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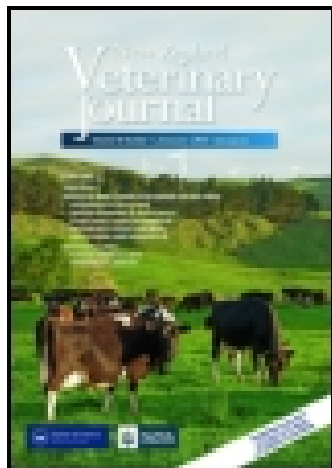
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### Associations between hoof shape and the position of the frontal plane ground reaction force vector in walking horses

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### *Scientific Article*

## **Associations between hoof shape and the position of the frontal plane ground reaction force vector in walking horses**

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### **Abstract**

**AIMS:** To determine the frontal plane position of the ground reaction force vector at its centre of pressure under the hoof of walking horses, and its projection through the distal limb joints, and to relate this to hoof geometric measurements.

**METHODS:** Reflective markers were glued to the forelimb hooves and skin of 26 horses, over palpable landmarks representing centres of the coffin, fetlock and carpal joints, and the dorsal toe at its most distal point. A 4-camera kinematic system recorded the position of these markers as the horse walked in hand across a force platform, to generate a frontal plane representation of the ground reaction force vector passing between the markers at the joints. The position of the vector was calculated as the relative distance between the lateral (0%) and medial (100%) markers at each joint. Digital photos were taken of the hoof in frontal and sagittal views to determine hoof geometric measurements. Associations between these and the position of the force vector at each joint were examined using Pearson correlation coefficients.

**RESULTS:** Mean vector position for both forelimbs at the toe, coffin, fetlock and carpal joint was 50.1 (SD 8.9), 53.0 (SD 9.2), 54.6 (SD 11.4) and 50.5 (SD 17.3)%, respectively, of the distance between the lateral and medial sides of the joint in the frontal plane. Across all four joints, the vector position was slightly more medial (2–4%) for the right than left limb ( $p > 0.05$ ). Medial hoof wall angle was correlated ( $p < 0.05$ ) with force vector position at the fetlock ( $r = -0.402$ ) and carpal ( $r = -0.317$ ) joints; lateral hoof wall angle with vector position at the toe ( $r = 0.288$ ) and carpal

( $r=-0.34$ ) joint, and medial hoof wall height with vector position at the fetlock ( $r=-0.306$ ) and carpal ( $r=-0.303$ ) joints.

**CONCLUSION:** The position of the two-dimensional frontal plane ground reaction force vector at the toe, and at the fetlock and carpal joints was associated with hoof shape. Mediolateral hoof balance has been shown *in vitro* to affect articular forces, which may be a factor in development of joint disease. The effect of hoof shape needs to be evaluated at faster gaits to determine the potential for joint injury in the presence of larger forces.

**KEY WORDS:** *Equine, hoof, ground reaction force, gait, joints*

## Introduction

There is considerable variability in shape of the equine hoof. Although much of the focus has been on sagittal plane mechanics (Crevier-Denoix *et al.* 2001; Eliashar *et al.* 2004; Kroekenstoel *et al.* 2006; Wiggers *et al.* 2015), mediolateral hoof conformation has also received some attention. Elevating the medial or lateral side of the hoof with wedges causes the centre of pressure under the hoof to move toward the wedged side (Wilson *et al.* 1998). Mediolateral imbalance has been demonstrated to disrupt the articular contact area in the distal interphalangeal joints of cadaveric limbs loaded in a hydraulic testing machine (Viitanen *et al.* 2003). The development of bilaterally uneven or asymmetric hoof shape may stem partly from postural behaviour by foals, in that preferential advancement of one limb during grazing appears to be associated with toe angle (van Heel *et al.* 2006). The ipsilateral geometry of the foal's hoof dictates to a large extent the shape of the adult hoof as the early shape persists through development (van Heel *et al.* 2010) and may affect the longer-term orthopaedic health of the competition horse (Ducro *et al.* 2009). Bilateral associations were reported between elements of the forelimb skeleton and hoof geometry, suggesting that variations in loading caused by these bilateral variations in hoof and limb morphometry could contribute to injury and reduced performance (Wilson *et al.* 2009). Previously, considerable bilateral asymmetry was identified in limb and hoof morphometry in a cohort of 108 racehorses and was related to performance (Weller *et al.* 2006a, b). Right-left asymmetries were also identified in horizontal moments around the forehoof centre of pressure in walking horses (Colborne *et al.* 2009; Heaps *et al.* 2011) suggesting that the two forelimbs contribute differently to propulsion during gait and are thus loaded differently.

The three-dimensional ground reaction force vector is the equal and opposite force, measured at the ground, of vertical and horizontal forces produced by the limb against the ground as it bears weight

in its stance phase. The vertical and craniocaudal forces are expressed as a two-dimensional vector in the sagittal plane, while the vertical and mediolateral forces are expressed in the frontal plane. In both cases, this vector has a point of origin under the hoof (the centre of pressure) and has amplitude and angle depending on the Pythagorean relationship between its two component forces. From its centre of pressure under the hoof, the force vector points up the limb, passing through the distal joints (Figure 1). There are no studies evaluating the path of the frontal plane ground reaction force vector up the limb, and so the purpose of this study was to identify the location of this vector relative to markers on the medial and lateral sides of the hoof, coronet band, fetlock and carpal joints, and to determine whether the location of the vector was related to ipsilateral hoof geometric measurements.

### **Materials and methods**

The horses used in this study were 26 client-owned horses of both sexes, presented at the University of Bristol Equine Centre for reasons other than musculoskeletal or lameness problems. Body masses were recorded at a single weighbridge. Horses attended unshod or shod with standard steel shoes. Any horses wearing corrective shoes were excluded from the study. Subjects were evaluated by the same experienced (Diplomate-level) clinician and were determined to be clinically sound after a standard lameness examination in straight line walk and trot (Grade 0 on the AEEP lameness scale; Anonymous 2005). Any horses graded 1 or higher at walk and trot were excluded from further evaluation. Horses under the height of 1.52 m at the withers were not accepted in order to minimise the effect of size on conformation. The study was approved by the University of Bristol's (Bristol, UK) local ethical review board.

#### **Gait analysis**

Twenty spherical retro-reflective markers, 18 mm in diameter, were glued to the horse's right and left forehooves and distal forelimb joints using two-sided tape (Figure 1). Markers were placed over the estimated centre of rotation of each joint according to palpable landmarks. Markers were located on the lateral and medial aspects of the distal hoof at its widest points, and on the dorsal toe at its most distal point. Two markers were located medially and laterally on the coronet band of the hoof, at the approximate location of the coffin joint, and one marker was on the most dorsal aspect of the coronet. Markers were located on the medial and lateral aspects of the fetlock and carpal joints, at the approximate location of each joint's centre of rotation in the sagittal plane. For the fetlock, these were the origins of the collateral ligaments, and for the carpus, they were placed on the medial and lateral styloid processes of the distal antebrachium. For all trials, the markers were applied by the same individual.

The horses were then led in hand across a Kistler force platform (Model 9287, Kistler Instruments AG, Winterthur, Switzerland) for several warm-up trials prior to collecting data, until the horse appeared to be walking normally. The handler always led the horse from the left side, and passes across the force platform were always in the same direction. The horse and handler made repetitive circuits around the inside of the building, crossing the force platform without interference from the handler, aside from lining the horse up on the walkway early in each approach to the platform. The horse had approximately five walking strides in a straight line before crossing the platform. Trials that resulted in the horse avoiding the platform or without striking it cleanly near the centre with one forehoof were discarded, and data were collected until seven good trials were recorded for each forelimb.

Force data were collected at 200 Hz in combination with kinematic data from four infrared cameras (Qualisys AB, Gothenburg, Sweden) located in front of the horse on its approach to the force platform. Two cameras were positioned to the right of the walkway, and two on the left, at heights of 0.8 m and 1.8 m in order to generate 3D kinematic data with maximal resolution in the frontal plane.

An L-shaped kinematic calibration frame, with four spherical markers, was placed with its origin at the exact position of the force plate centre and with its two arms aligned with the horizontal axes of the force platform. This was recorded so that the centre of pressure of the calculated force vector under the hoof and the frontal plane force vector could be related to the kinematic markers on the limb as recorded by the cameras. The centre of pressure is a point location under the hoof calculated from the vertical forces recorded by the transducers in the four corners of the force platform, and from the moment around the origin of the force platform coordinate system caused by the overall vertical ground reaction force. In this way, the centre of pressure represents the consolidated single point location of all the smaller forces between the hoof and the platform, where the overall vertical ground reaction force vector is applied. Periodic testing of this measurement system indicated the calibration between the cameras and the force platform centre of pressure was accurate to 2 mm. The resultant force vector in the frontal plane was calculated from the recorded vertical and mediolateral forces using Pythagorean theorem. Figure 1 illustrates the marker arrangement on the limb, and also illustrates two different force vector situations. The right forelimb illustrated in the left picture has its centre of pressure centrally located under the hoof, and the force vector nearly bisects the coffin (markers 4 and 6) and fetlock (markers 7 and 8) joints, whereas the left limb in the right picture shows a force vector that is medially situated.

Following the walking trials, each of the two forehooves was photographed in their frontal and sagittal planes (Figures 2 and 3) alongside a calibration scale for subsequent calculation of vertical and horizontal distances. The calibration scale, was marked in 2 cm increments, in both the vertical and horizontal axes, to account for any distortion caused by pixellation of the digital photo. The calibration scale was carefully positioned close to the hoof and in the same plane as the intended measurements to ensure accurate calibration of linear measurements. The digital photographs were taken from a distance of approximately 5 m, and zoomed to minimise parallax error.

The photographs of the distal limbs were printed on A4 paper and lines drawn on the paper to measure medial and lateral hoof wall angles, dorsal hoof wall angle, medial and lateral hoof wall height, and medial and lateral heel height. Using the calibration scale visible in the photos, heights were calculated as vertical measurements from the floor, and hoof wall angles were the obtuse angles subtended by a line drawn along the hoof wall, and the horizontal floor as reference.

The kinematic and force data were combined in a custom computer program to overlay the calibrated limb marker positions in the frontal plane with the centre of pressure under the hoof and the frontal plane force vector (Figure 1). Alignment of the kinematic calibration with the force platform origin and axes enabled the accurate location of the force vector relative to the markers on the limb. The trial was paused at the instant of the greatest vertical ground reaction force during stance, and the distance of the ground reaction force vector from the lateral limb marker was measured and recorded as a percentage of the distance between the lateral (0%) and medial (100%) markers at each joint. The calibrated positions of the markers and the force vector in the frontal plane were quantifiable by overlaying a crosshair on the markers to determine their transverse positions, and on the force vector where it crossed the straight line between the markers. The location of the force vector along that straight line was calculated as the percentage distance from the lateral marker per joint. Six trials per limb were evaluated for the vector location at each joint. If a single trial yielded a vector location that was visibly different from the other tri

### **Statistical analysis**

All of the individual trials across all horses were examined using one-way ANOVA to evaluate whether there were differences in force vector location between each of the right and left limb joints, and to assess whether trial number was a significant factor in force vector location.

At each of the four right and left forelimb locations (toe, coffin, fetlock, carpal joints), mean and SD were calculated for the frontal position of the force vector at the instant of peak vertical force, as the relative distance (0% lateral to 100% medial) between the lateral and medial markers at each joint.

Paired *t*-tests were used to determine whether there was a difference in vector position between the right and left limbs at each location.

Pearson correlation coefficients were calculated for the association between hoof geometry measurements and force vector position at each joint in each limb, from all trials. Mean vector location per right and left limb joint was regressed against the corresponding right or left hoof measurements, for the 26 horses. Separate multiple forward stepwise linear regression analyses were then used to determine which hoof geometric measurements were associated with the position of the force vector at each joint. The variables used in the stepwise regression were those identified in the Pearson correlation as associated ( $p < 0.05$ ) with the vector location at any joint. Statistical analysis was performed using SPSS v19.0 (IBM UK Ltd., North Harbour, Portsmouth, Hampshire, UK).

## Results

Twenty-six sound horses completed a total of 349 valid trials (172 for the right and 177 for the left forelimb). Mean body mass of the horses was 514 (SD 66) kg, ranging from 400 to 669 kg. There were no differences ( $p > 0.05$ ) in vector location between right and left limbs across the four joints or any effect by trial number, indicating that the data from repeated attempts were not biased by the horse accommodating to the walking task.

Table 1 shows the mean frontal plane ground reaction force vector position per joint across all horses. The mean position, as measured from the lateral side of the joint in each case, was close to 50%, indicating that overall, the vector bisected the joint in the frontal plane, but there was considerable variability and range in the positions, which increased from distal to proximal joints.

There were small differences between the force vector positions for the right and left limbs (Table 1). Across all four joints, the vector position was slightly more medial (2–4%) for the right limb. As the right vs. left differences were not significant, the data for both limbs were pooled for subsequent correlation analysis.

Pearson correlation coefficients of the pooled data revealed several significant associations between the force vector position and the measurements of hoof geometry. Medial hoof wall angle was correlated with force vector position at the fetlock ( $r = -0.402$ ,  $p = 0.004$ ) and carpal ( $r = -0.317$ ,  $p = 0.025$ ) joints. Lateral hoof wall angle was correlated with vector position at the toe ( $r = 0.288$ ,  $p = 0.043$ ) and carpal ( $r = -0.340$ ,  $p = 0.016$ ) joint. Medial hoof wall height was correlated with vector position at the fetlock ( $r = -0.306$ ,  $p = 0.031$ ) and carpal ( $r = -0.303$ ,  $p = 0.033$ ) joints. Negative coefficients indicated that as the medial hoof wall angle increased the vector location moved



laterally. Likewise, positive coefficients indicated that as lateral hoof wall angle increased, the vector position moved medially, whereas negative coefficients indicated the vector moved laterally. There were no associations between lateral hoof wall height or the sagittal hoof measurements (dorsal hoof wall angle, dorsal hoof wall height, heel height) and the frontal plane position of the ground reaction force vector ( $p>0.05$ ).

The final stepwise multiple linear regression models identified lateral hoof wall angle as being associated with force vector position at the toe ( $p=0.043$ ), medial hoof wall angle and medial hoof wall height being associated at the fetlock joint ( $p=0.002$ ), and lateral hoof wall angle and medial hoof wall height being associated at the carpal joint ( $p=0.003$ ; Table 2).

## Discussion

The vast majority of studies evaluating hoof shape have concentrated on the dorsal hoof wall angle and toe length, as those variables are known to affect the timing of hoof breakover, and therefore tension in the flexor tendons (Wilson *et al.* 1998; Eliashar *et al.*, 2004; Wiggers *et al.* 2015). Smith and Webbon (1994) suggested that poor mediolateral hoof conformation could cause uneven joint loading and lead to poor gait quality and lameness. There are few studies documenting mediolateral hoof asymmetry, but Wilson *et al.* (2009) evaluated 'hoof spread' against other skeletal limb measurements and found bilateral variations. Mediolateral foot placement at walk and trot was found to be related to dorsal and palmar hoof angles but did not depend on other hoof conformational measurements that did not include medial and lateral hoof wall angles (Wilson *et al.* 2014).

The results of this study indicate an association between hoof geometric measurements and the position of the frontal plane ground reaction force vector, with the stepwise regression showing medial hoof wall angle and medial hoof wall height as predictors of vector position. The models suggested a relationship between vector position and hoof shape for the fetlock and carpal joints, but these joints were also the most variable in terms of vector position (Table 1). The negative Pearson coefficients for medial hoof wall angle and height mean that as medial hoof wall angle and medial hoof wall height increase, the vector position moves laterally, which makes intuitive sense and agrees with *in vitro* wedge studies (Viitanen *et al.* 2003). The findings are less clear for lateral hoof wall angle, as the negative Pearson coefficient likewise indicates that as lateral hoof wall angle increases, the vector position moves laterally at the joints, which does not make intuitive sense. On the other hand, the positive association between lateral hoof wall angle and position of the ground reaction force vector at the toe does make sense, and these inconsistencies suggest an interrelationship between variables that is not apparent from the statistical models.

There are two ways for the vector position to change at the joints proximal to the hoof. One is for the vector's origin (the centre of pressure under the hoof) to move medially or laterally, and the other is for the angle of the vector in the frontal plane to change, irrespective of the location of the centre of pressure. At the level of the toe markers, or sole of the hoof, the vector can only change its location at the centre of pressure; there is no angle of the vector at the hoof-ground interface.

Medial or lateral hoof wall height is likely to be a factor in where the horse places its hoof in the frontal plane, and therefore in the direction and amplitude of the mediolateral ground reaction force, which affects the orientation of the vector in the frontal plane. Wilson *et al.* (1998) reported that horses could adapt reasonably easily to a lateral wedge by placing the hoof more laterally, but that there was limited scope for the horse to place its hoof more medially in response to a medial wedge. The negative coefficients in our results indicate that increasing medial hoof wall height was associated with a lateral shift in the frontal vector at the fetlock and carpus. This suggests that the horse did have some ability to adjust its foot position according to the medial hoof wall height, and that the resulting accommodation resulted in a change in vector angle, evident from the significant coefficients at the fetlock and carpal joints. The effect of a change in vector angle, combined with a small change to the centre of pressure, would be amplified as the vector proceeds up the limb, with small changes in angle having a larger effect on position at the proximal joints. Coupled to a change in mediolateral hoof placement would be a concomitant change in the frontal plane angle of the limb, which would then impact on the direction and amplitude of the frontal plane ground reaction force.

Medial and lateral hoof wall angles were less consistent in their relationships. Hoof wall angle might be associated with a larger transverse sole dimension, so changing the value of the transverse location of the centre of pressure under the hoof without necessarily changing its location relative to the superincumbent limb joints.

The shape of the hoof can vary in a number of ways, and it is puzzling that none of the geometric hoof measurements were related to vector position at the coffin joint. There is potential for the medial and lateral hoof wall angles to vary independently, and for hoof wall heights to vary independent of wall angle. The transverse position of the frontal centre of the coffin joint relative to the sole can therefore vary substantially, but there is probably less potential for malalignment of the superincumbent joints relative to the coronet. The lack of significant associations at the coffin joint likely relates to this variability in relation to the independent hoof wall angle and height measurements.

Carpal geometry might be expected to play a role in how the foot is placed, with those horses with valgus carpal joints placing their hoof more laterally at walk, which would then affect the ground reaction force angle independent of hoof shape, although hoof shape might well be affected by the carpal angle in the frontal plane. Anecdotally, in some of the trials for a few horses the ground reaction force vector passed lateral to the lateral marker at the carpus, despite the trial appearing outwardly normal. These trials were considered outliers because their vector location was visibly different from the other trials for that limb, and were not included in the analysis. Future work should probably evaluate such variables as standing width, carpal conformation and the frontal plane moments of force to determine the local effects when the force vector is suboptimal in its position at the carpus.

Random variation was probably introduced by small differences in walking velocity from trial to trial, and velocity does affect the placement of the hoof in the frontal plane. However, the inclusion of trial as a factor in the analysis indicated that small differences in velocity did not affect the results. The handler attempted to maintain a consistent velocity per horse, in an attempt to minimise the impact of this variable on the data. The vertical ground reaction force traces from walking horses typically have two loading peaks, with the second having the larger amplitude as the trunk comes forward over the stance forelimb (Weishaupt *et al.* 2010). Horses walking more slowly tend to have a flatter force profile, with a less discernible peak during late stance. The vector locations were determined at a single point in the stance phase, at the time of peak vertical force, and so the time of this peak will vary according to velocity. Future work might take into account the trajectory of the centre of pressure and the path of the force vector through the joints through the entire stance phase. A local force concentration might only be deleterious at times of peak ground reaction force, but migration of the vector to the extremes of a joint's articular surface for any length of time during stance might well result in local degradation.

That there were no significant associations between the force positional variables in the frontal plane and heel height, dorsal coronet height, or dorsal hoof wall angle indicates that while these geometric conformational variables might affect the position of the centre of pressure in the sagittal plane, they had no effect on the frontal plane position of the force vector.

This study has provided evidence for the importance of hoof geometry on the path of the frontal plane force vector through the forelimb joints at walk. There was substantial mediolateral range in the vector locations at all joints between horses. Medial hoof wall height and medial and lateral hoof wall angles were shown to be associated with the position of the frontal plane ground reaction force vector, especially at the fetlock and carpal joints. A force vector that passes medial or lateral

to the anatomic centre of a joint will exert a larger compressive force between the condyles of the loaded side and a moment around the joint centre in the frontal plane, and there is potential for this to result in local degradative changes to the joint. Further work is needed in horses moving at racing speeds to determine the impact of hoof geometry in the presence of substantially larger ground reaction forces.

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**Table 1. Mean ( $\pm$ SD) position (%) of the frontal plane ground reaction force vector at the toe, coffin, fetlock and carpal joints of right and left forelimbs of 26 horses, and both limbs combined. Vector position was calculated as the relative distance between the lateral (0%) and medial (100%) markers at each joint.**

Joint	Limb		P-value <sup>a</sup>	Combined	Min, max
	Left	Right			
Toe	49.1 $\pm$ 9.4	51.2 $\pm$ 8.5	0.383	50.1 $\pm$ 8.9	35, 75
Coffin	51.3 $\pm$ 8.6	55.4 $\pm$ 8.9	0.053	53.0 $\pm$ 9.2	31, 73
Fetlock	53.3 $\pm$ 10.6	55.9 $\pm$ 11.0	0.276	54.6 $\pm$ 11.4	28, 81
Carpus	48.5 $\pm$ 13.9	52.5 $\pm$ 19.5	0.31	50.5 $\pm$ 17.3	20, 87

<sup>a</sup> Significance of *t*-test comparing right and left limbs

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**Table 2. Results from final stepwise multiple linear regression models showing the hoof geometric measurements that were associated with frontal plane force vector position at the toe, fetlock and carpal joints of the forelimbs of 26 horses.**

Joint	Hoof measurement	Partial regression co-efficient ( $\beta$ )	Model R <sup>2</sup>	P-value <sup>a</sup>
Toe	Lateral hoof wall angle	0.494	0.083	0.043
Fetlock	Medial hoof wall angle	-0.769	0.237	0.002
	Medial hoof wall height	-0.323		
Carpus	Lateral hoof wall angle	-1.060	0.217	0.003
	Medial hoof wall height	-0.569		

<sup>a</sup> Significance of *F*-test

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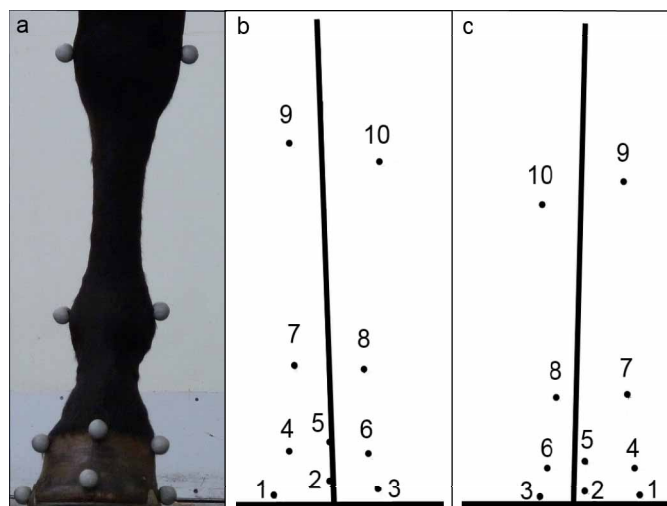


**Figure 1. (a) Photograph of the marker locations on the forelimb of a horse used to determine frontal plane ground reaction force vectors, and images illustrating vectors on frontal views of (b) the right and (c) left limbs at the time of maximal vertical force. The numbered dots are the centroids of the individual markers on the toe (1, 2, 3), coronet (4, 5, 6), fetlock (7, 8) and carpal (9, 10) joints. Markers 1, 4, 7 and 9 are on the lateral sides of the limb. The off-vertical line bisecting the markers is the frontal plane ground reaction force vector originating at the centre of pressure under the hoof.**

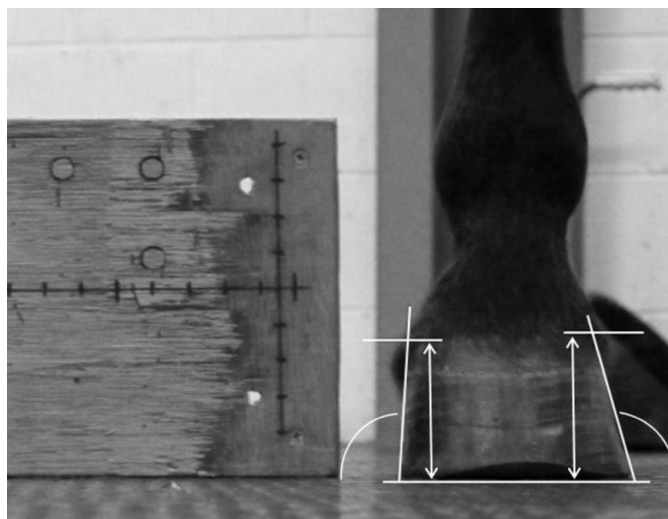
**Figure 2. Photograph of the frontal view of a hoof showing typical measurements of lateral and medial hoof wall angles (curved white lines), and lateral and medial hoof wall heights (white arrows), with a calibration scale marked in 2 cm increments.**

**Figure 3. Photograph of the lateral view of a hoof showing typical measurements of dorsal hoof wall angle (curved white line), and heel height (white arrow), with a calibration scale marked in 2 cm increments.**

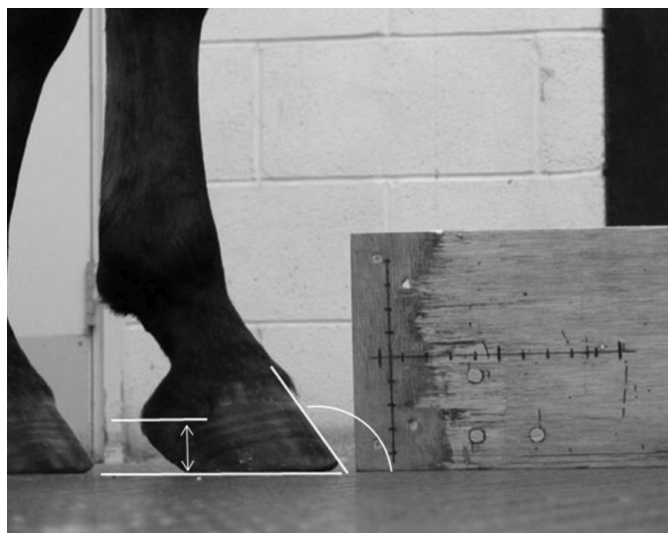
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