How does exercise intensity and type affect equine distal tarsal subchondral bone thickness?


Animal Health Trust, Lanwades Park, Kentford, Newmarket, Suffolk CB8 7UU (Murray, Branch, Dyson, Parkin) and The Royal Veterinary College and Institute of Orthopaedics and Musculoskeletal Science, UCL, Hawkshead Lane, North Mymms, Hatfield, Herts AL9 7TA (Goodship).

Corresponding author, phone 08700 502430, email rachel.murray@aht.org.uk

Running head: Effect of exercise on the distal tarsus.
Abstract

Adaptation of osteochondral tissues is based on the strains experienced during exercise at each location within the joint. Different exercise intensities and types may induce particular site-specific strains, influencing osteochondral adaptation and potentially predisposing to injury. Hypotheses: Patterns of equine distal tarsal subchondral bone (SCB) thickness relate to the type and intensity of exercise; and high intensity exercise leads to site-specific increases in thickness.  

Methods: SCB thickness was measured at defined dorsal and plantar locations on magnetic resonance images of cadaver tarsi collected from horses with a history of low (general purpose [n=20] and horse walker [n=6]) or high (elite competition [n=12], race training [n=15] and treadmill training [n=4]) exercise intensity. SCB thickness was compared between sites within each exercise group, and between exercise groups. Results: SCB thickness in elite competition and race training, but not treadmill training, was greater than low intensity exercise. For general purpose horses, lateral SCB thickness was greater than medial throughout. Horse walker exercise led to relatively thicker lateral and medial SCB compared with the midline. Elite competition was associated with increased SCB thickness of the proximal small tarsal bones medially and the distal bones laterally. For race training and treadmill training, there were minimal differences between sites overall, although the lateral aspect was greater than medial, and medial greater than midline at a few sites for race training.  

Conclusions: Different types of high intensity exercise were associated with different patterns of SCB thickness across the joints from medial to lateral and proximal to distal indicating that both exercise intensity and type of exercise affect the SCB response at any particular site within the equine distal tarsal joints.
Keywords: Subchondral bone, exercise, MRI, equine.
Introduction

Osteochondral structure is related to the loading history of the joint and position within the joint (11, 22, 23, 36, 37). Adaptation of the osteochondral tissues is based on the strains experienced during exercise at each location within the joint. Therefore a joint is likely to vary in structure dependent on the type and intensity of exercise that is undertaken by the individual. However, repetitive overloading is associated with osteochondral failure (23), so it is important to understand the balance between joint adaptation, which may prevent pathology, and the development of pathology during training.

It has been demonstrated that mechanical loading is not only a primary stimulus for adaptation, but is also implicated in joint degeneration (23, 27, 30, 33, 34). Therefore the type and intensity of exercise and associated tissue adaptation are important factors in understanding the presumed association of exercise with joint degeneration. Like humans, horses develop naturally occurring osteoarthritis, and exercise associated joint degeneration, and can provide an insight into the mechanisms of response to loading and joint degeneration (13, 23, 28, 29).

Differences have been seen in bone mass and bone turnover between human power athletes (sprinters, jumpers, hurdlers, multi-event athletes), endurance athletes (middle distance runners, distance runners) and non-athlete controls, suggesting that different strain types and magnitude cause bone to remodel at different rates (1). Equine athletes also train for different sport types and intensities, but there has been little investigation of the effect of training for different sports and levels on joints predisposed to osteochondral damage. Racehorses are trained at fast speeds to race at a gallop, with compression strains at the dorsal aspect of the third metacarpal bone reported to be in excess of -4000 microstrains (8). Dressage horses spend most time
working on lower impact surfaces, and undertake gymnastic-type exercises including specific turns, circles, and sideways movements at a variety of speeds. Event horses undertake both dressage-type exercise and jumping at lower speeds than racehorses. Horses walking, trotting and cantering experience lower compressive strains than at gallop. It was reported that peak compressive strains in the third metacarpal bone varied from approximately -400 at walk to -1600 at trot, and -2800 microstrains at canter (8). For walking in circles, peak strains in the metacarpus varied between medial, dorsal and lateral aspects (7). Bone strain is therefore considered to be lower than in the galloping racehorse, but direction of strain is more variable.

Treadmill and mechanical horse-walker exercise are used for both physiological investigation and for training of equine athletes. However, there has been little comparison of subchondral bone (SCB) structure between treadmill and over ground training, or the effect of exercising in a circle on a mechanical horse-walker. In the equine carpus, high intensity galloping treadmill exercise was associated with increased SCB thickness and evidence of cartilage degeneration at sites subjected to high loads (23), compared with horses undergoing horse-walker exercise. However, in equine metacarpophalangeal joints, treadmill exercise was associated with increased SCB volume, whereas horses trained over ground demonstrated evidence of SCB microfracture and failure (30). Further investigation of the effects of treadmill and horse-walker exercise on equine joints could be helpful for design of future studies or training programmes.

The distal aspect of the equine tarsus is a frequent clinical site of osteochondral degeneration. The distal aspect of the tarsus is loaded primarily in compression, with maximal strain dorsally and laterally (35). The maximum compression strain recorded was -600 x 10^{-6} m/m (35). In a previous study, radiopharmaceutical uptake patterns in
the equine tarsus supported increased osteoblastic activity dorsally and laterally compared with other sites (26). Subchondral bone thickness was greatest dorsally and laterally in tarsi from horses without pain with a history of low intensity, general purpose (GP) exercise (3), also supporting this loading pattern. However, tarsal SCB structure has not previously been investigated in horses undergoing different exercise types or intensities.

It is not known whether different patterns of loading during different gaits, or magnitude of the same load pattern have a greater effect on subchondral bone structure. To understand how exercise history may influence tarsal SCB structure, and to determine whether this may predispose to osteochondral pathology, it is important to have an appreciation of the structure of SCB in horses undergoing different types of sport.

This investigation tested the hypotheses that high intensity exercise is associated with greater SCB thickness at dorsal sites in the equine distal tarsus than low intensity exercise, and patterns of SCB thickness in the equine tarsus relate to the type and intensity of exercise.

The objectives were to 1: measure dorsal and plantar SCB thickness using magnetic resonance (MR) images, on the proximal and distal aspects of the central (CT) and third (T3) tarsal bones and the proximal aspect of the third metatarsal (MT3) bone at defined standard sites in tarsi from horses with a history of different exercise types and no hind limb lameness and 2: compare patterns of SCB thickness between exercise groups.
Materials and Methods

Sample collection

Twenty cadaver tarsi were collected from 11 mature horses (mean age 8.75 years, range 5 to 15 years), with a history of low-intensity GP exercise, defined as hacking and unaffiliated competition. The breed distribution was 4 Thoroughbred, 9 Thoroughbred-cross and 7 Warmblood. Twelve cadaver tarsi were collected from 8 mature horses (mean age 11.25 years, range 9 to 13 years) with a history of elite competition, defined as dressage at advanced medium or above (n=4) or eventing at advanced level or above (n=8). Breeds of horses were 8 Thoroughbred and 4 Warmblood. All horses were in work at the time of euthanasia except 2, which had been rested for 2 and 6 weeks respectively. Fifteen cadaver tarsi were collected from 13 Thoroughbred horses (mean age 6.53 years, range 3 to 12 years), with a history of high intensity race training, collected as part of an investigation into fatal distal limb fractures in racing Thoroughbreds in the United Kingdom (32). All racehorses had been trained for a minimum of 33 days (mean 122 days) with a mean of 14 (range 10-24) furlongs per week fast work. Six cadaver tarsi were collected from 6 previously untrained 2-year-old Thoroughbred mares, which had undergone low intensity exercise on a mechanical horse walker, restricted to 40 minutes walking in both directions daily for 19 weeks. Four cadaver tarsi were collected from 4 previously untrained 2 year old Thoroughbred horses, which underwent high intensity treadmill exercise designed to simulate race training, for 19 weeks on a high-speed treadmill at a 3% incline (27). There were therefore 2 low intensity exercise groups (GP and horse walker) and 3 high intensity exercise groups (elite competition, race training, treadmill exercise).
Tarsi were only included if horses had no history or clinical evidence of hind limb lameness and there was no radiographic abnormality of the tarsal joints. All tarsi were collected from horses undergoing humane destruction for reasons other than this study. Tarsi were collected within 6 hours of death for all groups except race training, which were collected within 36 hours of death. Limbs were stored frozen at –20°C. For MR imaging, tarsi were thawed at room temperature for 24 hours. In a previous study, freezing and defrosting equine specimens did not alter image quality (39).

**Magnetic resonance imaging**

Each tarsus was positioned as if in right lateral recumbency in an intact horse in a human extremity radiofrequency coil with the distal tarsal joints centred in the isocentre of the magnet. Three dimensional spoiled gradient echo (SPGR) images were acquired in a sagittal plane (echo time 3.3 ms, repetition time 8.1 ms, flip angle 30°, field of view 12 cm, slice thickness 1.5 mm, number of excitations 16, imaging options: variable band width, no phase wrap, zero fill interpolation processing 512 to reconstruct the image to a 512/512 matrix (15)) using a 1.5T GE Signa Echospeed magnet as previously described (3).

Subchondral bone thickness was measured using a digital image analysis programme, previously validated for this technique (24, 3). Measurements were obtained at standard sites at dorsal locations 15% of the depth of the T3 bone and at plantar locations 85% of the depth of the T3 bone in the dorsal to plantar dimension on the proximal and distal aspects of the CT and T3 bones, and proximal aspect of the MT3 bone. Dorsal measurements were made at medial, midline, and lateral sites, which were 30%, 50% and 70% of the width of the T3 bone from the medial aspect respectively (Fig. 1). Plantar measurements were made at midline sites 50% of the
width of the T3 bone. These standard locations have been shown to be reproducible (3). The talocentroquartal joint was represented by measurements on the proximal aspect of the CT bone, the centrodistal joint by the distal aspect of the CT and proximal aspect of the T3 bone and the tarsometatarsal joint by measurements on the distal aspect of the T3 bone and proximal MT3 (Fig. 1).

Statistical analysis

- Effect of exercise group on SCB thickness at specific sites

To test for differences between groups at each site, a one-way ANOVA (normally distributed data) or Kruskal-Wallis ANOVA (non-normally distributed data) were used. To determine which groups were different, multiple comparisons of means were performed using an independent samples T-test (normally distributed data) or a Mann-Whitney U test (non-normally distributed data). The significance level was set at p < 0.05. Analysis was carried out using statistical analysis software (Analyse-it)4.

A general linear mixed effect model was also used to take account of horse level clustering in groups where two tarsi were collected from some of the horses, and to allow for the effect of age on SCB thickness. Generalised linear mixed models were used to confirm differences in SCB thickness at specific sites in the tarsus, associated with the level of exercise, by comparison of the elite competition and race training groups with the low intensity general purpose group (reference group). The degree of clustering of tarsi within horses was assessed by calculation of intra-class correlation coefficients and variance inflation factors (9). These statistical analyses were performed using STATA 9.15.

- Patterns of variation in SCB thickness within each exercise group

To determine if there were significant differences between test sites within each exercise group, one-way ANOVA and Friedman ANOVA were used for parametric
and non-parametric data, respectively. To determine which sites were different, multiple comparisons of means were performed using a paired Student’s T-test for normally distributed data or a Wilcoxon signed ranks test with statistical analysis software (Analyse-it)\(^4\).

**Results**

*Effect of exercise group on SCB thickness at specific sites (Tables 1-3) (Fig 2)*

- **Talocentroquartal joint**
  On the proximal aspect of the CT bone, medial and midline SCB thickness was significantly greater for elite competition (p = 0.003; p = 0.023) and race training (p = 0.046; p < 0.001) than either low intensity GP exercise or horse walker exercise (p < 0.004, p < 0.03). Lateral SCB thickness was significantly greater in race training than low intensity GP exercise (p = 0.016).

- **Centrodistal joint**
  On the proximal aspect of the CT bone, medial SCB thickness was significantly greater in elite competition than in all other groups (p < 0.045) and significantly greater in race training than low intensity GP exercise (p = 0.044) or treadmill exercise (p = 0.03). On the proximal aspect of the T3 bone, medial SCB thickness was significantly greater for race training (p = 0.034) than low intensity GP exercise.

- **Tarsometatarsal joint**
  On the distal aspect of the T3 bone, midline SCB thickness was significantly greater in elite competition than low intensity exercise and horse walker exercise (p ≤ 0.040) and significantly greater in race training than low intensity GP, treadmill and horse walker exercise (p ≤ 0.049). Lateral SCB thickness was significantly greater in elite
competition than treadmill exercise \((p = 0.029)\) and significantly greater in race training than low intensity GP, treadmill and horse walker exercise \((p \leq 0.002)\).

On the proximal aspect of the MT3 bone, medial SCB thickness was significantly greater for elite competition and race training than low intensity GP and treadmill exercise \((p \leq 0.001)\). Midline SCB thickness was significantly greater in elite competition and race training than low intensity GP, treadmill and horse walker exercise \((p \leq 0.048)\). Lateral SCB thickness was significantly greater for low intensity GP exercise than treadmill exercise \((p = 0.043)\); significantly greater in elite competition than low intensity, treadmill, and horse walker exercise \((p \leq 0.009)\); and significantly greater in race training than treadmill exercise \((p = 0.040)\).

**Age and horse effect (generalised linear mixed model)**

The differences in SCB thickness between the elite competition and/or race training groups and the low intensity general purpose group were not significantly altered when the effect of age and horse level clustering were taken into account. The same regions of SCB were identified as being significantly greater thickness in the elite competition and/or race training groups.

*Patterns of variation in subchondral bone thickness within each exercise group*

**A. Medial to lateral comparison of dorsal SCB thickness (Tables 1-3) (Figs 2-3)**

- **LOW INTENSITY EXERCISE**

1. Low intensity general purpose exercise

For low intensity GP exercise, lateral SCB thickness was significantly greater than medial on the distal aspects of the CT and T3 bones (Fig. 3) and the proximal aspect of the MT3 bone \((p \leq 0.017)\), and significantly greater than midline on the proximal and distal aspects of the CT bone, distal aspect of the T3 bone and proximal aspect of
the MT3 bone (p ≤ 0.009). Medial SCB thickness was significantly greater than midline on the proximal and distal aspects of the CT bone (p ≤ 0.032).

2. Horse walker exercise

For low intensity horse walker exercise, lateral SCB thickness was significantly greater than medial on the distal aspect of the T3 bone (p < 0.001) and significantly greater than midline on the proximal and distal aspects of the CT bone, the distal aspect of the T3 bone and the proximal aspect of the MT3 bone (p ≤ 0.029). Medial SCB thickness was significantly greater than midline on the proximal and distal aspects of the CT bone and the proximal aspect of the MT3 bone (p ≤ 0.040).

HIGH INTENSITY EXERCISE

1. Elite competition

For elite competition, lateral SCB thickness was significantly greater than medial and midline on the distal aspect of the T3 bone and the proximal aspect of the MT3 bone (p ≤ 0.009). Medial SCB thickness was significantly greater than lateral on the proximal aspects of the CT and T3 bones (p ≤ 0.017) and significantly greater than midline on the proximal and distal aspects of the CT bone (p ≤ 0.011).

2. Race training

For high intensity race training, lateral SCB thickness was significantly greater than medial and midline on the distal aspects of the CT and T3 bones (p ≤ 0.010). Medial SCB thickness was significantly greater than midline on the distal aspect of the CT bone (p = 0.034).

3. Treadmill exercise

For high intensity treadmill exercise, lateral SCB thickness was significantly greater than medial on the distal aspect of the CT bone (p = 0.002).
B. Dorsal to plantar comparison (Fig. 4)

For low intensity GP exercise, dorsal SCB thickness was significantly greater than the plantar aspect on the proximal and distal aspects of the CT bone ($p \leq 0.003$). In elite competition, dorsal SCB thickness was significantly greater than the plantar aspect on the proximal and distal aspects of the CT bone, distal aspect of the T3 bone and proximal aspect of the MT3 bone at the midline ($p \leq 0.021$). For high intensity race training, dorsal SCB thickness was significantly greater than plantar at all proximal to distal locations ($p \leq 0.010$). There was not a significant difference between dorsal and plantar SCB thickness for treadmill and horse walker exercise, although dorsal SCB thickness tended to be larger than plantar overall.

Discussion

The results of this study support the hypothesis that high intensity exercise is associated with greater subchondral bone thickness than low intensity exercise and is site specific relative to the level of induced strain. The proximodistal and mediolateral SCB thickness patterns varied between groups, supporting our hypothesis that different exercise types and intensities would lead to different SCB thickness patterns. An increase in SCB thickness is likely to be related to increased magnitude and number of strain cycles in bone of horses undergoing high compared with low intensity exercise. This supports findings from other studies investigating the effect of strenuous training on bone (23, 31). The response of cortical bone to loading is strain rate dependent (20). In the galloping horse, bone experiences strain rates in excess of those recorded for any other species (12). Horses in race training undergo more galloping than in other types of training, leading to high impact forces and a
high rate of strain. Therefore it was not surprising that in the current study, high intensity race training was associated with thicker SCB than low intensity exercise (GP or horse walker). Elite competition was also associated with significantly thicker SCB than low intensity exercise, although to a lesser degree than race training. Horses undergoing elite competition training are likely to experience more intensive training than general purpose horses, and would be likely to experience greater compressive strain in the tarsus associated with jumping higher (38) or sustaining increased degree and duration of tarsal compression in dressage (16). As elite competition horses are unlikely to be undertaking galloping training (dressage horses) or will be galloping at slower speeds for a shorter duration (event horses) compared with the race training group, the bone is likely to experience lower impact and lower strain rate than horses in race training, which could explain the lesser degree of increase in subchondral bone thickness with elite competition than race training.

In contrast to over ground race training and elite competition, high intensity treadmill training was not associated with increased SCB thickness relative to low intensity exercise. This could be related to difference in age or training duration between the groups as the treadmill training duration was only 19 weeks in 2 year old horses compared with longer term race training in older horses. Horses reach skeletal maturity when the last growth plates of the appendicular skeleton close at approximately 4 years of age (18), so it is possible that differences in SCB thickness could be related to a cumulative effect of loading with age (2). However, difference in gait between treadmill and over ground training could have influenced the findings, relating to both overall thickness of subchondral bone and pattern of subchondral bone thickness across the articular surfaces. In humans, tibial compressive and tensile strain and strain rates were significantly greater during over ground running than
treadmill exercise (21) which would be supported by the thicker subchondral bone in horses trained over ground, suggesting greater strain and strain rates than treadmill exercise. If the hind limbs are not being used to propel the horse forward with the same force as they would over ground, the strain intensity would be relatively reduced and distribution altered. Differences have been established between the kinematics of horses exercised on a treadmill compared with those exercised over ground, with an increased stance duration, more caudal movement of limbs during retraction and less vertical movement of the hooves during treadmill exercise (4). Treadmill exercise has been associated with increased congruency of other joints (19), which could potentially alter load distribution (10) and SCB thickness across the articular surfaces, and may relate to exercise in a straight line leading to more even strain distribution across the articular surfaces. Other factors that were likely to have affected loading across the tarsus include the difference in treadmill surface to over ground training, which can affect loading of the limbs (17), the incline of the treadmill (horses in the current study worked at a 3% incline) and the lack of rider influence.

Although there was generally greater SCB thickness dorsally for all groups, this difference was maximal for elite competition and race training. The increased dorsal SCB in these exercise groups indicates that the dorsal aspect is experiencing greater strain than in low intensity exercise. This supports the findings of a previous study in which there was a greater dorsal to plantar ratio of radiopharmaceutical uptake in elite showjumping horses than in GP horses (26). This dorsal increase could relate to the increased duration of tarsal compression experienced by both elite dressage (16) and jumping (38) horses, and compression sustained in galloping. This could potentially predispose the dorsal aspect to repetitive overloading. Clinically, osteoarthritic change is reported to start on the dorsal aspect (6).
Both proximal to distal and medial to lateral variations between groups were present. In a previous study (3) a process for transfer of maximum compressive load from the proximal medial aspect of the tarsus to the distal lateral aspect of the tarsus was suggested. In the current study, variation in patterns between groups reflects the possibility of different gaits and exercise intensities leading to altered transfer of load through the tarsus from proximal medial to distal lateral. Low intensity exercise horses had increased SCB thickness on the lateral aspect while in elite competition CD joint SCB thickness was greater medially than laterally and TMT joint SCB thickness was greater laterally than medially, in horse walker exercise medial and lateral were greater than midline, and for race training and treadmill exercise horses there was a less distinct mediolateral pattern. These results illustrate that the tarsus is subjected to different patterns of loading in the different exercise groups. The pattern of loading in the joints of elite competition horses and horse walker exercise could be affected by working on a circle for a high percentage of time compared with race or treadmill training, which is primarily done in straight lines or straight lines with very large curves in the UK. Compressive strain in the third metacarpal bone is increased on the lateral aspect in the inside limb and the medial aspect of the outside limb during turning (7). Although the biomechanics of loading may be different in fore and hind limbs, it could be extrapolated that working on a circle may lead to greater compressive strain laterally in the inside tarsus and medially in the outside tarsus. This could provide an explanation for the patterns seen in both horse walker exercise and elite competition exercise. As horse walker exercise was performed in a circle in both directions, both medial and lateral aspects of the limbs would have been subject to increased compressive strain, and hence increased SCB thickness at these sites, with little strain on the midline. For elite competition exercise, it is possible that the
pattern observed is related to turns and circles at faster speeds, or related to the specific movements required, such as sideways movements and turns around a single hind limb carrying the bodyweights of both the horse and rider (pirouettes). In gaits performed during elite level dressage competition, such as passage, piaffe and pirouettes the tarsal joint is required to flex more than in other gaits (5, 16). These movements are unlikely to be undertaken by general purpose or race horses. It is possible that for elite jumping, tarsal compression required at take off and landing and the sharp turns between fences could alter the proximal to distal pattern of loading in a similar way.

Anecdotal clinical experience and a recent study indicate that flat race horses have reduced risk of distal tarsal osteoarthritis compared with general purpose or competition horses (25). It may be that the pattern of tarsal loading during race training is protective against the development of tarsal osteoarthritis. It is therefore possible that using training in straight lines during management of competition and general purpose horses with very early tarsal pain could simulate these loading patterns and potentially limit progression.

This study had a number of limitations. There were limited numbers in each group, and age variation between the groups. Although these were taken into account in the statistical analysis, the findings should still be interpreted in this light. It should also be taken into account that two horses in the elite competition group were not in elite level work at the time they were euthanased having recently been restricted to box rest and controlled walking exercise. Despite this reduction in activity, joints from horses in this group still had a proximal to distal SCB thickness pattern consistent with the remainder of the group suggesting that established changes to SCB thickness remain unchanged for at least 6 weeks after a reduction in exercise. In rats restricted to cages
for 15 weeks following 15 weeks running on a treadmill, structural properties of SCB remained unchanged, but material properties returned to control level quickly (14).

**Conclusion**

Subchondral bone thickness in the distal aspect of the equine tarsus is affected by both exercise intensity and type. Different types of high intensity exercise were associated with different patterns of SCB thickness across the joints from medial to lateral and proximal to distal indicating that both exercise intensity and type of exercise affect the SCB response at any particular site within a joint.

**Acknowledgements**

The authors wish to thank the Pet Plan Charitable Trust, the Horse Trust and the Barbinder Trust for funding of the low intensity and elite competition exercise portion of the study, and the Horserace Betting Levy Board for background funding in association with the high intensity race training, treadmill exercise and horse walker exercise part of the study.

**Manufacturers addresses**

1 Medical Advances Inc., Milwaukee, USA.

2 General Electric Medical Systems, Milwaukee, USA.

3 Scion Corporation, Maryland, USA.

4 Analyse-it Software Ltd., Leeds, UK.

5 StataCorp, College Station, Texas, USA.

**References**


Table 1

Subchondral bone thickness at medial locations (positioned 30% of the width of the tarsus from the medial aspect) in equine tarsal bones from horses with a history of low intensity general purpose (GP), low intensity horse walker exercise, high intensity elite competition, high intensity race training and high intensity treadmill exercise. Measurements were obtained using magnetic resonance images (mean +/- S.D in mm). a,b,c,d,e represent significant differences between exercise groups at each location (p<0.05). CT = central tarsal bone, T3 = third tarsal bone, MT 3 = third metatarsal bone.

<table>
<thead>
<tr>
<th>Location</th>
<th>Low intensity GP</th>
<th>Horse walker</th>
<th>Elite competition</th>
<th>Race training</th>
<th>Treadmill exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximal CT</td>
<td>3.82 ± 0.69b</td>
<td>3.63 ± 0.58c</td>
<td>4.87 ± 0.94cd</td>
<td>4.44 ± 0.75b</td>
<td>3.53 ± 0.47d</td>
</tr>
<tr>
<td>Distal CT</td>
<td>2.68 ± 0.74d</td>
<td>2.96 ± 0.91a</td>
<td>3.97±0.74abcd</td>
<td>3.20 ± 1.09ce</td>
<td>2.10 ± 0.63bc</td>
</tr>
<tr>
<td>Proximal T3</td>
<td>2.29±0.89abcd</td>
<td>2.64 ± 0.72</td>
<td>2.99 ± 0.63cd</td>
<td>3.66 ± 2.48e</td>
<td>2.45 ± 0.49</td>
</tr>
<tr>
<td>Distal T3</td>
<td>2.87 ± 3.15</td>
<td>2.36 ± 0.54</td>
<td>2.97 ± 0.73</td>
<td>3.25 ± 1.65</td>
<td>2.44 ± 0.21</td>
</tr>
<tr>
<td>Proximal MT3</td>
<td>3.23±0.61bd</td>
<td>3.59 ± 0.99</td>
<td>4.57 ± 0.75cd</td>
<td>4.23 ± 0.92ab</td>
<td>2.94 ± 0.40bc</td>
</tr>
</tbody>
</table>
Table 2
Subchondral bone thickness at midline locations (positioned 50% of the width of the tarsus from the medial aspect) in equine tarsal bones from horses with a history of low intensity general purpose (GP), low intensity horse walker exercise, high intensity elite competition, high intensity race training and high intensity treadmill exercise. Measurements were obtained using magnetic resonance images (mean +/- S.D in mm). \(^{a,b,c,d,e,f}\) represent significant differences between exercise groups at each location (p<0.05). CT = central tarsal bone, T3 = third tarsal bone, MT3 = third metatarsal bone.

<table>
<thead>
<tr>
<th>Location</th>
<th>Low intensity GP</th>
<th>Horse walker</th>
<th>Elite competition</th>
<th>Race training</th>
<th>Treadmill exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximal CT</td>
<td>2.45 ± 0.96(^{bd})</td>
<td>2.59 ± 1.09(^{ic})</td>
<td>3.81 ± 0.90(^{cd})</td>
<td>4.13 ± 1.23(^{ab})</td>
<td>2.73 ± 0.83</td>
</tr>
<tr>
<td>Distal CT</td>
<td>2.13 ± 0.96</td>
<td>1.96 ± 0.54</td>
<td>2.58 ± 1.41</td>
<td>2.72 ± 1.02</td>
<td>2.46 ± 1.27</td>
</tr>
<tr>
<td>Proximal T3</td>
<td>2.10 ± 0.73</td>
<td>1.92 ± 0.68</td>
<td>2.52 ± 1.25</td>
<td>3.39 ± 3.07</td>
<td>2.11 ± 0.36</td>
</tr>
<tr>
<td>Distal T3</td>
<td>1.95 ± 0.78(^{de})</td>
<td>2.11 ± 0.40(^{ce})</td>
<td>2.96 ± 1.19(^{cd})</td>
<td>3.96±2.99(^{abe})</td>
<td>2.19 ± 0.51(^{a})</td>
</tr>
<tr>
<td>Proximal MT3</td>
<td>3.23 ± 1.36(^{cd})</td>
<td>3.18 ± 1.00(^{bl})</td>
<td>4.88±2.18(^{bcd})</td>
<td>9.63±7.96(^{aef})</td>
<td>2.42 ± 0.29(^{ce})</td>
</tr>
</tbody>
</table>
Table 3

Subchondral bone thickness at lateral locations (positioned 70% of the width of the tarsus from the medial aspect) in equine tarsal bones from horses with a history of low intensity general purpose (GP), low intensity horse walker exercise, high intensity elite competition, high intensity race training and high intensity treadmill exercise. Measurements were obtained using magnetic resonance images (mean +/- S.D in mm). a,b,c,d,e represent significant differences between exercise groups at each location (p<0.05). CT = central tarsal bone, T3 = third tarsal bone, MT3 = third metatarsal bone.

<table>
<thead>
<tr>
<th>Location</th>
<th>Low intensity GP</th>
<th>Horse walker</th>
<th>Elite competition</th>
<th>Race training</th>
<th>Treadmill exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximal CT</td>
<td>3.54 ± 1.16d</td>
<td>3.77 ± 0.68</td>
<td>4.20 ± 0.96</td>
<td>5.21 ± 2.46d</td>
<td>3.43 ± 1.28</td>
</tr>
<tr>
<td>Distal CT</td>
<td>3.62 ± 0.80</td>
<td>3.54 ± 1.10</td>
<td>3.35 ± 0.60</td>
<td>4.56 ± 2.48</td>
<td>3.63 ± 0.68</td>
</tr>
<tr>
<td>Proximal T3</td>
<td>2.35 ± 1.15</td>
<td>2.20 ± 1.36</td>
<td>1.85 ± 1.11</td>
<td>2.84 ± 1.17</td>
<td>2.13 ± 0.76</td>
</tr>
<tr>
<td>Distal T3</td>
<td>3.81 ± 1.21c</td>
<td>4.06 ± 0.64a</td>
<td>4.65 ± 1.66d</td>
<td>5.91±1.76abc</td>
<td>3.28 ± 0.57bd</td>
</tr>
<tr>
<td>Proximal MT3</td>
<td>4.77 ± 2.92bd</td>
<td>3.76 ± 0.81a</td>
<td>9.12±2.15abc</td>
<td>14.09±7.43c</td>
<td>3.19±0.57bde</td>
</tr>
</tbody>
</table>
Figure 1

Diagram of the equine tarsus from the dorsal aspect. The talocentroquartal joint (TCQ) forms the articulation between the talus, central tarsal (CT) and fourth tarsal bones, the centrodistal joint (CD) forms the articulation between the CT and third tarsal (T3) bone and the tarsometatarsal joint (TMT) forms the articulation between the T3 bone and third metatarsal (MT3) bone.
Figure 2. Mean dorsal medial (30%), midline (50%) and lateral (70%) subchondral bone (SCB) thickness on the distal aspect of the third tarsal bone from horses that underwent low intensity general purpose exercise (low level), elite competition, high intensity race training, high intensity treadmill exercise and low-intensity exercise on a horse walker. Horses had no hind limb lameness. Significant differences between medial, midline and lateral sites are marked as * and +. Error bars represent standard deviations.
Figure 3
Dorsal plane 3-dimensional spoiled gradient echo image of the distal tarsal region from a mature horse with no hind limb lameness that had a history of low intensity general purpose exercise. Lateral is to the right of the picture. The talocentroquartal joint (TCQ), centrodistal joint (CD) and tarsometatarsal joint (TMT) are marked. The subchondral bone is thicker on the lateral aspect of the CD and TMT joints.
Figure 4. Mean midline dorsal and plantar subchondral bone (SCB) thickness on the distal aspect of the central tarsal bone in tarsi from horses that underwent low intensity general purpose exercise (low level), elite competition, high intensity race training, high intensity treadmill exercise and low intensity exercise on a horse walker. Horses had no hind limb lameness. Significant differences between dorsal and plantar sites are marked as *. Error bars represent standard deviations.
Exercise group.

SCB thickness (mm).

- Low level
- Elite
- High intensity racing
- Treadmill
- Horse walker

Dorsal
Plantar