or cancellous bone of P1 in horses. The strain patterns, biomechanics of high-speed exercise, and type of training (particularly in a clockwise direction) have most likely induced differences in adaptive responses in terms of bone deposition on the forelimbs. In this respect, it is arguable whether the bone could be predisposed to skeletal asymmetry between the left and right limbs given that if it were exclusively a training-induced phenomenon, there should have been a significant increase in thickness of the palmar cortical bone before and after training in each forelimb.

Ultimately, many factors could affect the strain pattern and biomechanical forces, including shoeing and the regularity of shoeing, track and training surface, and conformation (ie, pastern joint–foot axis). Horses accustomed to standard iron shoes have differences in movement and loading of the distal aspect of the limbs during the stance phase as a result of shoeing.31 The material used to make horseshoes influences the biomechanics through its weight and rigidity (ie, the rigidity of the shoe alters the way the hoof capsule accom-
modulates irregularities on the ground surface). Track and training surfaces affect acceleration, hoof vibration, and peak GRF None of these factors was considered in the present study, but our sample population was homogeneous with regard to track and training surfaces as well as shoeing.

Conformation can also affect biomechanics. The angle of the pastern joint is important in determining the amount of load on the lower portion of a limb, and horses with a long sloping pastern joint are at risk of developing fractures in P1 which suggests a higher strain pattern than that for horses with a short, upright pastern joint. Generally, conformation of the pastern joint is symmetric between the right and left limbs, but an asymmetric conformation can develop in cases of clinical or subclinical lameness. Horses with chronic lameness may have disparity in foot size, usually with the smaller foot being ipsilateral to the lame limb. The smaller foot often is contracted and more upright, and this condition can alter the pastern joint–foot axis and, consequently, the strain pattern. Although the clubfoot conformation appears to be tolerated in Thoroughbreds, horses that sustained any musculoskeletal injury, even a mild injury, but that required a lengthy period of rest were eliminated from the present study.

The study reported here has limitations, such as the use of conventional radiography and the small number of horses examined radiographically at the end of the training period. Digital radiography would have allowed for instant recognition of inadequate views and thus the ability to obtain additional radiographs instead of excluding the imperfect radiographs from the study. Additionally, the use of digital radiography allows correction, within limits, for errors in exposure and a computer program for use in measurement of the various structures. However, there are some disadvantages for use of this technique because the spatial resolution of digital radiography is limited by pixel size and is lower than that of film-screen radiography. In digital radiography, there is a common image-processing artifact that consists of the halo or Überschwinger artifact. There is high contrast for this artifact, but fine detail along sharp edges is destroyed and noise is accentuated. The study reported here was also limited by the lack of a control group of 2-year-old Thoroughbreds that were not subjected to a training period. Each horse acted as its own control animal to avoid bias in the data used for statistical analysis because 2-year-old Thoroughbreds are not all of similar maturity, which could have affected the response of variables.

Analysis of the data for the study reported here revealed that there are different patterns of bone deposition in P1 in the right and left forelimbs, which likely are a consequence of heritable factors and training. In this study, we collected data that can serve as the basis for future studies of weight-bearing distribution along P1 in horses running at a trot, canter, and gallop and evaluations of the relationship between exercise and bone remodeling of P1.

References


