Morphometric study of the equine navicular bone: variations with breeds and types of horse and influence of exercise

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ABSTRACT

Navicular bones from the 4 limbs of 95 horses, classified in 9 categories, were studied. The anatomical bases were established for the morphometry of the navicular bone and its variations according to the category of horse, after corrections were made for front or rear limb, sex, weight, size and age. In ponies, navicular bone measurements were smallest for light ponies and regularly increased with body size, but in horses, navicular bone dimensions were smallest for the athletic halfbred, intermediate for draft horse, thoroughbreds and sedentary halfbreds and largest for heavy halfbreds. The athletic halfbred thus showed reduced bone dimensions when compared with other horse types. Navicular bones from 61 horses were studied histomorphometrically. Light horses and ponies possessed larger amounts of cancellous bone and less cortical bone. Draft horses and heavy ponies showed marked thickening of cortical bone with minimum intracortical porosity, and a decrease in marrow spaces associated with more trabecular bone. Two distinct zones were observed for the flexor surface cortex: an external zone composed mainly of poorly remodelled lamellar bone, disposed in a distoproximal oblique direction, and an internal zone composed mainly of secondary bone, with a lateromedial direction for haversian canals. Flexor cortex external zone tended to be smaller for heavy ponies than for the light ponies. It was the opposite for horses, with the largest amount of external zone registered for draft horses. In athletic horses, we observed an increase in the amount of cortical bone at the expense of cancellous bone which could be the result of reduced resorption and increased formation at the corticoendosteal junction. Cancellous bone was reduced for the athletic horses but the number of trabeculae and their specific surfaces were larger. Increased bone formation and reduced resorption could also account for these differences.

Key words: Bone remodelling; navicular disease.

INTRODUCTION

Knowledge the histological architecture of the navicular bone is an important basis for understanding the reason why some breeds and types of horse are more susceptible to develop navicular disease (Gabriel et al. 1994). Navicular disease represents a chronic forelimb lameness in horses. This condition is a painful degenerative disease which may include the navicular bone, the navicular bursa and adjacent surface of the deep digital flexor tendon in one, or more often both front feet. The disease is considered to be responsible for one third of chronic forelimb lameness in all horses (Colles, 1982). The disease occurs most frequently in performance horses and is seldom seen in Arabians, ponies and heavy breeds (Hickman, 1989). American Quarter horses and warmbloods appear particularly susceptible (Rose, 1996). Despite the high incidence of the disease and the numerous research studies that have focused on it, the disease still remains the cause of much controversy and confusion, not only with regard to its nomenclature, aetiology and pathogenesis, but also to its radiological features and treatment (Wright & Douglas, 1993). The 2 major theories concerning its pathogenesis are circulatory disturbances (Colles &
Hickman, 1977; Rijkenhuizen, 1989) and alterations in the biomechanics of the digit. According to the mechanical theory, the pathogenesis of the navicular syndrome is due to a disproportion between the anatomical conformation and the mechanical load. Mechanical factors, such as concussion, compression, friction and tension from ligaments associated with the size, shape and balance of the foot and the shape of the navicular bone, have an aetiological role in the syndrome (Rooney, 1969; Östblom et al. 1982, 1989; MacGregor, 1986; Pool et al. 1989; Ratzlaff & White, 1989; Wright & Douglas, 1993; Dik & Van Den Broeck, 1995). Nevertheless, little information is available on normal navicular bone measurements, although several authors have postulated changes in bone dimensions in cases of navicular disease (Wintzer & Dämmrich, 1971; Verschooten et al. 1989).

Qualitative variations at the tissue or cellular levels may easily be studied by microscopic examination, but quantitative variations generally escape this kind of research. Morphometry uses stereological methods to obtain quantitative information on cellular or tissue structure and its modification in normal or pathological states (Weibel, 1967, 1992; Cruz-Orive & Weibel, 1990). A useful estimate of mechanical strength of the bone may be gained by determining the amount and structure of cortical and cancellous bone histomorphometrically (Savage et al. 1991).

Histomorphometric analyses have only recently been reported in the investigation of navicular bone disease in the horse (Östblom et al. 1989). The importance of normal reference material as a basis for comparison when diagnosing disease in an individual is well known, but such material is currently not readily available for the horse. Information on the effects of exercise on cortical bone in horses exists but no reports on these effects on short bones or on cancellous bone have been published (Jeffcott, 1992). The aim of this investigation was thus to study the anatomical and the microscopic appearances of the navicular bone from various morphological types of horse, using quantitative methods (morphometry and histomorphometry) and to determine the variations induced by exercise.

**Anatomical considerations**

The navicular bone (Os sesamoideum phalangis distalis) is located between the deep digital flexor tendon and the distal interphalangeal joint. Its distal border is broad and convex and united to the distal phalanx by the distal impar ligament (Ligamentum sesamoideum distale). The articular surface (Facies articularis) is directed by dorsoproximally. The navicular bone and distal phalanx are joined together by a narrow articular surface (palmar facet). The flexor surface (Facies flexoria) is directed palmodistally and forms the scutum distale (Scutum distale) which provide a gliding surface for the deep digital flexor tendon. The flexor surface is divided by the sagittal ridge. The navicular bursa (Podotrochlear bursa) lies between the tendon and the navicular bone. The elastic suspensory ligament of the navicular bone comprising the medial and lateral collateral sesamoidean ligaments (Ligamenta sesamoidea-collateralia), arises dorsal to the collateral ligament of the pastern joint. It then passes in a distopalmar direction and curves axially to be inserted on the navicular bone wing tips and roughened proximal border (Barone, 1996; Nickel et al. 1986; Collin, 1993). The 2 articular surfaces of the navicular bone, for the middle and distal phalanges, are covered by hyaline cartilage while the flexor surface is covered by fibrocartilage. Each has a subchondral bone plate and the intervening medulla consists of trabeculae with a regular dorsoproximal/palmarodistal arrangement (Fig. 1).

**Materials and Methods**

**Animals**

A total of 121 horses were initially included in the study but following macroscopic and radiographic
Evaluation of their feet and navicular bones, only 95 perfectly normal individuals were kept. The macroscopic and radiographic criteria used to separate normal from diseased navicular bones have been described previously (Gabriel, 1997) and were based on the studies of MacGregor (1986), Denoix et al. (1988), Verschooten et al. (1989), Kazer-Hotz & Ueltschi (1992), Pleasant et al. (1993) and Dik & van den Broeck (1995). Age was estimated by examination of the incisor teeth according to the tables developed by Barone (1966). The withers height was measured with a metric tape for each horse and their weights were recorded.

Nine categories of horses were defined according to their breed and type (Table 1). An initial distinction was made between young (< 2 y) and adult horses (> 2 y). Horses with a withers height less than 1.45 m were indexed as ponies. To classify the young horses in the same way, their adult height was calculated from growth tables (Martin-Rosset, 1983). The compactness index (weight/height) was used to further classify the ponies and horses.

Although their compactness index was similar, the horses classified as halfbred type 1 and 2 were separated. Indeed, type 2 horses were sound performance horses from the Large Animals Surgery department of the Faculty of Veterinary Medicine, who died suddenly because of serious surgical gastrointestinal complications.

### Methods

#### Morphometric study of the navicular bone

Navicular bones were extracted from the 4 hooves of 95 horses. Navicular bone morphometry was evaluated by means of different measurements as illustrated in Figure 2. The largest width was measured for the articular surface and the flexor surface. The largest thickness was measured at the level of the distal sagittal ridge. The width of the flexor surface was also divided into medial and lateral widths. The greatest length of the bone was determined at the level of the sagittal ridge. Navicular bone volume was calculated as described by Gabriel et al. (1997b).

#### Histomorphometric study of the navicular bone

Navicular bones from 61 horses were studied (Table 1). They were extracted as soon as possible after death (maximum 10 h postmortem), fixed and dehydrated in absolute methanol, immersed in chloroform for defatting, cleared in toluol and embedded without

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**Table 1. Categories of horses**

<table>
<thead>
<tr>
<th>Horse categories (with their compactness index)</th>
<th>Number of horses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draft horse (5.06 ± 0.86)</td>
<td>13</td>
</tr>
<tr>
<td>Heavy halbred (3.99 ± 0.32)</td>
<td>5</td>
</tr>
<tr>
<td>Type I halbred (3.14 ± 0.19)</td>
<td>10</td>
</tr>
<tr>
<td>Type II halbred (3.18 ± 0.4)</td>
<td>15</td>
</tr>
<tr>
<td>Thoroughbred (2.76 ± 0.29)</td>
<td>5</td>
</tr>
<tr>
<td>Fjord (3.78 ± 0.32)</td>
<td>9</td>
</tr>
<tr>
<td>Heavy pony (3.3 ± 0.23)</td>
<td>8</td>
</tr>
<tr>
<td>Pony (2.99 ± 0.24)</td>
<td>8</td>
</tr>
<tr>
<td>Light pony (2.42 ± 0.2)</td>
<td>22</td>
</tr>
</tbody>
</table>

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previous decalcification in methyl methacrylate (Dhem, 1965). The embedded navicular bones were cut into 120 μm thick serial sections with a vertical diamond wire saw (Well, type 3241, Switzerland). The axis of the sections was vertical with an arbitrary rotation (Baddeley et al. 1986; Gundersen & Jensen, 1987; Michel & Cruz-Orive, 1988; Mathiasen et al. 1991; Gabriel et al. 1997b). Sections were ground manually to a uniform thickness of 70–80 μm. Surface staining of the sections was performed either with methylene blue or with Goldner’s trichrome (Schenk et al. 1984) and the sections were then mounted for study. The microscope (Olympus, BH-2, Germany) was provided with an objective allowing projection of microscopic fields on a test system that consisted of staggered cycloids (Fig. 3). Three to 5 sections per bone were studied to evaluate navicular bone histomorphometry. For each section the following parameters (Fig. 3) were measured by point counting to determinate volumes ($V_v$ %): Articular cortex: mineralised cartilage, cortical bone, porosity; Flexor cortex: mineralised cartilage, cortical bone, external cortical bone, internal cortical bone, porosity; Distal border; Proximal border; Mineralised part of the distal impar ligament; Mineralised part of the collateral ligaments; Cancellous bone: trabeculae and marrow spaces.

$S_v(Trabeculae, Cancellous Bone)$ (trabeculae density surface) was determined by intercept counting with the cycloids. $V(Trabeculae, Cancellous Bone)$ (trabecular bone volume); total trabecular bone surface ($S$) and volume ($V$), and the ratio $S/V$ or trabeculae specific surface (Parfitt et al. 1983) were then calculated.

**Statistical tests**

To estimate effects of breed and type of horse on navicular bone morphometry and histomorphometry, an analysis of variance was conducted with procedure GLM (SAS, 1990). Horse category estimates were adjusted to a common effect of front and rear limb, sex, weight, size and age. A logarithmic transformation was applied to navicular bone volume and trabecular surface and volume, a ‘rank’ transformation (SAS, 1990) was applied to flexor cortex internal zone, and a square root transformation was applied to the mineralised part for the distal impar ligament to
obtain data more normally distributed than the original measurements.

RESULTS

Morphometric study of the navicular bone

All navicular bone measurements varied significantly ($P < 0.0001$) with horse type. Within the horse categories, navicular bone measurements were the smallest for type 2 halfbred, except for the flexor surface largest thickness. Draft horses, thoroughbred and halfbred type 1 had similar bone measurements, whereas heavy halfbred possessed the biggest navicular bones. As for the ponies, bone measurements were the smallest for light ponies, intermediate for ponies, and significantly larger for heavy ponies and the Fjord type. Table 2 gives the main results.

Histomorphometric study of the navicular bone

All navicular bone histomorphometric data varied significantly with horse type, except for $V_v$ for proximal border and trabecular specific surface (Table 3).

Comparisons between horses and ponies

The main results are listed in Table 4.

Articular surface (Fig. 4). The $V_v$ for articular surface cortex, mineralised cartilage and cortical bone was generally smaller for light horses and ponies and larger for heavy horses and ponies. On the other hand, porosity was more important for the lighter animals.

Flexor surface. The $V_v$ for flexor surface cortex and cortical bone was generally larger for light horses and ponies and smaller for heavy horses and ponies. Mineralised cartilage volume was larger for the heavier animals and porosity was larger for the lighter ones. In ponies, the external zone of the flexor cortex tended to be more developed for light ponies whereas in horses it was larger for heavy horses (Fig. 5). The internal zone of the flexor surface tended to be more developed in light horses. Thus in horses, the internal and external zones of the flexor cortex varied in an opposite way, as light horses tended to have a larger portion of internal zone and less external zone while it was the opposite for heavy horses. The external zone mainly consisted of some remodelled circumferential lamellar bone disposed in a distoproximal oblique direction, with few secondary osteons. External zone porosity seemed to be more important than that of the internal zone. The internal zone was highly remodelled and consisted mainly of secondary osteons. The haversian canals had a lateromedial oblique orientation.

Table 2. Variation of navicular bone measurements within horse categories

<table>
<thead>
<tr>
<th></th>
<th>Draft horse</th>
<th>Type 1 halfbred</th>
<th>Type 2 halfbred</th>
<th>Fjord</th>
<th>Light pony</th>
</tr>
</thead>
<tbody>
<tr>
<td>Articular surface largest breadth (cm)</td>
<td>$+0.62 (***)$</td>
<td>$+0.64 (***)$</td>
<td>$-0.02$</td>
<td>$+0.38 (**)</td>
<td>$5.33$</td>
</tr>
<tr>
<td>Largest length of the bone (cm)</td>
<td>$+0.23 (***)$</td>
<td>$+0.2 (***)$</td>
<td>$+0.1$</td>
<td>$+0.09 (*)$</td>
<td>$1.57$</td>
</tr>
<tr>
<td>Flexor surface largest breadth (cm)</td>
<td>$+1 (***)$</td>
<td>$+0.72 (***)$</td>
<td>$+0.17$</td>
<td>$+0.57 (***)$</td>
<td>$5.02$</td>
</tr>
<tr>
<td>Flexor surface lateral breadth (cm)</td>
<td>$+0.59 (***)$</td>
<td>$+0.5 (***)$</td>
<td>$+0.17$</td>
<td>$+0.32 (***)$</td>
<td>$2.52$</td>
</tr>
<tr>
<td>Flexor surface medial breadth (cm)</td>
<td>$+0.43 (***)$</td>
<td>$+0.24 (*)$</td>
<td>$+0.005$</td>
<td>$+0.28 (***)$</td>
<td>$2.48$</td>
</tr>
<tr>
<td>Flexor surface largest thickness (cm)</td>
<td>$+0.08$</td>
<td>$+0.22 (**)</td>
<td>$+0.13$</td>
<td>$+0.12$</td>
<td>$1.96$</td>
</tr>
<tr>
<td>Ln (Navicular bone volume) (cm$^3$)</td>
<td>$+0.21 (***)$</td>
<td>$+0.27 (***)$</td>
<td>$+0.09$</td>
<td>$+0.12 (*)$</td>
<td>$1.79$</td>
</tr>
</tbody>
</table>

Statistical significance is expressed with respect to the light pony: * $P < 0.05$; ** $P < 0.010$; *** $P < 0.001$.

Table 3. Statistical significance of the variation of histomorphometric data with horse type

<table>
<thead>
<tr>
<th>Horse type</th>
<th>Volume (%)</th>
<th>Articular surface cortex</th>
<th>Mineralised cartilage</th>
<th>Cortical bone</th>
<th>Porosity</th>
<th>External zone</th>
<th>Rank of internal zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draft horse</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.014</td>
<td>0.0008</td>
<td>0.0008</td>
</tr>
<tr>
<td>Type 1 halfbred</td>
<td>0.0005</td>
<td>0.0008</td>
<td>0.0002</td>
<td>0.0001</td>
<td>0.014</td>
<td>0.0008</td>
<td>0.0008</td>
</tr>
<tr>
<td>Type 2 halfbred</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.014</td>
<td>0.0008</td>
<td>0.0008</td>
</tr>
<tr>
<td>Fjord</td>
<td>0.0004</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.014</td>
<td>0.0008</td>
<td>0.0008</td>
</tr>
<tr>
<td>Light pony</td>
<td>0.0004</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.014</td>
<td>0.0008</td>
<td>0.0008</td>
</tr>
</tbody>
</table>
### Table 4. Variation of histomorphometric data within horse category

<table>
<thead>
<tr>
<th></th>
<th>Draft horse</th>
<th>Type 1 halfbred</th>
<th>Type 2 halfbred</th>
<th>Heavy pony</th>
<th>Light pony</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Volume (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Articular surface cortex</td>
<td>+1.19</td>
<td>-0.64</td>
<td>+4.93 (*)</td>
<td>+7.86 (***)</td>
<td>13.35</td>
</tr>
<tr>
<td>Mineralised cartilage</td>
<td>+0.61</td>
<td>+0.53</td>
<td>+1.14 (**)</td>
<td>+1.18 (***)</td>
<td>1.43</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>+2.32</td>
<td>-0.25</td>
<td>+4.77 (**)</td>
<td>+7.53 (***)</td>
<td>9.88</td>
</tr>
<tr>
<td>Porosity</td>
<td>-1.69 (***)</td>
<td>-0.81</td>
<td>-0.9 (*)</td>
<td>-0.76 (*)</td>
<td>1.92</td>
</tr>
<tr>
<td>2. Flexor surface cortex</td>
<td>-3.14</td>
<td>-1.13</td>
<td>+4.15 (*)</td>
<td>-0.06</td>
<td>23.36</td>
</tr>
<tr>
<td>Mineralised cartilage</td>
<td>+2.52 (***)</td>
<td>+1.46 (**)</td>
<td>+1.75 (***</td>
<td>+1.22 (**)</td>
<td>0.37</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>-2.84</td>
<td>-0.94</td>
<td>+4.86 (*)</td>
<td>+0.82</td>
<td>19.33</td>
</tr>
<tr>
<td>Porosity</td>
<td>-2.58 (***)</td>
<td>-1.44 (**)</td>
<td>-2.11 (***</td>
<td>-1.69 (***)</td>
<td>3.1</td>
</tr>
<tr>
<td>External zone</td>
<td>-7.64 (***)</td>
<td>-8.17 (***</td>
<td>-6.19 (***</td>
<td>-1.17</td>
<td>12.87</td>
</tr>
<tr>
<td>Rank of internal zone</td>
<td>-0.52</td>
<td>+0.14</td>
<td>+1.12 (*)</td>
<td>+0.36</td>
<td>-1.28</td>
</tr>
<tr>
<td>3. Distal border cortical bone</td>
<td>+2.22 (***)</td>
<td>+0.29</td>
<td>+1.23 (*)</td>
<td>+0.44</td>
<td>1.27</td>
</tr>
<tr>
<td>4. Proximal border cortical bone</td>
<td>+1.26 (*)</td>
<td>+0.47</td>
<td>+1.02 (*)</td>
<td>+1.1 (*)</td>
<td>1.47</td>
</tr>
<tr>
<td>5. V (Mineralised part for impar lig.)</td>
<td>+0.37</td>
<td>-0.3</td>
<td>+0.06</td>
<td>-0.27</td>
<td>0.58</td>
</tr>
<tr>
<td>6. Mineralised part for collateral lig.</td>
<td>-0.05</td>
<td>+0.009</td>
<td>+0.002</td>
<td>+0.34 (***)</td>
<td>0.03</td>
</tr>
<tr>
<td>7. Cancellous bone</td>
<td>-1.39</td>
<td>+1.64</td>
<td>-11.8 (**</td>
<td>-9.7 (**)</td>
<td>59.82</td>
</tr>
<tr>
<td>Trabeculae</td>
<td>+2.79</td>
<td>+2.36</td>
<td>-1.97</td>
<td>+1.33</td>
<td>21.19</td>
</tr>
<tr>
<td>Marrow spaces</td>
<td>-4.17</td>
<td>-0.72</td>
<td>-9.82 (**)</td>
<td>-11.03 (***</td>
<td>38.62</td>
</tr>
</tbody>
</table>

Cancellous bone characteristics

- **TBV (%)**: +4.34, +1.8, +3.54, +11.92 (***), 37.04
- **S (trabeculae, cancellous bone) (mm²/mm³)**: +0.2, +0.06, +0.27, -0.08, 3.5
- **Ls (V (trabeculae)) (mm³)**: +0.47 (***), +0.38 (**), +0.09, +0.26 (*), 0.12
- **Ls (S (trabeculae)) (mm³)**: +0.4 (*), +0.33 (*), +0.05, -0.05, 2.39
- **S (trabeculae)/V (trabeculae) (mm²/mm³)**: -0.77, -0.52, -0.49, -2.58 (**), 9.85

Statistical significance is expressed with respect to the light pony: *P* < 0.05; **P** < 0.01; ***P** < 0.001.

**Cancellous bone** (Fig. 6). The $V_o$ for cancellous bone was generally larger for light horses and ponies and smaller for the heaviest animals. Heavy horses and ponies possessed more trabeculae with a larger trabecular bone volume (TBV) and total trabeculae surface and volume, whereas light horses and ponies had more marrow spaces and a larger trabeculae specific surface.

**Distal and proximal borders.** The $V_o$ for distal and proximal borders was generally smaller for light horses and ponies and larger for heavy horses and ponies.

**Mineralised parts of ligaments.** The $V_o$ for the mineralised part of the distal impar ligament was smaller for light horses and ponies and larger for the heavier animals. The mineralised part of the collateral...
ligaments varied differently in horses and ponies: it was larger for heavy ponies but smaller for draft horses.

**Differences between type 1 (sedentary) and type 2 (athletic) halfbred**

The results are listed in Table 4 and illustrated in Figures 7 and 8. In type 2 halfbred horses, the navicular bone possessed larger $V_c$ for articular surface cortex (mineralised cartilage and cortical bone), flexor surface cortex (mineralised cartilage, cortical bone, external and internal cortical bone), distal and proximal borders and the mineralised part of the distal impar ligament. On the other hand, smaller $V_c$ were observed for articular and flexor surface cortex porosities, cancellous bone (trabeculae and marrow spaces), and the mineralised part of the collateral ligaments. The type 2 halfbred horses also possessed larger TBV, $S_{(Trabeculae, Cancellous Bone)}$ and a
larger trabeculae specific surface, whereas total trabecular surface and volume were smaller than for the type 1 halfbred.

**DISCUSSION**

**Navicular bone morphometry**

Navicular bone measurements were smaller for the light ponies and increased progressively with pony size with maximal dimensions for the Fjord type. Different observations were noted in horses. Navicular bone dimensions were smallest for athletic halfbred horses, intermediate for draft horse, thoroughbred and sedentary halfbred and largest for the heavy halfbred.

After excluding technical errors and individual variation, we considered that smaller navicular bone dimensions could be related to the reduction in hoof measurements we had observed in a previous study.
Fig. 8. Cancellous bone volume and trabecular bone volume (%) for type 1 and 2 halfbreds. Statistical signification is expressed with respect to the light pony. \* \( P < 0.05 \); ** \( P < 0.01 \); *** \( P < 0.001 \).

(Gabriel et al. 1997a). Indeed, athletic halfbred hooves were smaller than in the other horse categories, and this situation did not improve when the horse aged. Athletic horses are often shod as early as at 2 y of age, and we speculate that early shoeing might slow hoof growth and result in hoof atrophy. The horseshoe restricted horn deformation, especially in the caudal region, precluding the hoof normal shock absorber role.

The differences observed between athletic and sedentary horses could also be related to the growth period, the intensity of sporting activity and the time this activity had begun. The primary role of the appendicular skeleton is to provide rigid structures to withstand and transmit loads involved in locomotion. The overall shape and anatomical relationships of a bone are genetically determined but its final form, mass and detailed architecture are influenced by mechanical activity and are therefore a unique achievement for each animal (Lanyon et al. 1982). The bone’s ability to withstand loads depends on 2 main factors: (1) its structural geometry, encompassing mass and 3-dimensional shape, and (2) the mechanical properties of the materials of which it is composed. The shape and size of a bone are in large part determined during growth (Martin, 1991).

Shape and size changes are located on bone surfaces (periosteal and endosteal) and, during growth, there is more modelling than remodelling. Adults have little capacity for changing their bone shape and size, because modelling is reduced in rate and extent, but on the other hand remodelling can be increased by changes in mechanical loading. The effects of exercise loading on the skeletal system can vary because of many factors, such as exercise intensity, skeletal maturity, type of bone (trabecular or cortical) and anatomical location (weight-bearing vs non weight-bearing regions) (Raub et al. 1989). Rapidly growing bone is more sensitive to mechanical loading than mature bone. Low intensity training may stimulate long-bone length and girth increase (Raub et al. 1989), whereas high-intensity training may inhibit bone growth (Matsuda et al. 1986; Carter, 1987). In long bones, both an absence or an excess of physical activity can delay normal growth and we believe it could be the same for the navicular bone. To explain adequately the difference in bone morphometry we had observed between type 1 and 2 halfbreds, it would have been useful to have known the horse’s history.

It can be concluded that the athletic halfbred, when compared with other horse categories, shows a reduction in navicular bone dimensions, which involves an increase in the total applied mechanical load for similar work.

**Histomorphometric study of the navicular bone**

**Comparisons between horses and ponies**

**Navicular bone architecture.** Light horses and ponies possessed larger amounts of cancellous bone but less cortical bone (articular cortical bone, distal and
proximal border cortical bone) (Fig. 9). Bone is able to adjust its architecture in relation to its functional strain environment, the objective of which is assumed to be an appropriate compromise between form, mass, strength and need for tissue economy (Carter, 1987). It has long been recognised that a relationship exists between the severity of mechanical loading to which the skeleton is exposed during daily activities and the mass and strength of bones (Lanyon, 1990). Large heavy individuals who are physically active tend to have denser and stronger bones than frail sedentary individuals (Carter et al. 1987). Skeletal morphology interacts with physical activity to generate a certain type and range of strain in the locomotor system (Rubin & Lanyon, 1982; Rubin, 1984; Rubin et al. 1990). Two main kinds of adaptation for bone morphology are possible: either heavy animals possess larger bones, or heavy animals possess stronger bones. As the strength of bone decreases in an exponential way as porosity increases (Currey, 1988), it is reasonable to expect that cancellous bone, of which the volume fraction of solids is less than 70%, is less strong than cortical bone. Light horses and ponies possess more cancellous bone and less cortical bone, which could thus be related to their smaller body weights and, for the light pony, also probably to a lesser level of physical activity. On the other hand, the opposite situation exists for draft horses and heavy ponies whose skeleton is submitted to greater loads in relation to their larger body weights. Heavy horses and ponies thus seem to possess larger and stronger navicular bones than light animals.

**Cortical bone porosity.** Other compositional factors of bone strength such as cortical bone porosity were different for light and heavy horses. Porosity may be defined as the fraction of a bone volume occupied by voids filled with soft tissues (cavities, including blood channels such as haversian canals, and erosion cavities). Bone strength decreases in an exponential fashion as porosity increases (Currey, 1988; Riggs & Evans, 1990). Young’s modulus of bone is strongly dependent on the mineral content of the bone material (Currey, 1988). The mineral content of bone tissue is, other things being equal, inversely proportional to porosity. Bone stiffness rapidly falls with small changes in porosity when the material is mostly solid (compact bone). Thus heavy horses and ponies possess more stiff cortical bone than lighter animals.

**Mineralised cartilage and mineralised parts of ligaments.** The mineralised parts of articular and flexor surface cartilage were larger for heavy horses and ponies. Müller-Gerbl et al. (1987) had established that the thickness of the calcified layer of articular cartilage corresponds closely to that of the total cartilage. The value of the calcified layer expressed as a percentage of the total cartilage volume varied in human femoral heads from 3.72 to 8.8%. In horses, Yousfi et al. (1997) observed higher values (20%) for the talus. In humans, the volume of the calcified zone is constant for all joints of a single individual and depends upon mechanical factors. As we did not study the full cartilage or fibrocartilage volume, we are not able to relate the mineralised part to total volume, but it can be speculated that the situation is no different for horses than for man. Thus the larger amounts of
mineralised cartilage could be related to increased mechanical load. On the other hand, as mineralised cartilage exhibits a larger mineral density than cortical bone, and reduced mineralisation is considered to make bones weaker and more compliant, increased amounts of mineralised cartilage and fibrocartilage could also increase bone stiffness.

The mineralised part of the distal impar ligament was larger for heavy horses and ponies, whereas the mineralised part of the collateral ligament varied differently in horses and ponies, being smallest for draft horses and light ponies. The role of collateral sesamoidean ligaments is to maintain the position of the navicular bone relative to the middle phalanx and to assist the extensor branches of the suspensory ligament in resisting flexion at the proximal interphalangeal joint. The navicular ligaments are tensed in normal horses as the hoof breaks over at the end of the stance phase, and because of positional changes of the phalanges that occur during weightbearing. These ligaments are also under excessive tension in horses with a conformation where the wall-pastern axis of the hoof is broken back or when the horse has a low or underrun heel (Leach, 1993). These types of conformation create a long-standing tension on the ligaments. The importance of the mineralised part of the ligaments could be related to the strain encountered by the ligament and thus to hoof conformation. Light ponies and draft horses possess a peculiar hoof conformation, with a high ratio between heel height and toe height (Gabriel et al. 1997a) that could reduce the strain without the collateral ligaments. This could explain the fact that the mineralised part is less developed. The distal impar ligament firmly anchors the distal navicular bone to the distal phalanx (Ratzlaff & White, 1989). The importance of its mineralised part could be related to the size of the ligament, its bone attachment zone and the strain to which it is submitted.

*Flexor surface cortex.* Flexor surface cortex tended to be more developed in light horses and ponies whereas it was the opposite for the articular surface cortex. The external zone of the flexor cortex of the navicular bone is more developed in light ponies and heavy horses. The internal zone of the flexor surface is particularly well developed for light horses. Heavy horses thus show a larger amount of external zone but less internal zone whereas it is the opposite for light horses. The internal zone is more developed laterally and medially and is relatively thin at the level of the distal sagittal ridge whereas the external zone is especially well developed at the level of the distal sagittal ridge but its thickness diminishes medially and

laterally. To our knowledge, the existence of external and internal zones of the flexor cortex has not been reported in the literature before this study. We believe that the flexor cortex develops in response to the tension induced in the bone by the stretching of the ligaments during activity. Berry et al. (1992) have also postulated that the principal stress or strain are directed in a proximodistal direction within the navicular bone. Haversian canals of the internal zone seem well adapted to resist these tensile strengths. Heavy horses and light ponies tend to have the same hoof conformation: a high ratio between heel and toe height, which is the opposite for the Fjord type and light horses (Gabriel et al. 1997a). This conformation could diminish the tension within the collateral sesamoidean ligaments and could thus partly justify the fact that the internal zone is less developed. It can be speculated that the technique of treatment for navicular disease that consists in a desmotomy of the navicular collateral ligaments (Wright, 1993) could be a very effective means of diminishing and normalising the strain within the ligaments and the bone. Another speculation consists in considering flexor cortex architecture in relation to haversian remodelling. Remodelling could be less important for light ponies and heavy horses as they possess a larger amount of poorly remodelled flexor cortex external zone but a smaller amount of internal zone, which is mainly composed of secondary bone. The reduced level of haversian remodelling could also be related to a lesser level of functional strain within the cortex in relation to physical activity: light ponies are mainly used for juvenile riding or pleasure and draft horses are currently less used for agricultural works but instead are bred for pleasure. Different purposes are proposed for remodelling: (1) a homeostatic role, with quick release of significant quantities of calcium, (2) a mechanism for repair of microdamage, (3) replacement of dead osteocytes, and (4) an adaptation of bone to mechanical loading to achieve better material properties. But haversian remodelling weakens bone structure, causing primary lamellar bone to have a larger tensile strength than osteonal bone (Martin & Ishida, 1989). Thus draft horses and light ponies possess thicker and stronger flexor surface cortical bone and this finding could partly explain their lower susceptibility to navicular disease.

*Cancellous bone.* The amount of cancellous bone and marrow spaces in the navicular bone volume was more important for light horses and ponies, as well as trabeculae specific surface. Heavy horses and ponies possess larger amounts of trabeculae in cancellous
bone and in the navicular bone, and thus also possess larger trabecular bone surface and volume. Cancellous bone is found where the bone is loaded almost wholly in compression. It provides effective, broad and homogeneous support for transfer of compression loads from one bone to another. Cancellous bone increases flexibility and damping of a bone under load (Frost, 1964). The symmetry of the structure in cancellous bone depends on the direction of the applied loads. If the stress pattern in cancellous bone is complex, then the structure of the network of trabeculae is also complex and highly asymmetric (Mosekilde et al. 1987; Jensen et al. 1990; Goldstein et al. 1991), but in bones where the loading is largely uniaxial, as in the navicular bone, the trabeculae often develop a columnar structure with cylindrical symmetry (Whitehouse et al. 1971; Gibson, 1985). Within the navicular bone, the trabeculae are oriented in a dorsoproximal/palmodistal direction. Trabeculae are thus mainly adapted to resist compression exerted by the deep digital flexor tendon and compression exerted by the middle phalanx that transmits a portion of the weight to the navicular bone during weight bearing. There was no obvious difference for cancellous bone architecture between light and heavy horses though trabeculae seemed to be more transversely connected in heavy horses and ponies. In cancellous bone, the relative numbers and sizes of trabeculae, as well as their orientation and spacing, influence the elastic modulus: thus the stiffness of cancellous bone depends both on its porosity and its trabecular orientations. The fact that porosity was more important for light horses and ponies, cancellous bone, with a tendency for fewer transverse connections between trabeculae and thinner trabeculae (larger trabecular specific surface), can once more be related to the mechanical load encountered by the bone.

Differences between type 1 (sedentary) and type 2 (athletic) halfbred

Bone architecture and cortical bone mass. Navicular bones from athletic halfbreds showed larger amounts of cortical bone (articular and flexor surfaces, distal and proximal borders), but less cancellous bone (trabeculae and marrow spaces) than sedentary halfbreds (Fig. 10).

Exercise has been shown in a number of studies to increase the average mass, cortical thickness and structural strength of bone (Schryver, 1978; Millis, 1983; Frost, 1987; Jeffcott et al. 1987, 1988; McCarthy & Jeffcott, 1988; Raub et al., 1989; Buckingham & Jeffcott, 1990). Increased mechanical strain stimulates growth and modelling and depresses bone resorption.

In our study, an increased level of physical activity in a population of sound horses increased the percentage of cortical bone but diminished medullary bone volume. Woo et al. (1981) have also observed a decrease of medullary area in swine femora after 1 y of moderately intense training. But in their study, as well as that performed by Matsuda et al. (1986) on rooster tarsometatarsal bones, bone apposition mainly occurred on longitudinally compressed concave bone
surfaces. In our study, thickening was observed at the level of the distal and proximal borders, which are mainly loaded in longitudinal compression, but also at the level of the flexor cortex which is not loaded in longitudinal compression. Pool et al. (1989) have observed an increase in flexor cortex thickness for athletic horses, which was more radiodense, and have attributed this phenomenon to increased cortical bone loading during racing and to degenerative disease of the fibrocartilage with a decreased capacity of the cartilage matrix to diffuse forces transmitted to the subchondral bone. In our study, cortical thickening induced by training was also apparent in the articular cortex and occurred in the flexor cortex without degenerative disease of the fibrocartilage. Therefore flexor cortex thickening could be considered as a response to increased tension in the ligaments that involves adaptive remodelling of the cortex in response to the functional strain.

Reduced articular and flexor cortical bone porosity was observed for the navicular bones of athletic horses. Exercise is well known to induce extensive modelling with large amount of subperiosteal bone formation and a trend towards reduced resorption (Chen et al. 1994). McCarthy & Jeffcott (1992) have studied the effects of exercise and relative inactivity on the influence of exercise on cancellous bone in the navicular. As there is not much surface covered by periosteum in the navicular bone, subperiosteal bone formation does not seem to be implicated but reduced endosteal bone resorption and endosteal bone formation are certainly more important and leads to a reduction in cancellous bone volume.

Cancellous bone. There is a paucity of information concerning cancellous bone remodelling in horses (Savage et al. 1991). Cancellous bone volume, especially narrow spaces, was reduced for the athletic horses, but the amount of trabeculae and their specific surface were larger, which could be related to a larger number of trabeculae, with more transverse connections between them. Yeh et al. (1993) have studied the influence of exercise on cancellous bone of the aged female rat and have observed reduced bone resorption after 9 wk of training without effects on bone formation, whereas after 16 wk of exercise there was bone formation. Increased bone formation and suppressed resorption could also account for the effect of exercise on cancellous bone in the navicular. As cancellous bone plays an important role in shock absorbing and transfer of compression loads (Frost, 1964), a reduction in cancellous bone volume, associated with the reduction in bone dimensions could imply an unsuitable adaptation for the bone when it is subjected to high compressive loads from the deep digital flexor tendon.

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REFERENCES


Rubin CT, Lanyon LE (1982) Limb mechanics as a function of...


