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Relationship of foot conformation and force applied to the navicular bone of sound horses at the trot

E. ELIASHAR*, M. P. McGUIGAN[‡] and A. M. WILSON[†‡]

Department of Veterinary Clinical Sciences and †Structure and Motion Laboratory, The Royal Veterinary College, Hawkshead Lane, North Mymms, Hatfield, Hertfordshire AL9 7TA; and ‡Structure and Motion Laboratory, University College London, Brockley Hill, Stanmore, Middlesex HA7 4LP, UK.

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Summary

***Reasons for performing study:* Collapsed heels conformation has been implicated as causing radical biomechanical alterations, predisposing horses to navicular disease. However, the correlation between hoof conformation and the forces exerted on the navicular bone has not been documented.**

***Hypothesis:* The angle of the distal phalanx in relation to the ground is correlated to the degree of heel collapse and foot conformation is correlated to the compressive force exerted by the deep digital flexor tendon on the navicular bone.**

***Methods:* Thirty-one shod Irish Draught-cross type horses in routine work and farriery care were trotted over a forceplate, with 3-dimensional (3D) motion analysis system. A lateromedial radiograph of the right fore foot was obtained for each horse, and various measurements taken. Correlation coefficients were determined between hoof conformation measurements and between each of these and the force parameters at the beginning (15%) of stance phase, the middle of stance (50%) and at the beginning of breakover (86% of stance phase). Significance was defined as $P<0.05$.**

***Results:* The force exerted on the navicular bone was negatively correlated ($P<0.05$) to the angle of the distal phalanx to the ground and to the ratio between heel and toe height. This was attributed to a smaller extending moment at the distal interphalangeal joint. There was not a significant correlation between the angle of the distal phalanx and the degree of heel collapse, and heel collapse was not significantly correlated to any of the force parameters.**

***Conclusions:* Hoof conformation has a marked correlation to the forces applied to the equine foot. Heel collapse, as defined by the change in heel angle in relation to toe angle, appears to be an inaccurate parameter. The forces applied on the foot are well correlated to the changes in the ratio of heel to toe heights and the angles of the distal phalanx.**

***Potential relevance:* Assessment of hoof conformation should be judged based on these parameters, as they may have clinical significance, whereas parallelism of the heel and toe is of less importance.**

Introduction

The goal of farriers and equine clinicians is to achieve a dorsopalmar foot balance in which the foot-pastern axis is straight; i.e. the dorsal hoof wall is parallel to the dorsal surface of the pastern region (Balch *et al.* 1997; O'Grady and Poupard 2001; Parks 2003) and the horn tubules at the heels are at a similar angle to those at the dorsal hoof wall (Balch *et al.* 1997; Stashak 1987). In a broken-back, long-toe/low-heels conformation, the dorsal hoof angle is smaller than that of the pastern. In many of these horses the heels are weakened and the horn tubules in the heel region bend and their angle relative to the ground is decreased, resulting in the heels sinking and becoming under-run, termed collapsed heels (Colles 1983). It has been suggested that this change in conformation increases the load on the palmar aspect of the foot during weightbearing (Parks 2003), producing biomechanical changes including permanent extension of the distal interphalangeal (DIP) joint and decreased angle of deviation of the deep digital flexor tendon (DDFT) around the navicular bone. Furthermore, some authors contend that these changes increase the force exerted by the DDFT on the navicular bone predisposing horses to navicular disease (Colles 1982; Bushe *et al.* 1987; Hickman 1989; Pool *et al.* 1989; Wright and Douglas 1993; O'Grady and Poupard 2001).

A collapsed heel conformation does not, however, always lead to lameness and was found in 52% of sound horses (Turner and Stork 1988). This is assumed to be the result of the uneven hoof wall growth seen in shod horses (Hertsch *et al.* 1996), a sequel to stress concentration on the heels by a shoe that was left on for too long, or following the use of a small shoe (Moyer and Anderson 1975). Wright (1993) also identified this conformation in 72.8% of lame horses without navicular disease. The significance of collapsed heel conformation in relation to the forces applied on the navicular bone is therefore not yet determined.

Experimental evidence of acute change in hoof angle seems to support the theory that collapsed heels increase the force in the DDFT. Lochner *et al.* (1980) and Riemersma *et al.* (1996) found that lowering the hoof angle increased the tensile force in the DDFT, and raising the hoof angle had the opposite effect. Six degrees heel wedges were also shown to decrease the maximal force exerted on the navicular bone by 24% (Willemen *et al.* 1999).

*Author to whom correspondence should be addressed. [‡]Present address: Concord Field Station, Harvard University, Old Causeway Road, Bedford, Massachusetts 01730, USA.
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Fig 1: Lateromedial radiograph of a foot showing the measurements used for calculations of correlation coefficients. Note the metal marker on the dorsal hoof wall and the 2 lead markers on the palmar aspect of the hoof. a = toe angle; b = heel angle; c = angle of distal phalanx; d = angle of coronary band; S = weightbearing surface of the hoof wall; T = height of coronary band at the dorsal aspect of the hoof; H = height of the coronary band at the lateral heel; C = coronary band; P = solar aspect of the distal phalanx.

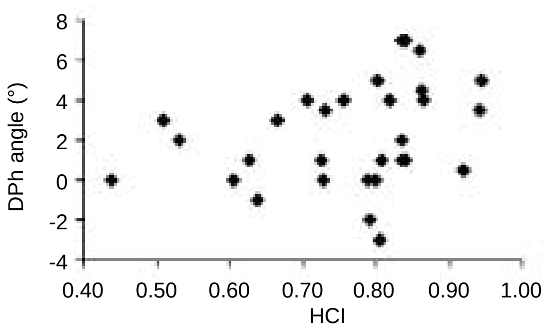

Fig 2: Plot of the relation between heel collapse index and the angle of the distal phalanx, demonstrating no significant correlation between these 2 parameters. HCI = heel collapse index; DPh = angle of the distal phalanx.

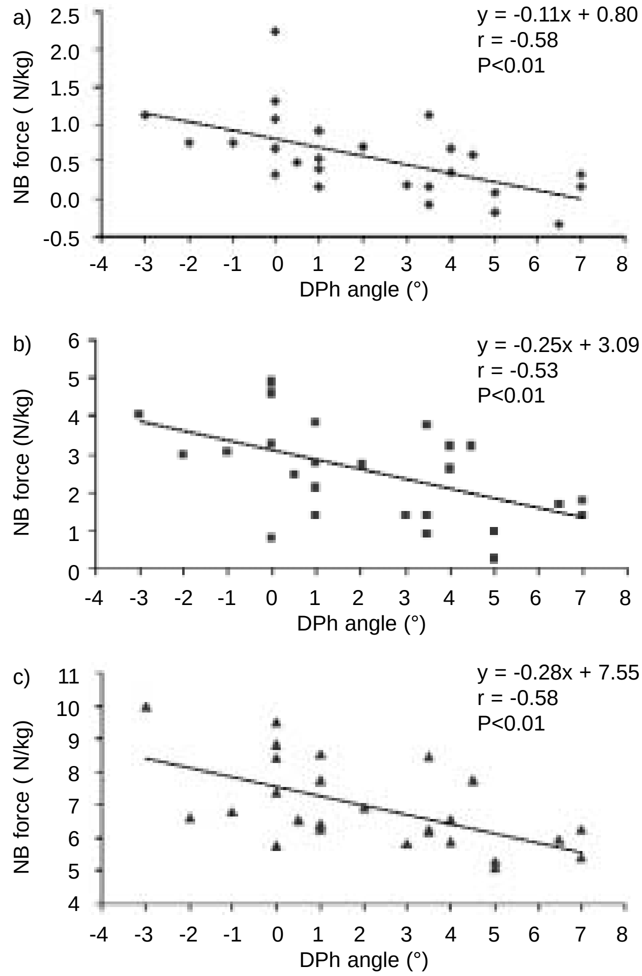

Fig 3: Correlation between the solar angle of the distal phalanx and the force exerted by the deep digital flexor tendon on the navicular bone at a) 15%, b) 50% and c) 86% of stance phase; n = 31. A negative force indicates that the GRF vector passes palmar to the centre of rotation of the DIP joint. DPh = distal phalanx; NB = navicular bone.

In a normal horse, the angle made by the solar border of the distal phalanx (DPh) and the ground varies from 2° to 10° (Parks 2003). In long toe/low heel conformation, this angle is different because the palmar processes of the DPh are closer to the ground compared to the cranial border (Butler *et al.* 2000), causing extension of the DIP joint. As the DPh is the insertion point of the DDFT, a change in its orientation, such as that seen with collapsed heels, may increase the length of the DDFT. Since the DDFT is loaded during stance by its accessory ligament (Wilson *et al.* 2001), and as there is an approximately linear relationship between DDFT length and force (Riemersma and Schamhardt 1985; McGuigan and Wilson 2003), this change in DPh orientation may also increase the DDFT tensile force and subsequently the force it exerts on the navicular bone.

In this study, we hypothesised that the angle of DPh is correlated to the degree of heel collapse and that foot conformation is correlated to the compressive force exerted by the DDFT on the navicular bone.

Materials and methods

Assessment

Thirty-one Irish Draught-cross type horses (527–794 kg bwt) in routine work and farriery care, shod with conventional toe-clip wide-web shoes, were selected for the study. All horses were judged to have good and stable foot conformation, and were assessed for lameness at trot in a straight line. Hemispherical markers were applied to the lateral aspect of the right forelimb, approximately over the centre of rotation of the DIP joint, the centre of rotation of the metacarpophalangeal (MCP) joint and the proximal end of the fourth metacarpal bone. The horses were trotted by an experienced handler at a speed comfortable for the individual horse over a forceplate (9287BA)[1], and a 3-dimensional (3D) motion analysis system (ProReflex)[2] was used to determine the position of the markers from the horse's right side. A minimum of 6 foot strikes were recorded for each horse and data were rejected if the horse was judged not to be moving at constant velocity or if the foot was placed on the edge of the forceplate.

Following removal of the right fore shoe, a 40 mm long metal wire was placed on the midline of the dorsal hoof wall extending distally from the coronary band. Additional 8 mm long lead markers were placed on the palmar aspect of the lateral heel at the level of the coronary band, and on the most palmar weightbearing surface, determined using a scalpel blade pushed under the lateral wall of the sole in a cranial direction along the ground surface while the horse was fully weightbearing on a flat surface. A lateromedial radiograph of the right fore foot was obtained for each horse (Fig 1).

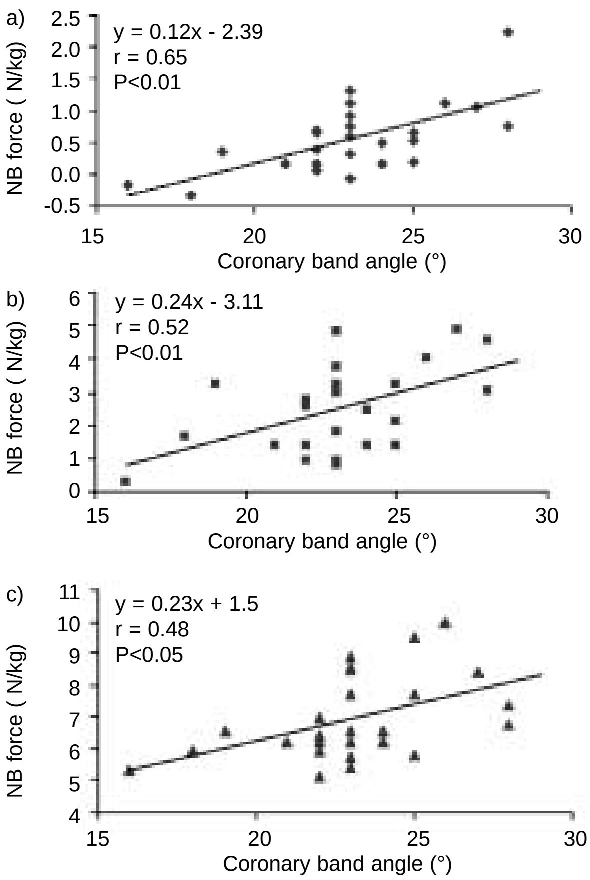

Fig 4: Correlation between coronary band angle and the force exerted by the deep digital flexor tendon on the navicular bone at a) 15%, b) 50% and c) 86% of stance phase; n = 31. A negative force indicates that the GRF vector passes palmar to the centre of rotation of the DIP joint. NB = navicular bone.

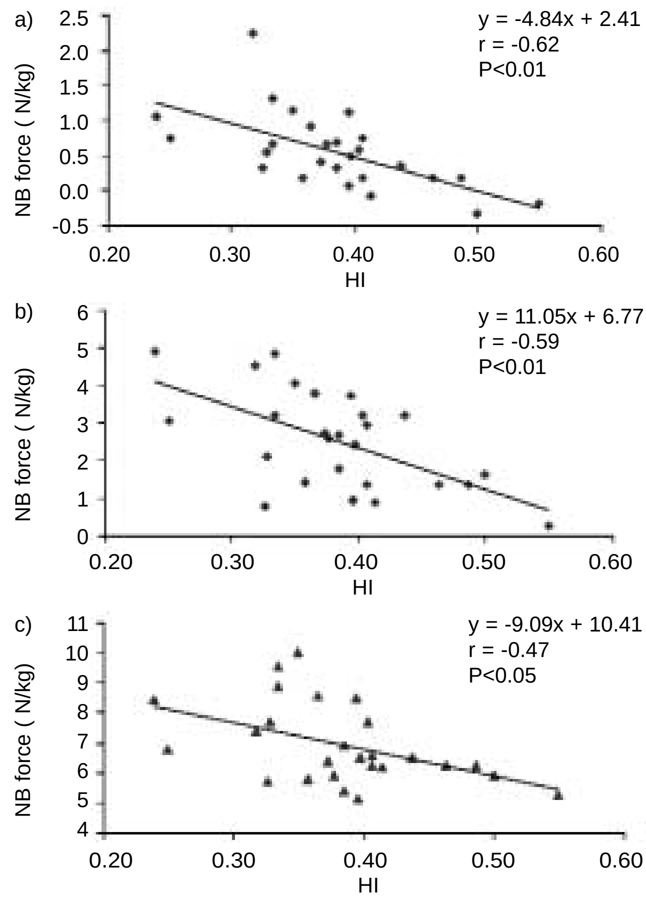

Fig 5: Correlation between height index and the force exerted by the deep digital flexor tendon on the navicular bone at a) 15%, b) 50% and c) 86% of stance phase; n = 31. A negative force indicates that the GRF vector passes palmar to the centre of rotation of the DIP joint. HI = height index; NB = navicular bone.

Data analysis

Stance phase was defined as the period when the vertical ground reaction force (GRF) was greater than 50 N. Using standard formulae and values obtained from the radiographs (Willemen 1999; Wilson *et al.* 2001; Eliashar *et al.* 2002), the point of zero moment (PZM), vertical and caudocranial components of GRF, DIP joint moment arm, extending moment at the DIP joint, angle of deviation of the DDFT around the navicular none, DDFT force and the force it exerts on the navicular bone were calculated throughout stance phase. The following were determined from the radiographs: the angle of the dorsal hoof wall (toe angle); the angle between the palmar 2 lead markers to the ground (heel angle); the angle between the solar aspect of DPh and the ground; and the angle of the coronary band, which was defined as the angle between a line connecting the dorsal marker and the lead marker on heel and ground (Fig 1). Furthermore, the heights of the coronary band above the ground at the dorsal hoof wall (dorsal marker) and at the palmar aspect of the lateral heel (lead marker) were also determined (Fig 1). Heel collapse index (HCI) was defined as the ratio between heel angle and toe angle. Height index (HI) was defined as the ratio between the dorsal coronary band height and heel height. DPh angle was defined as positive when the toe region of the bone was closer to the solar surface compared to the palmar region.

Linear correlation coefficients were determined between HCI, HI, angle of DPh and angle of coronary band, and between each of these and the force parameters at the beginning (15%) of stance phase, the middle of stance (50%), and at the beginning of breakover (86% of stance phase; Eliashar *et al.* 2002). Significance was defined as $P<0.05$.

Results

All values in the text are presented as mean ± s.d. Toe and heel angles were 50.5 ± 3.6° and 39.0 ± 7.3°, respectively, and HCI was 0.77 ± 0.13. Dorsal coronary band and heel heights were 83.9 ± 6.4 and 32.1 ± 7.8 mm, respectively, and HI was 0.38 ± 0.08. The angle of DPh was 2.5 ± 2.2° and that of the coronary band 23.5 ± 3.0°. Dorsal coronary band height and toe angle were not correlated to any of the other foot parameters. A tendency of correlation between DPh angle and HCI was found ($r = 0.32$), but this was not significant ($P = 0.08$; Fig 2). DPh angle and HCI were positively correlated with the height of the coronary band at the heels ($r = 0.45$, $P<0.05$ and $r = 0.66$, $P<0.01$, respectively) and HI ($r = 0.47$ and 0.72, respectively; $P<0.01$), and negatively correlated with coronary band angle ($r = -0.48$ and -0.66, respectively; $P<0.01$). A strong negative correlation was found between HI and the angle of the coronary band, as would be expected ($r = -0.86$, $P<0.001$).

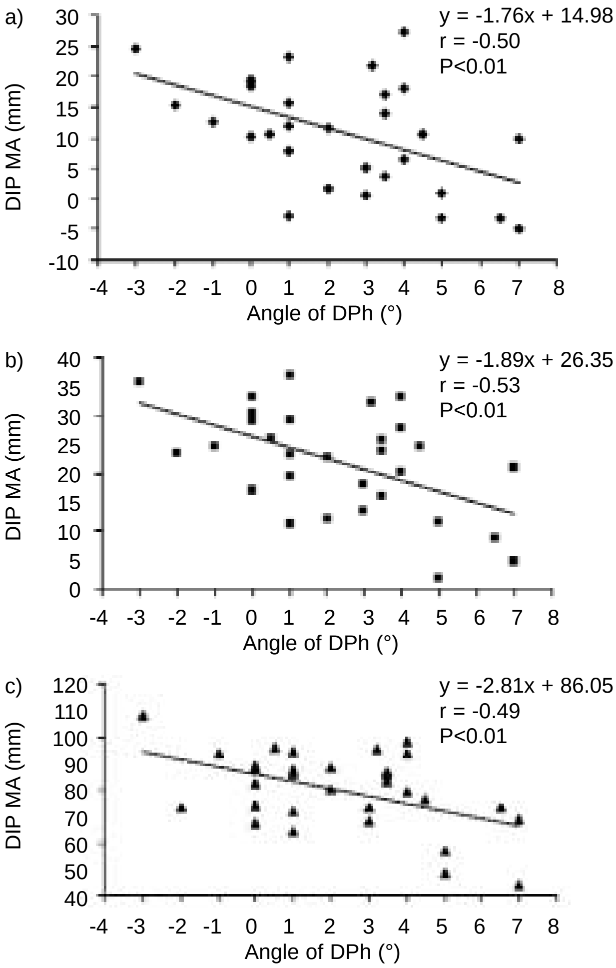

Fig 6: Correlation between the solar angle of the distal phalanx and the extending moment arm of the distal interphalangeal joint at a) 15%, b) 50% and c) 86% of stance phase; n = 31. DPh = distal phalanx; DIP MA = distal interphalangeal moment arm.

No correlations were found between HCI and any of the force parameters. At 15, 50 and 86% of stance phase, DPh angle and HI were negatively correlated and the angle of the coronary band was positively correlated to DIP moment arm, DDFT force and the force exerted on the navicular bone

Figures 3, 4 and 5 present the correlation between DPh angle, coronary band angle and HI, respectively, and the force exerted by the DDFT on the navicular bone at 15, 50 and 86% of stance. The linear regression equations of these graphs demonstrate that a DPh angle increased (coronary band angle decreased) by 1° reduces the force exerted on the navicular bone by 20% at early stance (15% of stance phase) and by 9–12% in mid stance (50% of stance phase). The peak force exerted by the DDFT on the navicular bone (86% of stance phase) is reduced by 4% for every 1° increase in DPh angle or decrease in coronary band angle.

Figures 6 and 7 present the correlation between DPh angle and DIP joint MA, and angle of coronary band and the DIP joint MA, respectively. A 1° increase in DPh angle reduces the DIP MA by 18% in the beginning of stance, 9% at mid stance and by 4% at 86% of stance phase (Fig 6). Decrease in the coronary band angle by 1° reduces the DIP MA at these time points of stance by 15, 7 and 3%, respectively (Fig 7).

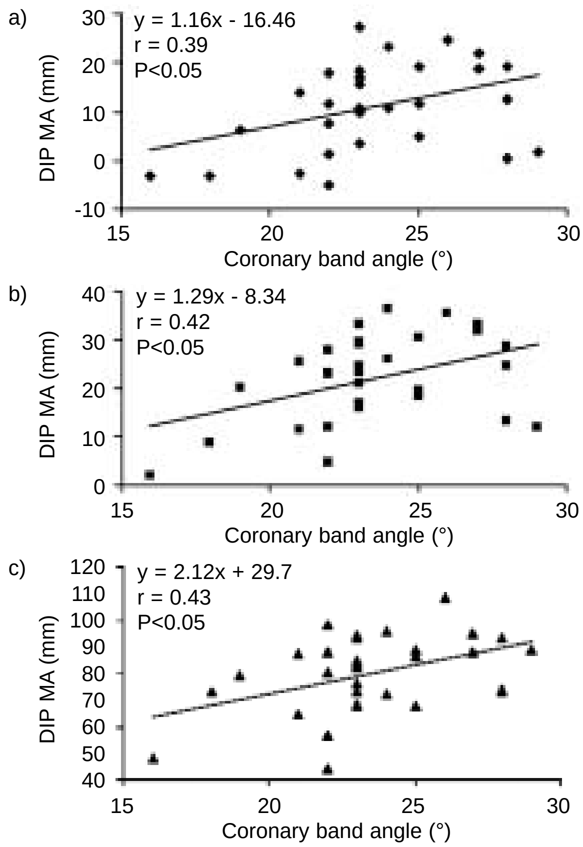

Fig 7: Correlation between angle of the coronary band and the extending moment arm of the distal interphalangeal joint at a) 15%, b) 50% and c) 86% of stance phase; n = 31. DIP MA = distal interphalangeal moment arm.

Discussion

It is usually accepted that in an optimal foot conformation the angle of the heel should be parallel to that of the toe (Balch *et al.* 1997; O'Grady and Poupard 2001; Parks 2003), which would result in a HCI of 1 in the present study, and that the angle of the DPh should be 2–10° (Parks 2003). In our study, both average HCI and the angle of DPh were smaller. The horses used in the study were under routine farriery care, and it is possible that these values were affected by the period elapsed since the most recent foot trimming. However, the effect of routine trimming on foot measurements undertaken in this study and the forces applied in the foot has yet to be clarified.

In this study, heel collapse (defined as a ratio between heel and toe angles) showed no correlation with the forces applied to the equine foot. This may be explained by the method used to determine HCI. As the heel collapses, the horn tubules bend inwards and dorsally (Parks 2003), and therefore the palmar-most weightbearing point moves axially in relation to the palmar-most aspect of the heel. Subsequently, when viewed from the lateral aspect on a 2-dimensional image such as a radiograph, the angle measured at the heel (as determined here) is greater compared to the true angle, and therefore HCI is susceptible to error. It is possible that, if HCI were corrected for this distortion, a correlation could be identified. It is therefore better to use toe and heel heights from the solar surface rather than their angles, since these heights are not distorted on a 2-dimensional image, and the possible error is therefore prevented. This study has identified a strong negative correlation between HI and the force parameters. A correlation between heel height and the forces measured was also identified in the horses used here.

When the heels collapse, the angle of the coronary band in relation to the ground becomes steeper and the DIP joint extends. The orientation of the DPh also changes, its palmar border moves closer to the ground and the angle between the sole and the distal aspect of the bone becomes smaller. In severe collapse, the palmar aspect of the distal phalanx may be closer to the solar surface compared to the toe region (defined as a negative angle in this study). A decrease in DPh angle or HI (increase in coronary band angle) moves the PZM towards the toe, increasing the DIP joint moment arm. Because the GRF is unlikely to be affected by the changes in foot conformation, the net result is an increase in the extending moment on the DIP joint. Since the moments at the DIP joint are in a quasistatic equilibrium during stance phase, the flexing moment generated by the DDFT must also increase. The outcome is greater tensile force in the DDFT, and because the moment arm of DDFT on the DIP joint does not change, any increase in the DDFT force leads to increase in the force it exerts on the navicular bone. The force exerted on the navicular bone is also dependent upon the angle of deviation of the DDFT around the navicular bone, but this angle appeared not to be significantly correlated to foot conformation in this study.

Willemen *et al.* (1999) have demonstrated that following application of a 6° heel wedge the force exerted on the navicular bone was reduced by 24% during the end of stance in sound Warmblood horses. Our study supports these findings. By using the correlation formulae, we could calculate that a PDh angle greater by 1° (coronary band angle smaller by 1°) has the effect of reducing the DDFT force and the force it exerts on the navicular bone by 4%. This is attributable to a similar reduction in the extending moment arm of the DIP joint.

The DDFT force, and the force and stress it exerts on the navicular bone at the beginning of stance, were found to be approximately 2-fold higher in horses suffering from navicular disease compared to control group values (Wilson *et al.* 2001). This was attributed to a contraction of the deep digital flexor muscle in early stance in an attempt to unload the heels. The present study demonstrates that for a PDh angle smaller by 1° (coronary band angle greater by 1°) the DDFT force and the force it exerts on the navicular bone increase by 20% at the beginning of stance. This is because of a similar increase in the extending moment arm on the DIP joint. Our study suggests that, in some horses, as a sequel to poor conformation, increased forces may be exerted on the navicular bone, predisposing these horses to navicular disease. The increased force exerted on the navicular bone due to contraction of the deep digital flexor muscle may be a manifestation of navicular disease in more progressive stages (Wilson *et al.* 2001). Some breeds of horses (for example Quarter Horses and Warmbloods) with navicular disease tend to have an upright foot conformation. Whether this represents a sequel to DDFT shortening (Wilson *et al.* 2001) or other factors is unknown.

In conclusion, this study confirms that hoof conformation has a marked correlation to the forces applied to the equine foot. Heel collapse, as defined traditionally by the change in heel angle in relation to toe angle, appears to be a less accurate parameter. The forces applied on the foot showed a strong correlation with the changes in the ratio of heel to toe heights and the angles of the distal phalanx and the coronary band. We therefore suggest that assessment of hoof conformation should be judged based on these parameters, as they may have clinical significance, whereas parallelism of the heel and toe is of less importance. Our findings also support the practice of applying heel wedges to horses with collapsed heels. However, heel wedges tend to concentrate the forces applied on the heels as do heel calks (Moyer and Anderson 1975), while exacerbating the degree of collapse (Parks 2003).

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[1]Kistler Instruments Ltd., Alton, Hampshire, UK.
[2]Qualisys AB, Sävedalen, Sweden.

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