Correlation of quantitative ultrasound measurements with material properties and bone mineral density in the equine metacarpus

G Whan¹, J Runciman¹ and M Hurtig²,*

¹School of Engineering, University of Guelph, Guelph, Ontario, Canada
²Department of Clinical Studies, University of Guelph, Guelph, Ontario, Canada, N1G 2W1
*Corresponding author: mhurtig@uoguelph.ca

Submitted 20 June 2003: Accepted 3 November 2003

Abstract

This study explored the relationship between speed-of-sound (SOS) measurements and the material properties of metacarpal bones in order to validate a device that uses linear unicortical transmission of ultrasound. SOS, ultimate tensile strength and modulus of elasticity were determined at nine experimental sites. Measurements of SOS and bone mineral density were collected at three of the nine experimental sites. Twenty-five equine metacarpal (MC3) bones were used. Micro-computerized tomography was used to validate testing protocols. SOS measurements were highly site- and horse-dependent. One or more statistically significant correlations were found with ultimate tensile strength, modulus of elasticity and bone mineral density in four of the nine experimental sites. A previously described pattern of high lateral and medial cortical stiffness and SOS was found in the mid-diaphysis that correlated with bone mineral density ($r^2 = 0.25$, $P < 0.01$) and modulus of elasticity ($r^2 = 0.14$, $P < 0.05$). SOS and ultimate tensile strength correlated strongly in the distal dorsal metacarpus ($r^2 = 0.47$, $P < 0.001$). Lateral and medial distal-level sites just above the fetlock joint had a variable amount of cancellous bone, reducing the ultimate strength of these sites. The study indicates that quantitative ultrasound is sensitive to differences in the quality of equine metacarpal bone, so this technique may be useful for monitoring adaptation to exercise and bone development.

Keywords: equine metacarpus; ultrasound; biomechanical testing; bone mineral density

Introduction

Stress fractures in horse bones are a serious threat to soundness and functionality because they undermine the load-carrying capacity of bones and lead to catastrophic accidents¹. The ability of the equine metacarpal bone to adapt to exercise is becoming better understood²–⁸, but dorsal metacarpal disease (bucked shins), diaphyseal stress fractures and condylar fractures remain common clinical problems. Any tool that could be used in the field to identify horses with late-developing, injured or remodelling metacarpal bones would be welcomed by racing jurisdictions, owners and trainers⁹–¹².

The equine metacarpus is particularly susceptible to high-strain cyclical fatigue for several reasons, as outlined by Nunamaker¹³,¹⁴. The biomechanics of the metacarpus are complicated by the following:

- changing strain patterns with respect to speed of travel, age and exercise-related remodelling that redistributes bone mass around the medullary cavity;
- persistent non-adaptive remodelling that creates foci of porosity and stress risers; and
- considerable site-to-site variation in material properties.

While training regimes can influence the rate and type of bone remodelling¹⁵, individual variation makes it difficult to know the stage of remodelling and hence any horse’s readiness for high-speed competition.

The development and adaptation of bone and other connective tissues are difficult to assess without invasive procedures. This is particularly true in clinical practice, where assessment techniques are limited to radiography, scintigraphy and ultrasonography. Radiography is
inexpensive and fast, but detectable changes in horses often lag behind clinical signs and the sensitivity to bone mineral loss is poor\cite{10}, so horses with stress fractures are at risk from life-threatening fractures if training continues\cite{10}. Also, radiography uses ionizing radiation that comprises a health risk for humans.

Scintigraphy produces a more functional assessment of bone blood flow but requires expensive imaging equipment and radiation safety measures\cite{17,18}. The utility of scintigraphy for the diagnosis of radiographically silent lesions such as stress fractures and incipient infections cannot be denied, but the time and expense required make it awkward for use in screening large numbers of horses.

Neither of these imaging techniques provides detailed information about bone quality and the ability of bone to withstand exercise. In fact, pre-race inspection and direct manual palpation of the metacarpus in actively racing Thoroughbreds may still be one of the most clinically relevant tools in competitive horses\cite{10,12}.

Several other techniques are available for the assessment of bone in living horses; however, limitations include:

- the complexity and fragility of the equipment;
- the need for a controlled working environment;
- the requirement for general anaesthesia;
- long study times;
- the small areas analysed;
- a lack of three-dimensional data; and
- the use of ionizing radiation.

These techniques include single (SXA) and dual-energy X-ray absorptiometry (DEXA)\cite{19}, computerized tomography (CT)\cite{20} and magnetic resonance imaging (MRI). Biochemical assessment of bone markers in serum, urine or joint fluid may be able to detect bone remodelling and resorption in the horse\cite{21,22}, but these laboratory tests require time, standardization with an accepted panel of normal values and are not widely available.

The ideal method for assessment of bone quality in the horse would be portable, fast and inexpensive. It should produce no hazardous radiation and be applied in the sometimes harsh conditions of equine stables. During measurement, horses should require little or no restraint. In order for a single measurement to be meaningful, normative databases for comparison must be available and variables such as breed, age and sex must be included. Serial measurements on the same horse could be used to monitor adaptive response to training, as well as developmental progress or injury.

Speed-of-sound (SOS) measurement is an accepted method for the detection of osteoporosis in human clinical medicine and is predictive of pathological fractures in osteoporosis\cite{23,24}. Bone architecture, cortical thickness and mineral content all contribute to sound wave propagation\cite{25}, although the exact algorithm that describes the contribution of each is not known\cite{20}. Bone architecture is possibly the most variable and complex factor because it is influenced by anisotropy, porosity, trabecular shape, thickness and connectivity.

Comparative aspects of bone pathology must be considered when applying such technologies to another species. The bone fragility associated with human osteoporosis is a systemic disease that causes thinning, reduced bone mineral content and perforation, and loss of continuity of trabeculae. This is wholly different from the focal lesions arising from intracortical remodelling that are found in the cortical bone of the equine metacarpus\cite{9}.

The first attempts to use SOS in the horse required orientation of transmitters and receivers on opposite sides of the cortex\cite{19,27,28}. Use of this transcortical transducer configuration in the equine metacarpus was complicated by variation due to ambient temperature, summation of disparate bone properties across the large region of interest, multiple paths for the sound waves, and no accurate way of measuring the geometry of the medullary cavity. A positive relationship between SOS and bone density was established by Jeffcott and McCarthy\cite{28}, but single-photon absorptionmetry was needed with SOS measurements to predict bone material properties\cite{29}. The same authors demonstrated the potential for monitoring bone adaptation during training.

A more recent quantitative ultrasound (QUS) configuration (Sunlight Equs with Omnipath™ axial transmission; Sunlight Medical, Rehovot, Israel) has been developed for multi-site SOS measurements in people and horses\cite{21,30}. This portable sonometer consists of two pairs of transmitting and receiving transducers embedded in a single probe. Acoustic gel or silicone oil can be used as a coupling medium and the probe placed on the longitudinal axis of the bone. The transducers are aimed toward the bone surface using a critical angle that maximizes propagation axially along the one cortex under the probe while minimizing the influence of overlying soft tissues. Bone within the first 5 mm contributes to the SOS measurement\cite{31}. In cadaveric human tibias, SOS strongly correlated with bone density \((r^2 = 0.89)\) and ultimate breaking strength \((r^2 = 0.75)\)\cite{32}. In human subjects, multi-site SOS measurements with this sonometer were correlated with bone mineral density (BMD) in the radius, calcaneus and tibia\cite{25,33}.

At least three groups of investigators have published equine in vivo data generated with this instrument. In one study, intra-operator variation was 0.52–3.15% and inter-operator variation was 0.78–2.70%, for
measurements in the equine metacarpus. Cadaveric metacarpi produced similar SOS measurements with the soft tissues intact and after skin and tendons were removed. SOS was highly site-dependent and a typical pattern of sound velocity was established for the equine metacarpus where the lateral and medial cortices have higher SOS than the dorsal cortex. In a study that compared BMD and SOS in cadaveric metacarpi, moderate correlations were found in five of 18 metacarpal sites. These authors concluded that SOS and BMD may be used to evaluate equine bone, but these two modalities measure fundamentally different properties.

Use of QUS as a clinical tool is growing but well-controlled studies are few. Davies monitored two- to six-year-old Thoroughbred racehorses during training and racing by using SOS measurements and radiographs at the mid-length of the dorsal cortex. As the dorsal cortex remodelled and became thicker due to the production of less-organized bone, SOS declined. Horses with lower SOS and thicker dorsal cortices were judged to be at greater risk from injuries. While these preliminary data are promising, there has been no objective validation of equine quantitative ultrasound that links SOS with material properties of bone and the risk of injury.

The aim of the current study was limited to comparing the material properties and mineral density of bone with SOS measurements made in the equine metacarpus. The hypothesis was that SOS measurements would correlate with the biomechanical strength, elasticity or mineral density of the metacarpus.

**Methods**

**Collection and preparation of samples**

One single and 12 pairs of equine third metacarpal (MC3) bones were harvested from 13 horses presented for post-mortem examination at the University of Guelph. Metacarpi were harvested from horses humanely sacrificed for reasons unrelated to musculoskeletal diseases of the forelimbs (Table 1). Horses in active racing careers, broodmares, pleasure riding horses and horses in training were included, but the exact activity level was unknown. The breed, ages and backgrounds of the horses can be found in Table 1. The metacarpi were dissected away from the rest of the limb within 24 h of euthanasia and stored at −20°C double-wrapped in physiological saline-soaked gauze and polyethylene plastic wrap.

Nine experimental sites were identified for this study (Fig. 1). The diaphysis of the whole bone was divided into thirds using the carpometacarpal articulation proximally and the proximal aspect of the sagittal ridge distally. The proximal, middle and distal thirds were designated levels A, B and C, respectively. Each level was then divided into three positions, medial (M), dorsal (D) and lateral (L), and these were combined so nine individual site labels were possible (Fig. 1). Prior to testing, metacarpals were thawed in warm water for a minimum of 4 h. Skin and soft tissues were removed, leaving only the periosteum and second and fourth metacarpal bones intact.

![Fig. 1 Nine experimental site locations on the equine metacarpus](image)

**Table 1** Signalment of horses used for obtaining metacarpal bones

<table>
<thead>
<tr>
<th>Horse</th>
<th>Age (years)</th>
<th>Breed</th>
<th>Sex</th>
<th>Diagnosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>Standardbred</td>
<td>M</td>
<td>Hock OCD&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Thoroughbred</td>
<td>F</td>
<td>Head trauma</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>Standardbred</td>
<td>M</td>
<td>Pelvic fracture</td>
</tr>
<tr>
<td>4</td>
<td>22</td>
<td>Quarter Horse</td>
<td>M</td>
<td>Colitis</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>Standardbred</td>
<td>M</td>
<td>Wobbler syndrome</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>Standardbred</td>
<td>M</td>
<td>Normal</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>Quarter Horse</td>
<td>M</td>
<td>Lymphangitis</td>
</tr>
<tr>
<td>8</td>
<td>11</td>
<td>Standardbred</td>
<td>F</td>
<td>Colitis</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>Standardbred</td>
<td>F</td>
<td>Colitis</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>Thoroughbred</td>
<td>M</td>
<td>Hepatitis</td>
</tr>
<tr>
<td>11</td>
<td>6</td>
<td>Standardbred</td>
<td>F</td>
<td>Lymphangitis</td>
</tr>
<tr>
<td>12</td>
<td>9</td>
<td>Standardbred</td>
<td>M</td>
<td>Colitis</td>
</tr>
<tr>
<td>13</td>
<td>4</td>
<td>Hanoverian</td>
<td>M</td>
<td>Colitis</td>
</tr>
</tbody>
</table>

M – male; MC – gelding; F – female.
<sup>a</sup>Osteochondritis dissecans.
**Speed-of-sound measurements**

The Sunlight Omnisense™ QUS CM probe (1.5 cm × 4.2 cm) was used after calibration on a polymeric plastic phantom supplied with the system. Daily calibrations are stored in an electronic file so that the user is alerted if the probe has been damaged. The probe was placed on the metacarpal periosteal surface with the long axis along the length of the metacarpus, with the cabled end distally. Ultrasound transmission gel (Aquasonic 100; Parker Laboratories, Inc., Fairfield, NJ) was used as a coupling medium. The probe consisted of two signal generators operating around a central frequency of 1.25 MHz at one end of the probe, and two signal detectors at the opposite end. The first signal to reach the transducer was from cortical bone because ultrasound propagation speeds through cortical bone (4000 m s\(^{-1}\)) are known to be much faster than those through soft tissue (1540 m s\(^{-1}\)).

The operating system collected 1000 individual measurements over a 2 min period and reported the 95th percentile as the final SOS value. Integrated software stopped the SOS measurement if the probe angle was more than 5° off perpendicular, or if probe contact was broken. Embedded measurement software required three measurements for each site, and reported the mean if the variance was less than 5%. Higher variances resulted in rejection of the previous data and prompted the operator to make another series of measurements.

**Biomechanical testing**

Each of the nine experimental sites (Fig. 1) was cut from the metacarpal bone using a low-speed band saw so that the contact area of the QUS probe defined the periosteal surface area of these sites. Three-dimensional parallelepipeds, 5 mm thick, were shaped using an air-driven router with a 0.25 in up-spiral bit (Fig. 2). These samples consisted of three regions: web, transition and flared end. The web consisted of a cross-sectional testing area of 25 mm\(^2\) and was 20 mm long. Flared ends were necessary for holding the samples in grips during biomechanical testing in tension. Each sample was tested to failure in a universal testing machine (Instron model 4204; Instron Corp., Canton, MA) equipped with a 50 kN load cell at a rate of 6 mm min\(^{-1}\). A set of modular strain-measurement clips was used to measure the strain in the bone sample. Output signals from the load cell and strain clips were recorded at 120 Hz, using data-acquisition software and a 16-bit analogue-to-digital converter (National Instruments, Austin, TX). The modulus of elasticity (\(E\)) and ultimate tensile strength (UTS) of each sample were calculated by plotting the resultant stress-strain curves. \(E\) was determined from the mid-section of the linear region of the curve and UTS was determined as material stress at failure.

**Bone mineral density measurement**

BMD measurements were conducted on mid-level (Fig. 1, B) samples only. The larger of the two fragments remaining after biomechanical testing was used for BMD measurement. A DEXA densitometer (PIXImus™; Lunar Corp., Madison, WI) was used with a resolution of 0.18 mm × 0.18 mm pixels. This device was calibrated daily using a phantom and quality control procedures. Each sample was aligned in the centre of a bone tray, dorsal side up, proximal to the right orientation. Images were captured and a 0.36 cm\(^2\) region of interest within the web area of each sample was used to determine BMD.

**Micro-computerized tomography**

To estimate the composition of cortical and trabecular bone in the distal lateral (CL) and distal medial (CM) experimental sites, six samples were submitted to micro-computerized tomography (microCT) (GE Medical Systems, EVS Preclinical Imaging, London, Ontario) at an isotropic pixel resolution of 20 µm. All samples...
were imaged in saline using a stationary gantry and a rotating specimen platform.

**Statistical design**
SAS software (release 6.11; SAS Institute, Cary, NC) was used throughout. A randomized complete block, split plot design with four factors (animal, left or right side, level, position) was used, blocking on animal. Analysis of variance using a general linear model was used to compare SOS, UTS, $E$ and BMD values, and any interactions. If the overall $F$-statistic was significant, then pair comparisons based on a $t$-statistic were used. A modified Tukey’s correction was applied. Pearson product correlations were made between SOS, $E$, UTS and BMD. A 95% confidence level was used to test for significance in the data.

**Results**

**Collection and preparation of samples**
A total of 225 small bone samples were prepared for biomechanical testing and 72 of the samples were subjected to BMD (DEXA) testing. Biomechanical testing data were obtained for 212 of the samples. The remaining 13 samples were lost due to preparation and testing logistics. Samples from seven of the nine experimental sites were composed of cortical bone only, whereas the distal medial (DM) and distal lateral (DL) experimental sites included both cortical and cancellous bone.

**Speed-of-sound measurements**
Lateral and medial proximal sites were more difficult to measure because the flat contact surface of the transducer did not conform to the curved surface of the metacarpal bone in this region. As the transducer was moved closer to the small second and fourth metacarpal bones, this misfit was more obvious. This curved geometry also made sample preparation difficult, and of 13 samples removed from analysis, nine were from the proximal level.

At all three levels (proximal, middle and distal) SOS was highest in the lateral cortex, intermediate in the medial cortex and lowest in the dorsal cortex (Fig. 3). Left and right limbs did not have different SOS values so these data were pooled. SOS was significantly different between horses ($P < 0.001$) and experimental sites ($P < 0.01$).

**Biomechanical testing, bone mineral density and microCT analysis**
Of the 225 samples, 110 samples failed within the known cross-sectional area of the web zone. A second group of 96 samples failed within the transition zone, where accurate cross-sectional areas could be determined. Six samples failed outside these two zones and UTS could not be calculated.

Figure 3 summarizes SOS and biomechanical data according to experimental site and demonstrates global patterns. Differences between animals with respect to UTS were significant ($P < 0.05$), as were differences between experimental sites ($P < 0.001$). $E$ was not significantly different between different horses or experimental sites, although there was an interaction between horses and sites ($P < 0.01$). BMD at the middle level was highest laterally (0.72 ± 0.4 g cm$^{-2}$) and dorsally (0.72 ± 0.03 g cm$^{-2}$), and lowest at the medial site (0.71 ± 0.05 g cm$^{-2}$), although these three values were not significantly different ($P < 0.53$) from each other. The following patterns were evident from the above UTS data:

- values for the lateral and medial cortex were equal to or higher than those for the dorsal cortex,
except for the distal level sites where this pattern was reversed. The modulus of elasticity showed a repeatable pattern at all levels;

- the medial cortex was lowest, followed by the dorsal site; and

- the lateral cortex had the highest values.

Pearson product correlations (Table 2) demonstrated statistically significant correlations of SOS and \( E \) at the proximal medial (AM) \( (r^2 = 0.19, P < 0.05) \) and distal lateral (CL) \( (r^2 = 0.16, P < 0.05) \) sites. There was also a statistical trend for correlation between SOS and \( E \) at the mid-dorsal site (BD) \( (r^2 = 0.14, P < 0.07) \). SOS correlated with UTS at the proximal medial (AM) site \( (r^2 = 0.18, P < 0.04) \) and the distal dorsal (CD) site \( (r^2 = 0.48, P < 0.001) \). SOS correlated with BMD at one of the three sites tested, the mid-dorsal (BD) site \( (r^2 = 0.40, P < 0.01) \). Sample size calculations were done and significant correlations between SOS and \( E \) at the mid-dorsal site would have been found if three more horses were included in the analysis.

Volumetric analysis of microCT images (Microview CT analysis software; Sourceforge software, http://sourceforge.net) (Fig. 4) showed that the cancellous portion of the distal medial and lateral samples occupied up to 45% of the sample and that the BMD of this trabecular bone was 55–65% that of the adjacent cortical bone. Porosity of the adjacent cortical bone was also highly variable.

**Discussion**

Considerable care was taken to standardize the measurement protocols used in this study. The coefficient of variation for SOS measurements made with the QUS device is 1–3% and measurement error is not a significant source of variance in these studies. Animals, and sites within the metacarpus, are inherently more variable. Nevertheless, positioning of the ultrasound probe and alignment with the longitudinal axis of the metacarpus is critical because of the anisotropic nature of the Haversian systems in cortical bone. SOS in bovine cortical bone resulted in longitudinal velocities \( (>4000\,\text{m/s}) \) consistently higher than transverse or radial velocities \( (3-400\,\text{m/s}) \). To avoid such artefacts, we used carefully controlled laboratory conditions to identify experimental sites using anatomical landmarks and plastic templates that confined SOS, biomechanical, mineral density and microCT measurements to a small piece of bone. Making the sample thickness equal to the 5 mm penetration ability of QUS, and the sample dimensions the same as the footprint of the QUS probe, ensured that bone characteristics in the experimental sites would be detected by QUS and our methods for measuring material properties.

The 5 mm penetration limit for QUS in cortical bone is a theoretical limitation, but most stress fractures and foci of non-adaptive bone remodelling involve the periosteal surface or bone adjacent to it. Davies demonstrated that such remodelling makes the dorsal cortex thicker and SOS lower; so in the authors’ opinion, when remodelling due to stress fractures is present in the equine metacarpus, SOS should be a sensitive diagnostic tool. A more significant limitation is the area examined by the clinician. Microfractures can be extremely small and a multi-site QUS examination that covers the entire dorsal, dorsomedial and dorsolateral metacarpus may be time-consuming. Timing of the examination is also relevant. A small fracture may not significantly delay propagation of ultrasound, but QUS may be more useful in the subacute phase when new periosteal bone or porosity due to remodelling is present. Repeated measurements at monthly intervals are probably the most logical application of QUS as a tool to monitor adaptation to training.

In this study, metacarpi were collected from a heterogeneous group of horses presented for post-mortem examination. Unfortunately, the activity level of each horse could not be documented. Nevertheless, this wide spectrum of bone quality was a good test of whether SOS correlated to material properties of bone that determine its function. In this type of study, a broad range of sample material was useful to test how architecture, mineral content and material properties contributed to SOS. A reference database is embedded in the Equus Omnisense software that compares an individual horse’s mid-level metacarpal SOS with sex-, age- and breed-matched populations. In humans, this

<table>
<thead>
<tr>
<th>Correlation: SOS vs.</th>
<th>Medial (M)</th>
<th>Dorsal (D)</th>
<th>Lateral (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UTS</td>
<td>E</td>
<td>BMD</td>
</tr>
<tr>
<td>Proximal (A)</td>
<td>0.18*</td>
<td>0.19*</td>
<td>no data</td>
</tr>
<tr>
<td>Middle (B)</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Distal (C)</td>
<td>NS</td>
<td>NS</td>
<td>no data</td>
</tr>
</tbody>
</table>

SOS – speed-of-sound; UTS – ultimate tensile strength; \( E \) – modulus of elasticity; BMD – bone mineral density; NS – not statistically significant. *\( P < 0.07 \); **\( P < 0.05 \); ***\( P < 0.01 \); ****\( P < 0.001 \).
approach has been successful for predicting fractures from multi-site QUS data. While Davies has established a link between developing lesions and SOS, further epidemiological studies in horses are needed to confirm this relationship.

Other limitations of the study include the induction of microtrauma during cutting and shaping of the samples and subjecting the bones to two freeze–thaw cycles before biomechanical testing. Boutros et al. showed that controlling the hydration state of the bone during handling is more important than the number of freeze–thaw cycles. For this reason, care was taken to use saline-soaked gauze wrappings around the bones, and to double-wrap all samples in polyethylene plastic. Induction of microfractures, and heating during the cutting and shaping of specimens, could also reduce UTS and E no matter what method was used.

Different modes of biomechanical testing were considered, and testing in tension was chosen to simplify sample loading and because failure at ultimate tensile stress would be detected easily using existing laboratory equipment. Testing in tension was deemed valid because the equine dorsal metacarpus is often in tension at low speeds and receives compressive loading for a shorter portion of its loading history at high speeds. The highly comminuted spiral oblique fracture configurations that occur in racehorses suggest that these bones are subject to a combination of tensile and torsional loading. Some care needs to be exercised in interpreting tensile testing results if the specimens fracture outside the web area. Inclusion of samples that failed in the transitional zone reduced the strength of statistical correlations, indicating that a better testing regime is needed. Testing in compression could be used but there is some inherent error due to changes in the specimen sidewall dimensions by a phenomenon known as 'barrelling'.

Many of the samples that were difficult to test in the tensile loading regime were from the distal medial (CM) and lateral (CL) sites. Unlike the other experimental sites that were composed of only cortical bone, these specimens were composed of variable amounts of cortical and cancellous bone, as demonstrated by the microCT images (Fig. 4). This architecture makes such specimens more unpredictable when small samples are tested in tension. The increased porosity and decreased mineral content of these samples explains why UTS is reduced in these sites compared with the dorsal cortex (CD) (Fig. 3). SOS and E at the distal level followed patterns similar to the more proximal levels, with increasing values from medial to lateral. Statistical correlations with E in the lateral site and UTS in the dorsal site were still found, demonstrating that QUS is able to assess the contribution of both cortical and cancellous bone to sites in the distal metacarpus.

The patterns of SOS and UTS reported here are consistent with other biomechanical studies that found the lateral and medial cortex of the metacarpal diaphysis is stiffer than in dorsal sites. This pattern of stiff lateral and medial cortical bone enhances or controls sagittal bending in the metacarpus. In the present study, mid-level sites are strictly diaphyseal, and QUS operators should expect SOS values to be lower in the dorsal cortex than in the medial or lateral cortex. Horses with SOS measurements that do not conform to this pattern should be evaluated for lameness in both forelimbs.

The correlation coefficients reported here are low, indicating that SOS changes slowly with change in a second parameter. Stronger correlations in the clinically important mid-dorsal and distal dorsal sites indicate that SOS will be sensitive to small changes in bone mineral content and ultimate strength, and we recommend that these sites be included in clinical evaluation regimes. Low correlation coefficients may also mean that the interplay between mineral content and material properties does not fully account for metacarpal bone quality. Measurement of Haversian bone morphometry may clarify these relationships further.

Questions still remain as to how QUS will be used in the field. In a study of human cross-country runners, left versus right asymmetry in tibial SOS measurements was associated with injuries such as stress fractures. In the authors’ opinion, horses with marked differences in left versus right metacarpal SOS measurements should be followed up with scintigraphy and radiography. Serial assessments of equine athletes over the
competitive season may be useful in monitoring and adapting training regimes and in preventing SOS asymmetries from developing. Unlike human multi-site QUS, where measurement at several sites improves predictive power for osteoporosis-related pathological fractures, equine metacarpal QUS should be used to detect sites that do not conform to established patterns and normative data embedded in the software. The focal nature of remodelling events and injuries in the equine metacarpus can make these sites a stress riser from which catastrophic fractures may arise. Accordingly, QUS may be used to locate and monitor focal sites that represent a weak link in the complex biomechanical chain that is the equine forelimb.

Conclusions

Statistical trends and correlations for SOS and E, UTS or BMD were demonstrated at four of nine equine metacarpal sites. The strongest correlation between SOS and UTS was in the distal third of the dorsal metacarpus, and this site should be included in clinical evaluations of bone quality. Results from this study indicate that the hypothesis tested was correct, and changes in bone material properties were reflected in QUS measurements at several sites. Based on these and others’ findings, horses with marked left-to-right SOS measurement asymmetry, or mid-diaphyseal SOS values that do not conform to established patterns, should be followed up with a lameness examination and possibly radiography or scintigraphy. Multi-site QUS may be suitable as a tool for assessment of horses at risk for metacarpal stress fractures and monitoring of bone adaptation to training.

Acknowledgements

The authors would like to thank Dr Mark Grynpas for assistance with bone densitometry, GE Preclinical Imaging for microCT images, as well as Deb McWade and Nicole Kudo for preparation of metacarpii; Gabrielle Monteith assisted with the statistical models. Sunlight Medical and the Equine Research Program of the Ontario Ministry of Food and Agriculture provided funding for this project.

References

Ultrasound measurements in the equine metacarpus


