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Morphometrical Variations of the Carpal Bones in Thoroughbreds and Ponies

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Summary

There is scant morphological data for equine carpal bones despite the frequent pathology in Thoroughbreds (TB). This study aimed to identify morphological and morphometrical variations and similarities in carpal bones between and within TB and Ponies (Po). Carpal bones from nine TB and 13 Po were prepared by boiling and drying. Lateromedial width, dorsopalmar depth, proximodistal height, relative density and volume of each bone were measured. Normalized measurements of the radial (Cr) and third (C3) carpal bones were significantly different in all dimensions, and there were significant variations in relative sizes of articular facets of the ulnar (Cu), C3 and fourth (C4) carpal bones between the groups. Bilaterally, the proportionate volume of the intermediate carpal bone (Ci) was significantly greater in Po while that of Cu and C4 were significantly greater in TB. Relative density of most bones was greater in Po. The palmar tuberosity of the proximal surface of Ci and palmar tubercle on the palmar surface of Cu were more prominent and relatively larger in TB. In the second carpal bone (C2), the distal extent of the proximal articular surface on the palmar surface was greater in Po. The inconsistent first carpal bone (C1) was relatively larger in Po. Morphometrical similarities and differences in carpal bones between TB and Po indicate potential effects of selection for body size or fast exercise.

Introduction

The carpus is one of the most complex regions in the limbs. The carpus, or wrist, includes the carpal bones, joints and ligaments and is the region between the radius and ulna proximally and the metacarpal bones distally (Getty, 1975; Evans, 1993). In equines, the carpus is composed of seven to nine carpal bones arranged in two rows. The seven constant carpal bones are the radial, intermediate, ulnar, accessory, second, third and fourth carpal bones. The first carpal bone is variably present thus is termed an inconstant carpal bone (Getty, 1975; Dyce et al., 1996). Additionally, there is a fifth carpal bone which has been occasionally observed radiolographically (Thrall, 1994; Wright and Butler, 1997; Butler et al., 2000). The proximal row, which articulates with the radius through the radiocarpal joint, consists of, from medial to lateral, the radial, intermediate, ulnar and accessory carpal bones, while the distal row, which articulates with the metacarpal bones through the carpometacarpal joint, includes the first, second, third and fourth carpal bones (Nickel et al., 1986). The first carpal bone, when present, and the accessory carpal bone are not part of the column of bones that directly support the body weight (Getty, 1975). The carpal bones within the two rows have an interlocking wedge arrangement which might play an important role in dissipating any impact forces and damping any peak forces through the interosseous ligaments (Bramlage et al., 1988; Deane and Davies, 1995). In the mid-carpal joint, this interlocking arrangement is mostly applied through the articular facets such as the radial and intermediate facets of the third carpal bone. Although these two facets are on the same bone, the former facet, which receives greater loading (Ross, 2003), is more susceptible to fractures than the intermediate facet (De Haan et al., 1987).

Thoroughbreds have been selected for fast exercise speed, while Ponies have been selected for a relatively small size. Hence, if there are specific morphological features that are associated with running fast and with supporting more weight, as in the Thoroughbreds, then these features should show consistent differences between these disparate groups of horses.

Although the carpal bones have been described in a general manner, description of morphological variations between the equine breeds is still lacking, neither are there description available for normal variations between the two limbs within an individual. The current study hypothesized that despite Thoroughbreds and Ponies being from the same species, their differences in body size and type of activities would be associated with some anatomical variations in the morphometrics of the carpal bones. Therefore, the purpose of this study was to identify morphological and morphometrical variations of the carpal bones between the two groups as well as between the two limbs in each group.

Materials and Methods

Animals

Both left and right carpal regions were collected from 23 horses in Victoria, Australia that had died or were euthanized for non-orthopaedic reasons. Breed, age and gender were recorded for each horse. Racing history and weights of the horses were not available. There were 10 Thoroughbreds and 13 Ponies. Their age varied from 1.5 to 23 years old. In Thoroughbreds, the mean age was 7.3 ± 8.0 (SD) years, and in Ponies, it was 3.8 ± 5.2 years. Any horses with obvious carpal pathology visible on post-mortem examination were excluded from the study. Carpi from one Thoroughbred were excluded from width, depth, height, relative density and volume measurements as they were sectioned during processing.

Bone preparation

The right and left carpi from each horse were bagged separately and were boiled at 98.5°C for 48 h to detach the soft tissue. Despite carpal bones from horses less than 3 years old requiring less time to detach the soft tissue, all carpi were boiled for the same time. Following boiling, the carpi were examined carefully for the presence of the first and fifth carpal bones. The carpal bones were then air dried for 24 h followed by heating at 49.5°C for 8 h to achieve the constant dry weight for each bone. This constant dry weight was used to determine relative density.

Morphology

A morphological description was recorded for the most obvious variations between and within the groups in each carpal bone. The main morphological details included: (1) Shape of articular surfaces, including concavity and convexity, (2) Extent of articular surfaces, (3) Surface texture, (4) Facets, (5) Tubercles and (6) Fossae. In respect to the first carpal bone, its morphological description was confined to its articulations with the adjacent bones and its shape.

Bone volume

The volume of each bone was determined by displacement in water as follows: At a room temperature of 27°C, the bone was attached to a fine thread which was extended from a holder. A beaker was filled with water. The filled beaker was fixed on a scale and its weight was recorded. Then, the bone was completely immersed in the filled beaker but without any contact between the bone and beaker. Then, the weight was recorded again. The difference between these two measurements was calculated and the result represented the bone volume. The volumes of the bones in each carpus, excluding the first carpal bone, were added together to give the total bone volume for each carpus. The volume of each carpal bone was then expressed as a percentage of the volume of the whole carpus to normalize measurements for comparisons between the different sized carpi.

Relative density (specific gravity)

Relative density of each carpal bone was calculated using the following: (1) Constant dry weight, (2) Volume and (3) Water density. During measurement of the volume of the bones, the room temperature was 27°C, and according to Duck (1990), at this temperature the water density would be 0.996 g/cm^3. The following formula was used to determine the relative density of each carpal bone:

$$\text{Relative density} = \frac{\text{constant dry weight in air}}{\text{volume of bone} \times \text{water density at room temperature}}$$

Linear measurements

The following measurements were taken of the constant carpal bones:

1. Width (lateromedial), depth (dorsopalmar) and height (proximodistal) of each constant carpal bone were measured using a caliper (Matuidoki, Japan). The absolute measurements of these dimensions are shown in Table 1. The varying size between the two groups was normalized using the height of the Cr and C3 (Cr+C3) as a factor. This factor was used for measuring the three carpal dimensions in each carpal bone.

Table 1. The lateromedial width, dorsopalmar depth and proximodistal height (mean ± SD in mm) of the carpal bones in 9 Thoroughbreds and 13 Ponies

	Lateromedial width		Dorsopalmar depth		Proximodistal height	
Bone	TB	Po	TB	Po	TB	Po
Cr						
R	33.11 ± 2.07	22.38 ± 1.96	49.00 ± 2.39	33.50 ± 2.67	33.47 ± 1.68	20.96 ± 2.67
L	33.28 ± 1.92	22.56 ± 1.88	49.00 ± 2.15	33.54 ± 2.66	33.69 ± 1.76	21.02 ± 2.70
Ci						
R	36.36 ± 1.47	24.79 ± 2.17	44.58 ± 3.72	30.48 ± 2.58	32.47 ± 3.37	21.50 ± 2.30
L	36.14 ± 1.26	24.62 ± 2.22	44.39 ± 3.58	30.52 ± 2.54	32.58 ± 3.26	21.50 ± 2.30
Cu						
R	22.06 ± 2.00	14.19 ± 1.28	37.53 ± 3.01	24.38 ± 2.25	34.50 ± 2.06	21.69 ± 2.61
L	22.14 ± 2.03	14.15 ± 1.28	37.53 ± 2.95	24.19 ± 2.26	34.44 ± 2.16	21.77 ± 2.55
Ca						
R	18.86 ± 1.74	13.60 ± 0.85	50.33 ± 2.92	33.73 ± 3.89	41.33 ± 1.84	27.23 ± 2.56
L	18.83 ± 1.79	13.62 ± 0.94	50.44 ± 3.03	33.73 ± 3.91	41.11 ± 2.08	27.17 ± 2.47
C2						
R	18.44 ± 1.53	11.71 ± 1.09	29.92 ± 3.21	20.44 ± 1.94	23.44 ± 1.55	15.12 ± 1.61
L	18.53 ± 1.44	11.71 ± 1.03	29.78 ± 3.01	20.62 ± 1.77	23.61 ± 1.14	15.15 ± 1.60
C3						
R	51.06 ± 2.14	35.42 ± 3.10	47.78 ± 2.96	32.08 ± 2.99	24.44 ± 1.59	16.02 ± 1.75
L	50.94 ± 1.94	35.33 ± 2.88	47.89 ± 2.93	32.15 ± 3.02	24.72 ± 1.37	16.13 ± 1.87
C4						
R	27.33 ± 2.98	16.08 ± 2.29	38.22 ± 3.13	24.27 ± 2.37	26.83 ± 1.98	17.00 ± 1.46
L	27.22 ± 2.75	16.12 ± 2.30	38.42 ± 3.07	24.27 ± 2.32	27.08 ± 2.04	16.92 ± 1.52

TB, Thoroughbred; Po, Pony; R, Right; L, Left.

For example, the absolute measurement of width of Cr in a Thoroughbred was 31 mm and the heights of Cr and C3 were 32 and 22 mm, respectively. Hence, normalizing the width of Cr was

$$\frac{\text{width of Cr}}{\text{height of Cr} + \text{C3}} = \frac{31}{54} = 0.57$$

The lines of measurement for each carpal bone were taken as follows:

Radial carpal bone (Cr): Width was measured lateromedially as the maximum width of the dorsal half of the proximal articular surface. Depth was measured dorsopalmarly as the maximum depth of the middle of the lateral surface. Height was measured proximodistally from the dorsal surface, the line extending from the most proximal point of convexity on the proximal surface to the most distal point of the distal articular surface (Fig. 1).

Intermediate carpal bone (Ci): Width was measured lateromedially as the maximum width of the dorsal part of the proximal articular surface. Depth was measured dorsopalmarly as the maximum depth of the middle of the distal surface. Height was measured proximodistally lateral to the mid-line of the dorsal surface to include the most distal point of the distal surface (Fig. 1).

Ulnar carpal bone (Cu): Width was measured lateromedially at the widest point that was coincident with the middle of the distal surface of the bone. Depth was measured dorsopalmarly at the widest part of the distal third of the lateral surface. Height was measured proximodistally from the palmar edge of the proximal articular surface to the most distal point of the lateral surface (Fig. 1).

Accessory carpal bone (Ca): Width was measured lateromedially as the widest point of the bone in the region of the proximal articular facet. Depth was measured dorsopalmarly from the medial surface from the distal edge of the proximal facet to the most palmar point of the bone. Height was measured proximodistally from the lateral surface as the maximum height of the bone (Fig. 1).

Second carpal bone (C2): Width was measured lateromedially as the maximum width at the middle of the proximal articular surface. Depth was measured dorsopalmarly from the medial surface as the maximum depth of the bone. Height was measured proximodistally from the medial surface as the maximum height of the bone (Fig. 2).

Third carpal bone (C3): Width was measured lateromedially at the middle of the dorsal surface coincident with the transverse ridge. Depth was measured dorsopalmarly from the proximal articular surface to include the transverse ridge of the dorsal surface and the palmar tubercle

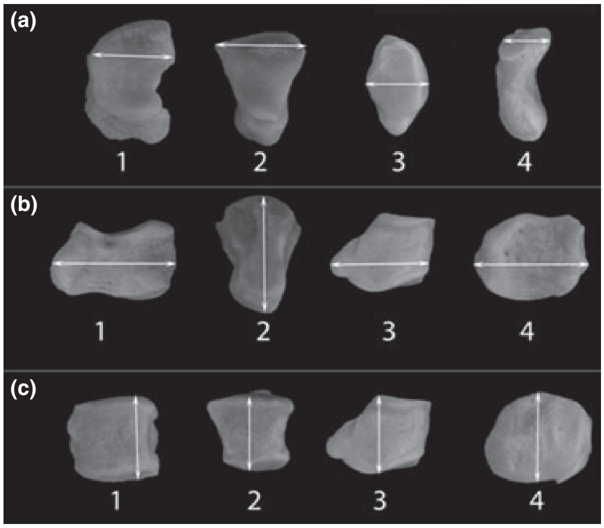

Fig. 1. Linear measurements of the proximal carpal row of a Thoroughbred. (a) Width (lateromedially): 1 and 2. Proximal aspects of Cr and Ci; 3. Distal aspect of Cu; 4. Proximal aspect of Ca, the width was measured on the dorsal surface of the bone. (b) Depth (dorsopalmarly): 1. Lateral aspect of Cr; 2. Distal aspect of Ci; 3. Lateral aspect of Cu; Medial aspect of Ca. (c) Height (proximodistally): 1 and 2. Dorsal aspects of Cr and Ci; 3 and 4. Lateral aspects of Cu and Ca.

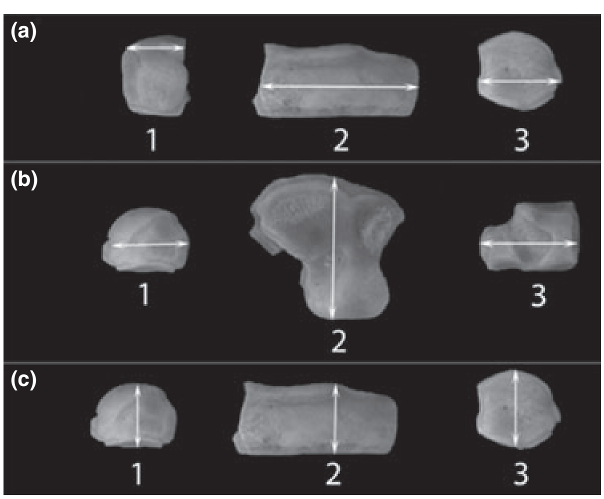

Fig. 2. Linear measurements of the distal carpal row of a Thoroughbred. (a) Width (lateromedially): 1. Dorsal aspect of C2, the width was measured on the proximal surface of the bone; 2 and 3. Dorsal aspects of C3 and C4. (b) Depth (dorsopalmarly): 1. Medial aspect of C2; 2. Proximal aspect of C3; 3. Medial aspect of C4. (c) Height (proximodistally): 1. Medial aspect of C2; 2 and 3. Dorsal aspects of C3 and C4.

of the palmar surface. Height was measured proximodistally from the dorsal surface extending from the junction between the radial and intermediate facets proximally to the distal articular surface distally. The upper lip of the caliper included the border between the radial and intermediate facets and also the palmar part of the proximal articular surface (Fig. 2).

Fourth carpal bone (C4): Width was measured lateromedially from the dorsal surface as the maximum width of the bone. Depth was measured dorsopalmarly from the medial surface as the maximum depth of the bone. Height was measured proximodistally from the dorsal surface as the maximum height of the bone (Fig. 2).

2. Articular facets:

a. Distal articular facets of the ulnar carpal bone: The maximum dorsopalmar extent of the concave facet and the maximum dorsopalmar depth of the convex facet of the same bone were measured using a ruler graduated in millimeter. The ratio of the former facet to the latter was calculated (Fig. 3).

b. Proximal articular facets of the third carpal bone: The maximum lateromedial width of the radial facet and the maximum lateromedial width of the intermediate facet of the same bone were measured using the ruler. The ratio of the former facet to the latter facet was calculated (Fig. 3).

c. Proximal articular facets of the fourth carpal bone: The maximum lateropalmar extent of the lateral facet and the maximum dorsolateral extent of the medial facet of the same bone were measured using the ruler. The ratio of the former facet to the latter facet was calculated (Fig. 3).

The Shapiro–Wilk test was used to test the assumption of Normality of the observations within each group and limb. A two-sample t-test was used to compare between the groups. A paired t-test was used to compare left versus right limb within group. Two-tailed P values <0.05 were considered to be statistically significant.

Results

The results of this study highlight that, although the general morphology of the carpal bones was similar, there were significant morphometrical variations between the groups as well as some significant variations between the right and left carpal bones within groups (Table 2) where the right had a larger value than the left. Even though the means for the right and left carpi were almost the same in many cases, the correlation coefficients between the right and left were very high, and hence, there were some very small standard errors of the differences (for example, Ci width in the Pony group gave means of 0.674 on the right and 0.666 on the left and a correlation coefficient of 0.9768 with a $P = 0.016$).

The normalized lateromedial width, dorsopalmar depth and proximodistal height of the constant carpal bones showed some significant differences between and within

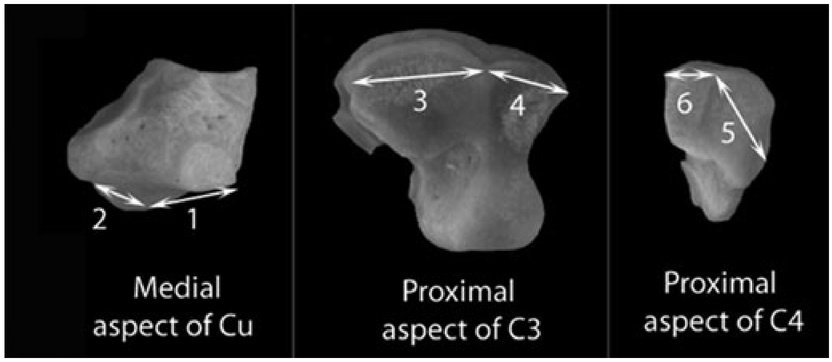

Fig. 3. Linear measurements of articular facets of Cu, C3 and C4 of a Thoroughbred. 1 and 2. Concave and convex articular facets of distal surface of Cu; 3 and 4. Radial facet and intermediate facets of proximal surface of C3; 5 and 6. Lateral and medial articular facets of proximal surface of C4.

Table 2. Normalized lateromedial width (mean ± SD), dorsopalmar distance (mean ± SD) and proximodistal height (mean ± SD) of the carpal bones in nine Thoroughbreds and 13 Ponies

	Lateromedial width		Dorsopalmar depth		Proximodistal height	
Bone	TB	Po	TB	Po	TB	Po
Cr						
R	0.57 ± 0.024	0.61 ± 0.049*	0.85 ± 0.036	0.91 ± 0.052**	0.58 ± 0.0068	0.57 ± 0.010**
L	0.57 ± 0.024	0.61 ± 0.049*	0.84 ± 0.027	0.91 ± 0.052**	0.58 ± 0.0063	0.57 ± 0.012*
Ci						
R	0.63 ± 0.037	0.67 ± 0.044*	0.77 ± 0.068	0.83 ± 0.049*	0.56 ± 0.042	0.58 ± 0.018
L	0.62 ± 0.033	0.67 ± 0.044* +	0.76 ± 0.068 + +	0.83 ± 0.052*	0.56 ± 0.039	0.58 ± 0.020+
Cu						
R	0.38 ± 0.030	0.39 ± 0.022	0.65 ± 0.031	0.66 ± 0.050	0.60 ± 0.025	0.59 ± 0.024
L	0.38 ± 0.030+	0.38 ± 0.022	0.64 ± 0.030	0.65 ± 0.043	0.59 ± 0.028	0.59 ± 0.023
Ca						
R	0.33 ± 0.021	0.37 ± 0.031**	0.87 ± 0.015	0.91 ± 0.026***	0.72 ± 0.055	0.74 ± 0.030
L	0.32 ± 0.021	0.37 ± 0.031***	0.86 ± 0.017	0.91 ± 0.027***	0.71 ± 0.056+	0.73 ± 0.029
C2						
R	0.32 ± 0.017	0.32 ± 0.023	0.52 ± 0.055	0.56 ± 0.042	0.41 ± 0.011	0.41 ± 0.016
L	0.32 ± 0.014	0.32 ± 0.026	0.51 ± 0.052	0.56 ± 0.038*	0.40 ± 0.010	0.41 ± 0.017
C3						
R	0.88 ± 0.050	0.96 ± 0.048**	0.83 ± 0.037	0.87 ± 0.050*	0.42 ± 0.0068	0.43 ± 0.010**
L	0.87 ± 0.039	0.96 ± 0.058**	0.82 ± 0.029	0.87 ± 0.050*	0.42 ± 0.0063	0.43 ± 0.011*
C4						
R	0.47 ± 0.047	0.43 ± 0.027*	0.66 ± 0.035	0.66 ± 0.029	0.46 ± 0.023	0.46 ± 0.023
L	0.47 ± 0.043+	0.43 ± 0.025*	0.66 ± 0.034	0.66 ± 0.030	0.46 ± 0.024	0.46 ± 0.023

The *P* values (*) show the significance of differences between the Thoroughbreds and the Ponies. The *P* values (+) show the significance of differences between the right and left limbs within each group (all greater on the right).
* or +: $P < 0.05$; ** or ++: $P < 0.01$; ***$P < 0.001$.
TB, Thoroughbred; Po, Pony. R, Right; L, Left.

the groups (Table 2). Generally, the radial and third carpal bones were the most variable bones while the ulnar and second carpal bones had the most similarity in the dimensional measurements between the groups. All the carpal bones were proportionately wider lateromedially in the Ponies than in the Thoroughbreds except for the fourth carpal bone which was proportionately wider in the Thoroughbreds. The most significant difference between the groups was in the left accessory carpal bone ($P = 0.0007$). The mean lateromedial width of the left Ca in the Ponies was 0.37 ± 0.031, while in the Thoroughbreds, it was 0.32 ± 0.021.

The normalized dorsopalmar depth was significantly greater in the Ponies than in the Thoroughbreds except for the right second carpal bone and the ulnar and the fourth carpal bones bilaterally. The left accessory carpal bone showed the most significant difference with a P-value of 0.00022. In the Ponies, the mean dorsopalmar depth of the left Ca was 0.91 ± 0.027, whereas in the Thoroughbreds, it was 0.86 ± 0.017. Unlike the width and depth, the normalized proximodistal height demonstrated significant variations between the groups only in the radial and third carpal bones bilaterally. The height of radial carpal bone was greater in the Thoroughbreds than in the Ponies with P values of 0.0067 in the right side and 0.016 in the left side. However, the height of the third carpal bone was larger in the Ponies than the Thoroughbreds on both sides.

In respect to the comparisons between right and left carpi in each group, the intermediate, ulnar, accessory and fourth carpal bones showed some significant differences between the two sides. In all of these significant variations, the right side was always greater than the left side. The lateromedial width of the ulnar and fourth carpal bones in the Thoroughbreds and the intermediate carpal bone in the Ponies was larger on the right side than the left side. Their P values were 0.021, 0.028 and 0.012, respectively. The dorsopalmar depth of the intermediate carpal bone in the Thoroughbreds was also significantly greater ($P = 0.0081$) in the right side. The proximodistal height of the accessory carpal bone ($P = 0.036$) in the Thoroughbreds and the intermediate carpal bone ($P = 0.047$) in the Ponies were greater on the right side than the left side.

The proportionate volume of the following carpal bones varied significantly between the groups; the right and left intermediate, right and left ulnar, right accessory, right second, and right and left fourth carpal bones (Table 3). The proportionate volume of the intermediate carpal bone was significantly greater in the Ponies than in the Thoroughbreds bilaterally. The means for the right were 17.99 ± 0.67% in Ponies and 17.17 ± 0.57% in the Thoroughbreds ($P = 0.007$). The means for the left were 17.92 ± 0.72% in the Ponies and 17.06 ± 0.60% in the Thoroughbreds ($P = 0.008$). Additionally, the proportionate volume of the right accessory carpal bone was significantly greater in the Ponies than in the Thoroughbreds. In contrast, the proportionate volumes of the right and left ulnar, the right second, and right and left fourth carpal bones were significantly greater in the Thoroughbreds than in the Ponies. The most significant variation ($P = 0.0003$) in the proportionate volume was in the right fourth carpal bone, where the mean was 9.46 ± 0.68% in the Thoroughbreds and 8.28 ± 0.58% in the Ponies (Table 3).

The relative density of most of the carpal bones was significantly greater in the Ponies than in the Thoroughbreds (Table 3). The left second carpal bone had the most substantial difference ($P = 0.001$) between these two groups, with the second carpal bone from the left forelimb of the Thoroughbreds being 1.27 ± 0.26 g/cm^3, while that of the Ponies was 1.60 ± 0.14 g/cm^3. The carpal bones that showed no significant differences in relative density between the groups were the radial, intermediate and third carpal bones from both the right and left sides as well as the right side accessory carpal bones.

The ratio between the mid-carpal joint articular facets of the ulnar, third and fourth carpal bones showed significant variations between the Thoroughbreds and the Ponies. In the distal articular surface of the right ulnar carpal bone, the ratio of the dorsopalmar depth of the dorsal concave facet to the dorsopalmar depth of the

Table 3. The mean proportionate volume (in percentages) and the mean relative density (in g/cm^3) of carpal bones from the left and right limbs of 9 Thoroughbreds and 13 Ponies

		Mean proportionate volume (±SD)		Mean relative density (±SD)	
Bone	Side	TB	Po	TB	Po
Cr	Right	23.16 ± 0.95	23.18 ± 0.71	1.27 ± 0.15	1.39 ± 0.15
	Left	23.19 ± 0.91	23.41 ± 0.45	1.26 ± 0.15	1.38 ± 0.15
Ci	Right	17.17 ± 0.57	17.99 ± 0.67**	1.22 ± 0.15	1.33 ± 0.16
	Left	17.06 ± 0.60	17.92 ± 0.72**	1.23 ± 0.14	1.33 ± 0.15
Cu	Right	8.53 ± 0.22	8.18 ± 0.39*	1.14 ± 0.12	1.33 ± 0.19*
	Left	8.60 ± 0.48	8.19 ± 0.28*	1.15 ± 0.14	1.32 ± 0.16*
Ca	Right	13.82 ± 1.10	14.95 ± 1.14*	1.2 ± 0.21	1.35 ± 0.15
	Left	14.11 ± 0.89	14.88 ± 1.05	1.18 ± 0.22	1.37 ± 0.15*
C2	Right	5.41 ± 0.30	4.95 ± 0.40**	1.31 ± 0.25	1.58 ± 0.16**
	Left	5.32 ± 0.38	4.97 ± 0.41	1.27 ± 0.26	1.6 ± 0.14**
C3	Right	22.38 ± 0.75	22.45 ± 1.54	1.32 ± 0.20	1.42 ± 0.21
	Left	22.41 ± 0.93	22.38 ± 0.57	1.29 ± 0.17	1.43 ± 0.16
C4	Right	9.46 ± 0.68	8.29 ± 0.58***	1.21 ± 0.22	1.44 ± 0.11**
	Left	9.32 ± 0.74	8.28 ± 0.48***	1.23 ± 0.25	1.44 ± 0.10*

The P values (*) show the significance of differences between the Thoroughbreds and the Ponies.
*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.
TB, Thoroughbred; Po, Pony.
Relative density of Ca, C2 and C4 was measured from 12 Ponies.

palmar convex facet was significantly greater ($P = 0.033$) in the Ponies than in the Thoroughbreds. The mean of this ratio in the right ulnar carpal bone was 2.18 ± 0.65 in the Ponies and 1.66 ± 0.22 in the Thoroughbreds. In addition, the ratio of the lateromedial width of the radial facet to the lateromedial width of the intermediate facet of the left third carpal bone was significantly greater ($P = 0.021$) in the Thoroughbreds than in the Ponies. The mean of this ratio in the left third carpal bone was 1.66 ± 0.073 in the Thoroughbreds and 1.55 ± 0.11 in the Ponies. Moreover, in the proximal articular surface of the right and left fourth carpal bones, the ratio of the lateropalmar width of the lateral facet to the dorsolateral width of the medial facet was significantly greater ($P = 0.0097$ in right and 0.0073 in left side) in the Ponies than in the Thoroughbreds. The mean of this ratio in the right fourth carpal bone was 2.92 ± 0.47 in the Ponies and 2.40 ± 0.31 in the Thoroughbreds. In the left side, the mean was 2.98 ± 0.42 in the Ponies and 2.39 ± 0.33 in the Thoroughbreds.

On the proximal part of the lateral surface of the radial carpal bone, there was a small fossa of variable size and appearance. In 90% of the Thoroughbreds, the fossa was pronounced. In the Ponies, although 46% of the Ponies had a pronounced fossa, the fossa was indistinct in 23%.

The palmar region of the proximal articular surface of the intermediate carpal bone possessed a tuberosity (Fig. 4). This feature was bilaterally similar in all individuals and was prominent in all the Thoroughbreds, eight of which possessed a large-sized tuberosity, while in the other two Thoroughbreds, the tuberosity was intermediate in size. In contrast, this tuberosity was bilaterally small in eight Ponies, intermediate in size in three Ponies and large in size in two Ponies.

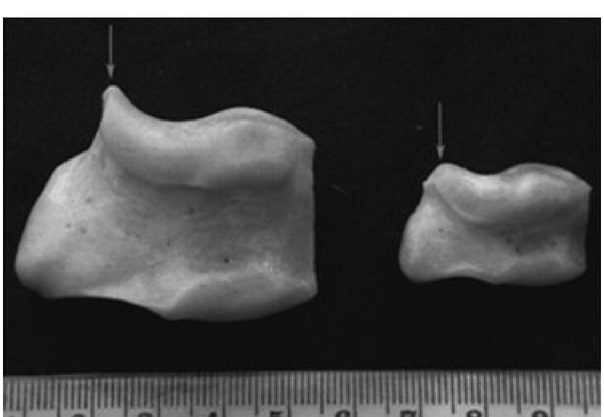

Fig. 4. Medial aspects of the left intermediate carpal bone from a Thoroughbred (left) and a Pony (right). The arrows show the tuberosity, which was prominent in all Thoroughbreds and very small in eight of the thirteen Ponies. The ruler is graduated in mm.

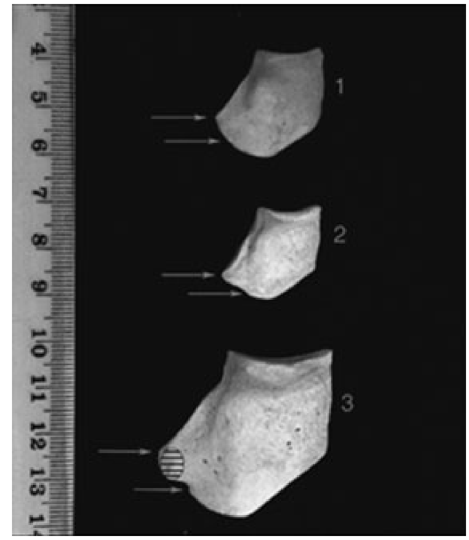

Fig. 5. The lateral aspects of the right ulnar carpal bones from a Thoroughbred (3) and two Ponies (1 and 2). The shadowed area in bone 3 indicates the palmer tubercle which was very distinct in all the Thoroughbreds but in the Ponies, it was small in seven Ponies (bone 2), very small in two and absent in one Pony (bone 1). In each bone, the upper arrow indicates the distal edge of the palmar ulnar facet, while the lower arrow indicates the palmar end of the distal articular surface of the bone. The ruler is graduated in mm.

The palmar tubercle of the ulnar carpal bone was bilaterally similar in all individuals and was very distinct in all the Thoroughbreds (Fig. 5). However, in the Ponies, the tubercle was small in seven, very small in two and absent in one.

The palmar part of the proximal articular surface of the second carpal bone extended distally over the palmar surface to a variable degree. In all the Thoroughbreds and in 62% of the Ponies, this extension was approximately between the middle and second third of the palmar surface, whereas in 39% of the Ponies, the extension was up to the distal articular surface. In addition, the distal surface of the bone was flat for articulation with the second metacarpal bone. Palmolaterally, it bore a small facet for articulation with the third metacarpal bone. One Thoroughbred and two Ponies had no small facet bilaterally. Furthermore, the facet was absent unilaterally in two Thoroughbreds (one from the left and the other from the right carpi) and in one Pony from the left carpus. The small facet varied in its confluence with the flat facet. In 44% (n4/n9) Thoroughbreds who had the facets, there was a confluence between them. In contrast, 91% (n10/n11) of the Ponies who had the facets, the facets were confluent.

In respect to the inconstant carpal bones, there was no fifth carpal bone found in any of the specimens. However, first carpal bones were found in three horses in each of the groups. In the Ponies, all the first carpal bones were bilaterally present and each had an articulation with the second carpal bone. In addition, two of the Ponies had first carpal bones which also articulated with the second metacarpal bone in both limbs. In the Thoroughbreds, the bone was bilaterally present in only one horse while both unilaterally present bones were found in the right carpus and only in one specimen did this bone articulate with the second carpal bone. Although there was an obvious difference between the size of the groups, the largest first carpal bone, with a proximodistal height of 10 mm, was found in one Pony.

Discussion

This study indicated that, despite the similar general anatomy of carpal bones in Thoroughbreds and Ponies, there were some significant morphometrical differences between the two groups. The lateromedial width, dorsopalmar depth and proximodistal height of all the constant carpal bones were normalized using their size in relation to the height of Cr+C3. This factor was used to remove the effect of differences in the body size between the two groups. The current study found that the differences in the normalized width and depth between the two groups were significant in most of the bones. Identifying reasons for these variations needs more investigation. However, the variation in body size and different types of activity between the groups might reasonably highlight possible effects of these factors on the carpal bone shape. In the metacarpal bone for example, it was found that exercise caused changes in dorsopalmar (Davies et al., 1999) and lateromedial (Hiney et al., 2004) diameter. In respect to the height of the carpal bones, the differences between the two groups were only significant in the radial and third carpal bones. This result may be important clinically as these two bones were reported as the most damaged bones in the equine carpus (Backer, 1969; Schneider, 1979). Interestingly, the radial carpal bone was proportionately higher in the Thoroughbreds, and the third carpal bone was proportionately higher in the Ponies. The Ponies were identified as a group mainly through their height at the withers. Hence, the lack of differences in normalized heights for the other carpal bones between the Ponies and Thoroughbreds suggests that the use of the Cr+C3 height as a factor related well to the differences in height at the withers between the two groups and, further, that differences in height at the withers between individuals were likely to be reflected in the height of Cr+C3.

There were a few significant variations between the carpal bones in the right and left limbs within the two groups. All the significant variations showed larger right bones than the left. There are many reports of a varying susceptibility between left and right limbs to some pathological conditions within Thoroughbreds. For instance, Palmer (1986) reported that in 211 Thoroughbreds, slab fracture was more common in the right carpus than in the left. However, the lack of significant variations between right and left limbs in the dimension of the highly fractured carpal bones suggests that the normal anatomy by itself is not enough to explain Palmar's reported laterality in fracture incidence. In other studies which observed the effect of racing direction, the higher incidence of fractures in the right mid-carpal joint was attributed to increased pressure on this side during high exercise speeds in counterclockwise racing (Schneider et al., 1988). In contrast, Larsen and Dixon (1970) reported that within horses who raced in a clockwise direction, the left carpus was more affected with carpal fractures than the right. Hence, the effect of loading in relation to racing direction seems to be the best explanation for variations in the incidence of fractures between the two sides.

An increase in relative density has been associated with increased exercise in many studies (Firth et al., 1999). The tendency for the Ponies to have a greater relative density in the majority of the carpal bones in the current study could have been due to the selected population of Ponies having been more active than the Thoroughbreds. This seems unlikely because the majority of Thoroughbreds in Victoria, Australia are trained for racing. Alternatively, the greater relative density in the Ponies may have been associated with a greater proportionate loading of the carpal bones in the Ponies which could be due to a relatively smaller size of the carpal bones in relation to body weight in the Ponies. This relationship could be supported by some studies which used the pressure plate technique to measure the peak vertical force. They have found that the peak vertical force in the forelimb was 130% of body weight in the Ponies (Oosterlinck et al., 2010), while in the Thoroughbreds, it was 107.8% of body weight at the trot (Dow et al., 1991). Unfortunately, no live weight data were available for these specimens so this hypothesis remains to be tested. However, if relatively large carpal bones are required to distribute the forces associated with race-training, then perhaps the Thoroughbreds have been selected for relatively large carpal bones of lower density. There may have been further selection pressure for relatively larger right carpal bones if the right side carpal bones have a greater risk of fracture as has been reported for Thoroughbreds (Palmer, 1986). Such selection pressure might help to explain the relatively low density of carpal bones in the untrained Thoroughbreds in previous reports (Firth et al., 1999; Firth and Rogers, 2005) and the relatively greater volume of the right side carpal bones in the Thoroughbreds in our study.

The relative density varied between all the carpal bones. This might suggest that there are consistent differences in the loading on the different carpal bones or in the way the carpal bones develop during growth.

The lack of any significant difference between the two groups in the proportionate volume of the radial and third carpal bones, and the low variation between individuals, suggests that the proportionate sizes of the radial and third carpal bones have a more consistent mechanical function irrespective of the type of work.

The proportionate volume in the left and right intermediate carpal bone was significantly greater in the Ponies than in the Thoroughbreds. Furthermore, the relative density still showed a tendency (non significant, Table 3) to be greater in the Ponies. This suggests that, unlike in Thoroughbreds where the main axial loading is concentrated through the radial carpal bone and the third carpal bone (Bramlage et al., 1988), the intermediate carpal bone might contribute more to that loading in the Ponies. Possibly the intermediate carpal bone has been proportionately reduced in volume in the Thoroughbreds during their selection for speed or size as it may be less mechanically important than the radial carpal bone in supporting body weight during fast movement.

The proportionate volume of the right and left ulnar and the right and left fourth carpal bones, which form the lateral part of the carpus, was significantly greater in the Thoroughbreds than in the Ponies. This might indicate that the lateral sides of the right and left carpi have a variable response to loading between these groups. Greater loading on the medial side of the right front limb and on the lateral side of the left front limb in horses that race counter-clockwise has been proposed (Schneider et al., 1988). In Victoria, Australia, all races are counter-clockwise so the Thoroughbreds in this study are likely to have been trained and selected for counter-clockwise racing. Hence, there would presumably be differences between the right and left limbs in the Thoroughbreds if the selection for fast exercise and stability in cornering was the primary explanation for the differences in carpal bone volume; instead, the left and right bones are remarkably similar.

The tuberosity on the palmar region of the proximal articular surface of the intermediate carpal bone was prominent in all the Thoroughbreds and only two of the thirteen Ponies, being small or indistinct in eight of the Ponies (Fig. 4). Along with the reciprocal shape of the distal extremity of the radius, this tuberosity may assist in preventing the transverse movement of these bones in the hinged radiocarpal joint. It may be more important in supporting the joint in this way during fast movement, especially around turns during racing; however, any stabilizing effect of this tuberosity must be complex as this region is not recognized as a site of pathology in horses with damaged carpi. The majority of racetrack breakdowns occurs in the Thoroughbreds during turns (Clanton et al., 1991) and this is where there may be some selective pressure for an increase in carpal stability in racing Thoroughbreds in contrast to Ponies. However, exactly what structures contribute to this and how they contribute remains to be investigated.

In this study, the ratio of the radial facet to intermediate facet of the third carpal bone was significantly greater ($P = 0.021$) in the Thoroughbreds than in the Ponies on the left side. Consequently, the percentage of the intermediate facet of the third carpal bone was greater in the Ponies. This might suggest that the radial facet of the third carpal bone receives proportionately more axial loading from the radial carpal bone in the Thoroughbreds than in the Ponies. This mainly axial loading transfers entirely to the radial facet without any ability to dissipate the force to the soft tissues (Bramlage et al., 1988). This could help to explain the findings of Schneider (1979) and De Haan et al. (1987) who reported that the radial facet of the third carpal bone in racing horses was more susceptible to fractures than the intermediate facet.

The proportionate volume of the intermediate carpal bone was significantly greater in the Ponies, and the intermediate facet of the third carpal bone was also greater in the Ponies. It seems likely that in the Ponies, the intermediate facet might receive a greater proportion of the axial loading through the intermediate carpal bone.

The ratio of the lateropalmar width of the lateral facet to the dorsolateral width of the medial facet in the right and left fourth carpal bone was significantly greater in the Ponies than in the Thoroughbreds. In addition, although there was no obvious variation between the groups in the distal extent on the palmar aspect of the proximal articular surface of the third carpal bone, in the second carpal bone, the proximal articular surface extended more distally on the palmar surface in some (39%) of the Ponies than in the Thoroughbreds. Effects of such variation on the range of flexion of the mid-carpal joint, which was estimated to be 45° (Dyce et al., 1996), were not investigated in the current study. However, as the second and fourth carpal bones of the Ponies had more extended articular surfaces palmarly, it may be assumed that this group had a greater range of flexion than the Thoroughbreds.

Although Getty (1975) mentioned that the inconstant first carpal bone was bilaterally present in half of the specimens, the current study was more in agreement with Butler et al. (2000) who found the bone in about one-third of specimens. In the current study, 26.1% of the specimens had this bone regardless of whether it was bilaterally present or not. The articulation of the bone with the second carpal bone was present more commonly in the Ponies, while the articulation with the second metacarpal bone was present only in the Ponies. Furthermore, the relative size of the bone was larger in the Ponies. Thus, the first carpal bone might have reduced in the Thoroughbreds, possibly because of their selection for high speed exercise.

The smaller relative size of the first carpal bone, the tuberosity of the intermediate carpal bone and less extensive proximal articular surfaces of the second and fourth carpal bones in the Thoroughbreds are possible adaptations to support a greater body weight at fast exercise speeds. The significantly greater proportionate volume of the intermediate carpal bone and the wider intermediate facet of the third carpal bone in the Ponies might suggest that these areas have an increased mechanical role in receiving the axial body loading in the Ponies. The wider radial facet of the third carpal bone in the Thoroughbreds may allow these horses to bear more axial body loading medially. There were general morphological similarities and some significant morphological variations in the carpal bones between the Thoroughbreds and the Ponies. Further studies are needed to identify any mechanical factors that might be associated with these specific variations.

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