Locating Rotation Centers of the Equine Digit and their Use in Quantifying Conformation

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A method for locating the biomechanical center of rotation of the coffin joint from radiographs is shown to be accurate by direct experimental measurement. Using the locations of the center of articulation of the coffin and pastern joints, a well-defined method for measuring the angular alignment of the major bones of the equine digit is proposed. Examples of using this method are presened.

Introduction

Equine practitioners are regularly asked to assess foot conformation. The process is subjective and largely based on the individual's previous experience with similarly conformed animals. No quantitative assessment is regularly made of the hoof capsule or the boney column within it. A recently introduced technique[1] offers a standardized method by which exact measurements can be quickly made of both anatomical components using radiographs and photographs. These images are then recorded to a database for comparison to other horses and for future reference as changes are made to the individual patient. This offers practitioners a well-defined and consistent way to communicate concerning the conformation for the equine digit.

A central method used in our analysis of the latero-medial radiograph is the fitting of a circle to the distal ends of the first two phalanges, P1 and P2, and taking the center of those circles to represent the center of articulation (COA) of the corresponding joint. This paper reports on experiments performed to validate this assumption. We compare the experimentally located center of articulation of the coffin joint with the location as would be found in our method of picking points on an image of a latero-medial radiograph.

We propose an important use for the centers of articulation of the coffin and pastern joints: these points are central to establishing a well-defined way to measure the angulations of the bones in the equine digit. Such a technique offers a reliable way for practitioners to communicate regarding conformation of the equine digit.

Materials and Methods

Two cadaver forelimbs, both from young Arabian horses, were used in the experimental portion of this work. The limbs were cut just below the carpus and were in good physical condition with no pre-existing damaged anatomical structures noted. Skin and other superficial tissues were removed to allow two sites on each of the major bones to be viewed from the lateral side. Care was taken to ensure the integrity of the joints and all connective ligaments and other tissues. In the phylangeal and third metacarpal bones (P3, P2, P1, and Canon) two small metal markers were set – one near the distal end, and one near the proximal end. These markers were visible in digital photographs taken from a lateral viewpoint, and also visible in latero-medial radiographs taken of the legs.

The legs were placed in a press that was used to apply loading from above. The press, along with a variety of wedge pads placed under the toe and alternately the heel, allowed the limb to take on a variety of articulated configurations. The goal was to make the joints move throughout 'normal ranges' of a horse in motion. The range of motion experienced by the three joints in our experiment was approximately: 50 degrees for the coffin joint, 7 degrees for the pastern joint, and 60 degrees for the fetlock joint. These ranges of motion correspond well with other published studies[2] on the normal ranges of motion for these joints for a horse trotting at 4 meters per second.

For each limb, approximately 40 digital photographic images were taken, each with the limb in a slightly different configuration, due to articulations of the coffin, pastern, and fetlock joints. Additionally, two latero-medial radiographs were taken of each leg: one in a "standing" configuration, and one in a "loaded" configuration.

The Metron equine hoof conformation software system[a] was used to make all of the measurements in the photographs and radiographs. This system makes use of scale markers and can compensate for the magnification inherent in radiographs[1], hence we were able to correlate measurements in the photographs to those made in the radiographs.

The two markers set in P2 were used to define a reference coordinate system. The distal marker locates the origin of this system, and the proximal marker indicates the pointing direction of the x-axis. The y-axis is then defined as being orthogonal to the x-axis. In each image, we measure the coordinates of the distal marker on P3 and the proximal marker on P1 in terms of this coordinate system affixed to P2. As the coffin and pastern joints articulate, these marker points on P1 and P3 move relative to the reference coordinate system on P2. Likewise, we used the two markers on the Canon bone to define a reference coordinate system, and then measured the location of the distal marker on P1 in all images in terms of this reference system. In this way, as the fetlock joint moves, this point moves relative to the Canon reference system.

By taking high resolution digital images (1600x1200 pixels) and by careful picking of the points the images, we believe we achieved very good accuracy in the location of the marker points. For the numerical optimizations described in the following section, Powell's conjugate gradient method[3] algorithm was used. The objective function to minimize was the root-mean-square (RMS) error between the data points and a proposed circular fit.

The Computational Procedure Used

We first used the Metron system on the radiographs to fit circles to the distal ends of P1 and P2 as done in normal use of this system. Following the method used in Metron[a] (as more fully described in an earlier paper[1]) we picked points on the radiographs so as to locate proposed centers of articulation for the coffin and pastern joints as shown in Figure 1. Picking any three points which lie on the distal end of P2 uniquely define a circle. Likewise, three points picked at the distal end of P1 uniquely define a circle at that joint. We have reported elsewhere[1] on the accuracy achievable when different practitioners perform this picking.

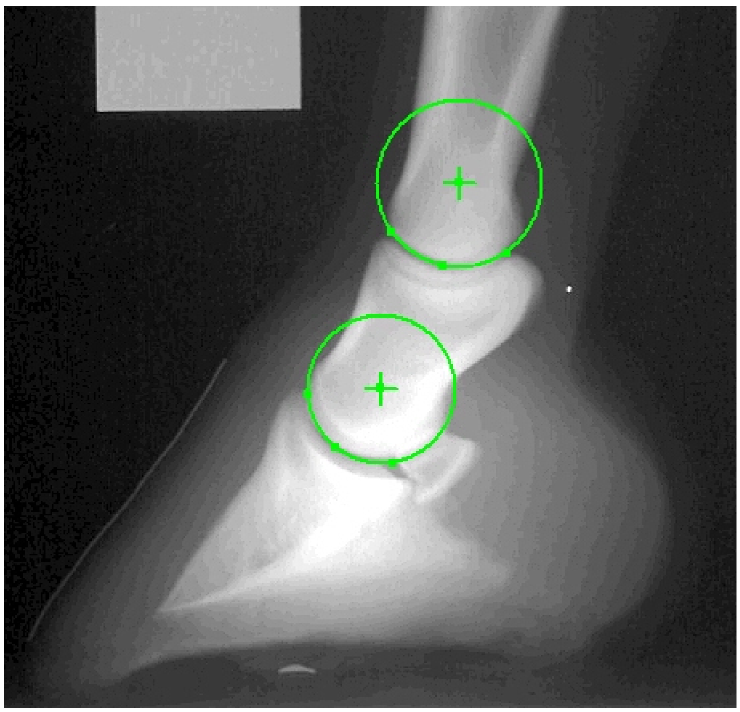

Figure 1. Method used in Metron to establish circles at the distal ends of P1 and P2.

We also used the two metal markers in P2 to establish a reference system affixed to P2 in the radiograph. The centers of the circles computed by Metron were recorded as an (x,y) coordinate pair in this reference system. We hope to show that by the simple circle-fitting method used in Metron, a reasonable value for the location of the Center of Articulation (COA) is found.

We plotted the location of the COA found from the radiograph on one of the photographs of the leg. This was possible using the same markers to define the reference system affixed to P2. We then plotted all of the data points corresponding to the location of the marker at the distal end of P3 overlaying them all on the same image. These images are shown in figures 2a and 2b.

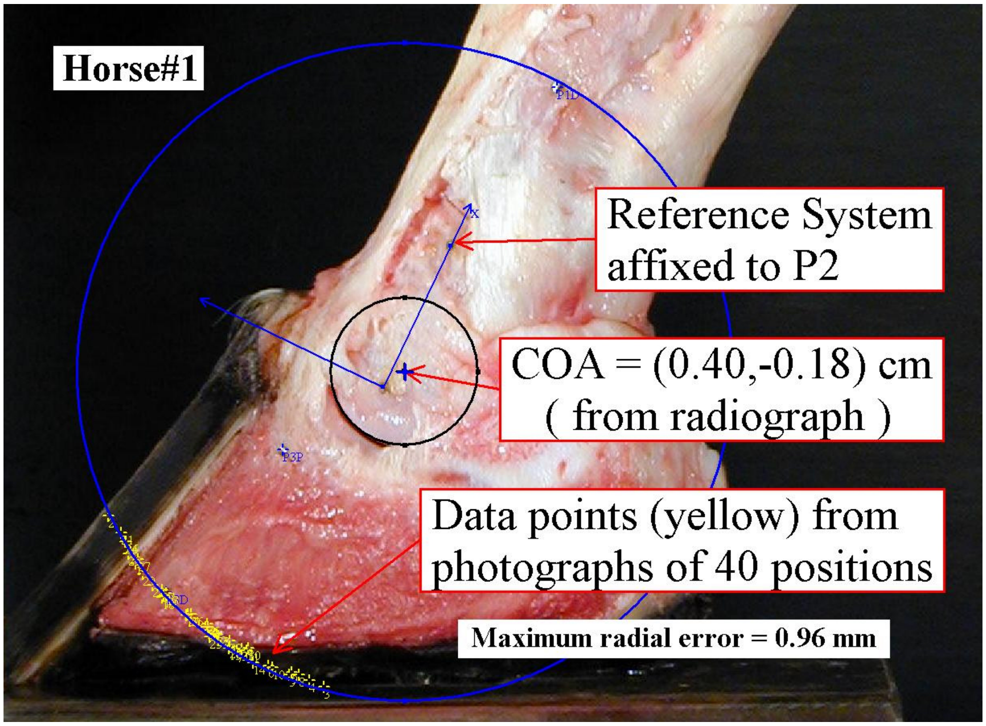

Figure 2a. Data points generated by rotating the coffin joint appear to lie on a circle centered on the Center Of Articulation (COA) found from a simple circular fit to the distal end of P2 in the corresponding radiograph.

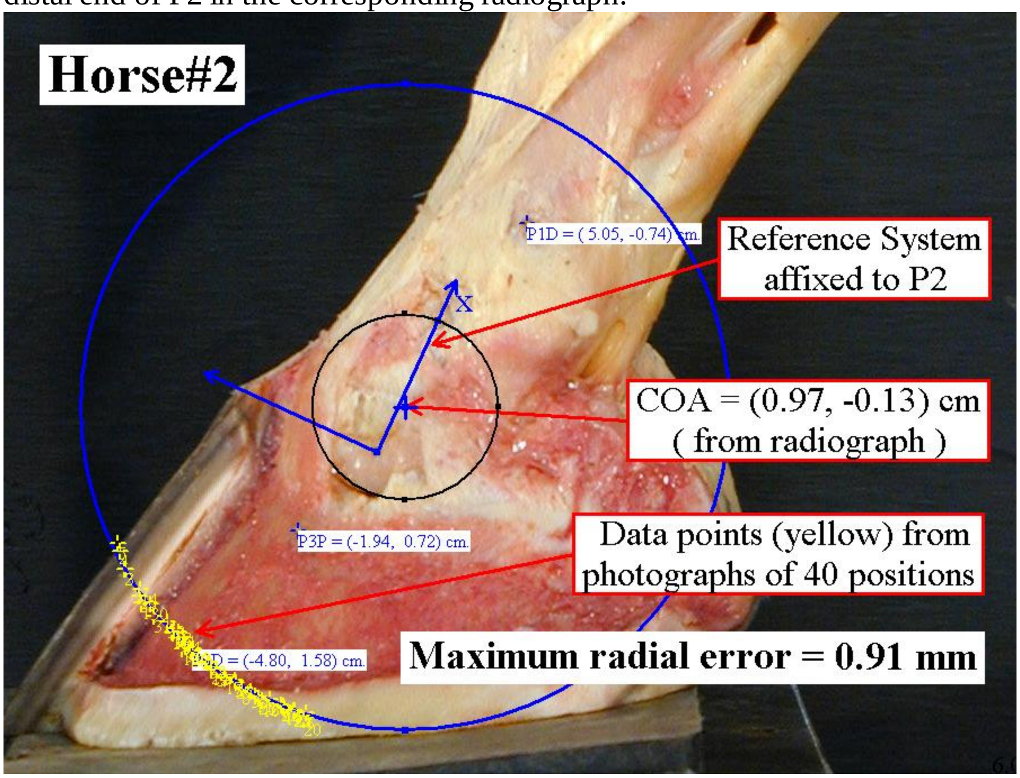

Figure 2b. Data points generated by rotating the coffin joint appear to lie on a circle centered on the Center Of Articulation (COA) found from a simple circular fit to the distal end of P2 in the corresponding radiograph.

A numerical optimization was performed to determine the radius of a circle which would optimally fit the points representing the distal marker of P3 as measured in the reference system attached to P2. The criteria used was to find a radius for which the root-mean-square (RMS) error is minimized. The result of this optimization are the blue circles shown in figures 2a and 2b. The value of radius found is not important because it is an arbitrary distance depending on where we placed the distal marker on P3. What *is* important is the 'residual error' value – that is, how well the data points lie on the circle.

Results

Shown in figures 2a and 2b, the fit to a circle looks reasonable to the eye. Indeed, the RMS error for horse#1 was 0.43 mm, and for horse#2 was 0.42 mm. The *worst case* point for each horse is still within 1 mm of the circle. Worst case points may come from the extreme points measured – when the leg is flexed or extended to an extreme position, some eccentricities of the joint may begin to appear. Stated another way, for both horses studied, the maximum radial error (relative to a perfect circular fit) was less than 1.5% of the radius. We feel our results show that over the 'normal functional range' of the coffin joint, the articulation can be modeled as a simple hinge joint, operating about a well-defined center of articulation. A similarly good fit to a circle was obtained at the fetlock joints.

A challenge in this procedure is that we are fitting a circle to data points which lie over only a fraction of a circle. In the case of the coffin and fetlock joints, having data representing a 50 degree arc is sufficient for a good result – however, we found that it was not possible to obtain reasonable results for the pastern joint for which the data lay on an arc of only 7 degrees. Fitting a higher-order curve (such as an ellipse) to the data would make matters worse, and since we found a good fit to the circle, we did not attempt fitting to higher order geometries. An attempt to gather data over a larger arc of the circle by forcing the joints to move over a greater distance would begin to compromise the joint capsules and ligamentous structures, and in any case would not result in data valid for the normal operating ranges of these joints.

For more insight into the meaning of our circle-fitting results, we implemented a search for a center of articulation that would fit the data more precisely than the proposed location from the radiographs. To do this, we implemented a numerical optimization which searched in x, y, and circle radius. The result was that the residual error was only slightly improved as compared to our proposed COA locations. For horse#1, the residual error reduced from 0.96 mm to 0.74 mm, and for horse#2 the error reduced from 0.91 mm to 0.88 mm. The 'optimal' COA was about 2 mm away from the radiograph COA for horse#1, and about 3 mm away for horse#2. Consideration of the suitability of the available data to accurately locate these centers was considered, and this led us to plot the residual error (using a color coded display) as a function of proposed center of articulation, as shown in figures 3a and 3b.

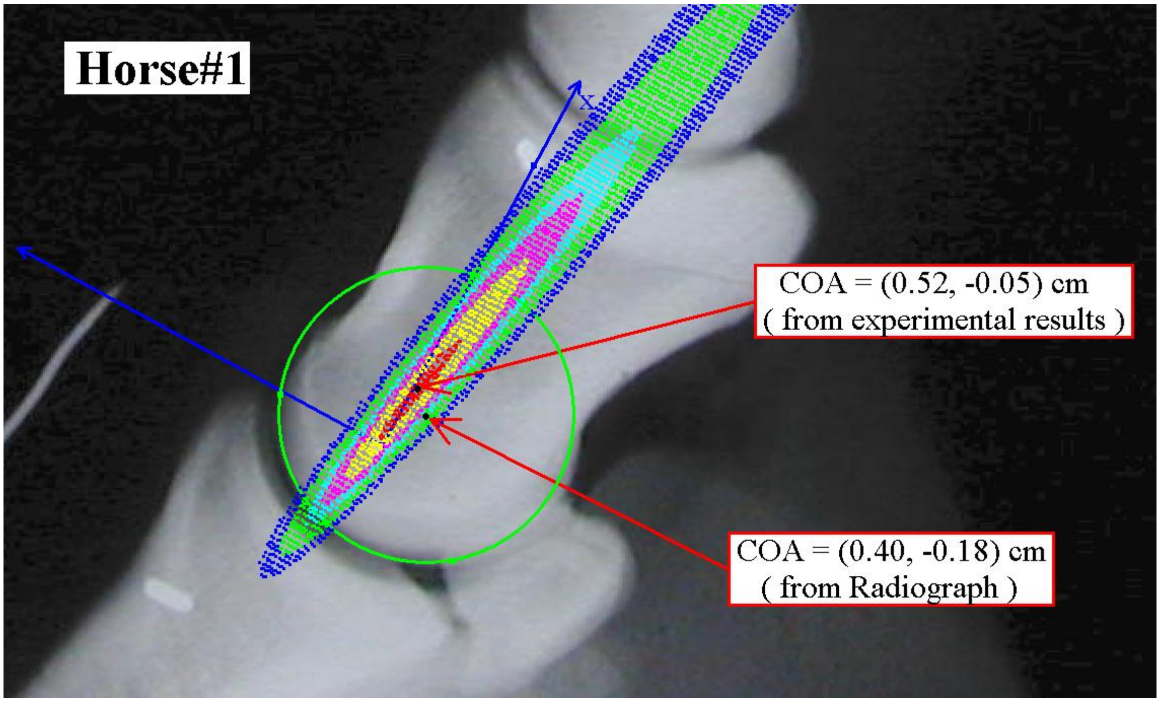

Figure 3a. The colors encode the residual error after circle fitting, showing the most likely location of the COA to be in the red zone, next best is yellow, next best is cyan, and so forth. The shape of the curves is due to the fact that we are fitting a circle to 50 degree sector of data located near the toe of the foot.

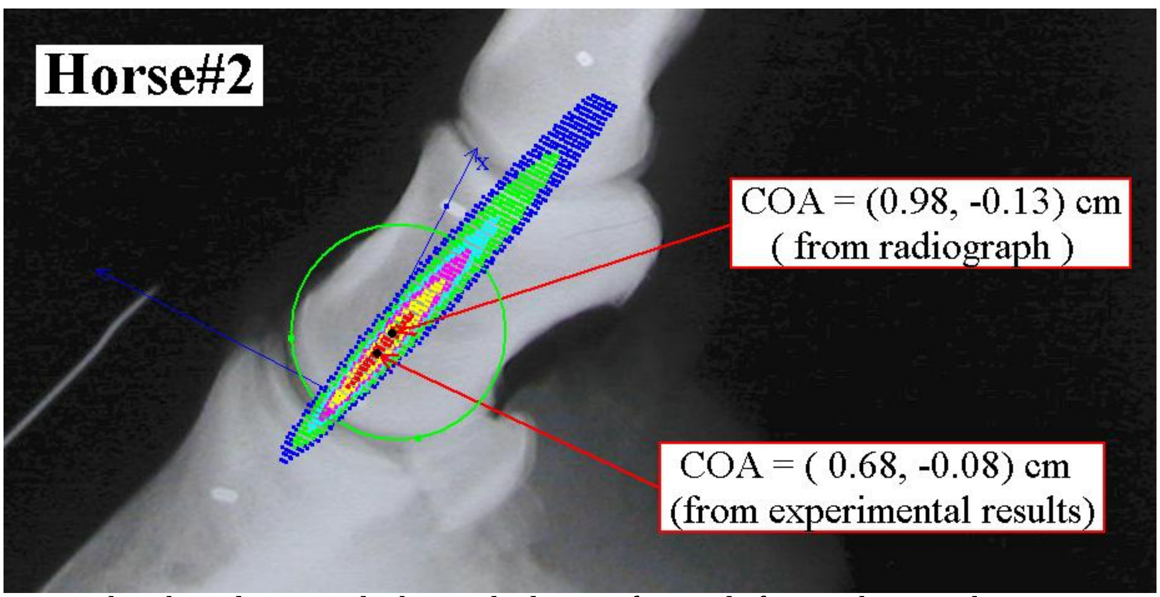

Figure 3b. The colors encode the residual error after circle fitting, showing the most likely location of the COA to be in the red zone, next best is yellow, next best is cyan, and so forth. The shape of the curves is due to the fact that we are fitting a circle to 50 degree sector of data located near the toe of the foot.

Figures 3a and 3b illustrate that while the location of the center of articulation can be computed accurately in one direction (roughly aligned with the Y axis of the P2 reference system) it is difficult to accurately compute the location in the other direction. This is because data was obtained only along a 50 degree arc of the circle. However, it does appear that the center of articulation found from the radiographic method falls within a very likely region. Such a plot for the location of the pastern joint's COA would show that there is a large uncertain zone, because those points were taken over an arc of only about 7 degrees. Although not shown in this paper, good fits were also found for the COA for the fetlock joint.

Discussion

While our experiment was unable to confirm a precise location of the COA for the pastern joint, we feel the bone morphology, quite similar to that of the coffin joint, suggests that the radiographic circle-fitting technique yields a reasonable location for the pastern joint's center of articulation.

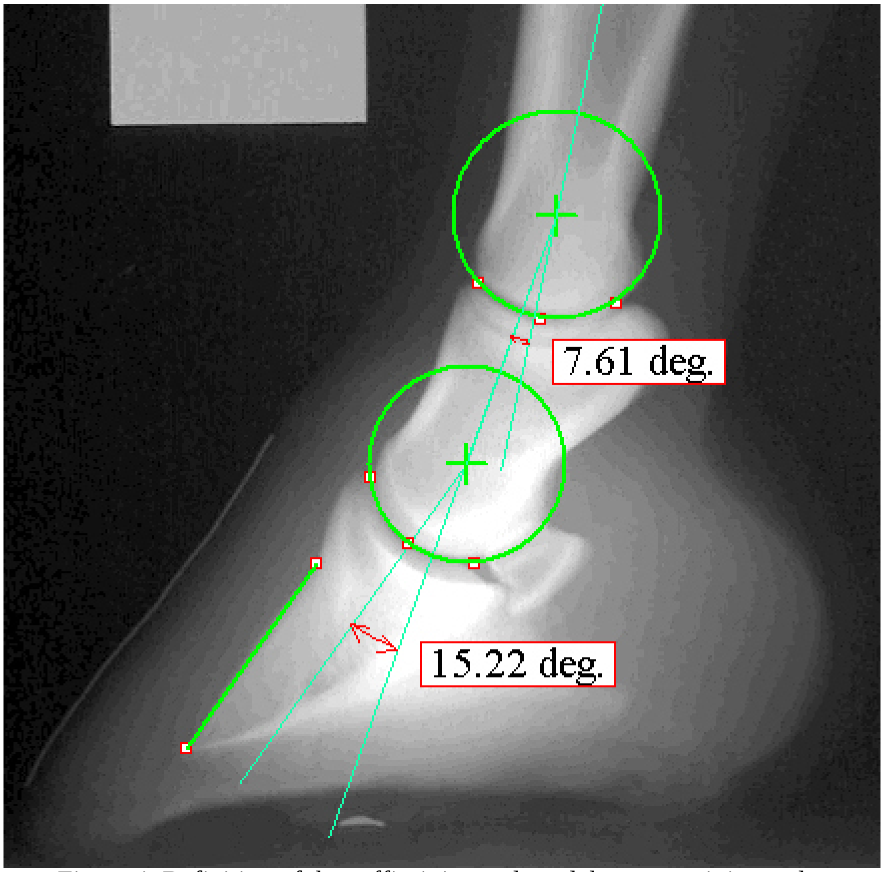

Figure 4: Definition of the coffin-joint angle and the pastern-joint angle.

Note that the biomechanical motion of the limb involves rotations at these two centers as well as others found in the proximal direction up the limb (e.g., at the fetlock joint, at the carpus, etc). The notion of "center of articulation of the foot" that is sometimes mentioned is hence not well defined, as the foot articulates due to several rotation centers. Only with a gross simplification can we speak of a single "center of articulation" for the foot. One such simplification apparently sometimes used, is to assume no motion at the pastern joint (or the other more proximal joints), and refer the center of rotation of the coffin joint as the "center of articulation" of the foot.

We may now define a precise way to measure the rotational position of the coffin and pastern joints as seen in lateral radiographs. In figure 4 we show these joint-angle values. To quantify the coffin-joint angle, construct a line from the rotation center associated with the coffin joint extending down towards the sole and parallel to a reference orientation defined on the dorsal aspect of P3. The value of the coffin-joint angle is the geometric angle formed between this constructed line, and the line defined by connecting the two rotation centers. In the example shown in figure 4, this value is 15.22 degrees. The positive sense is defined such that a positive rotation of the coffin-joint makes the major axis of P2 become more upright in the image.

To quantify the pastern-joint angle, construct a line that connects the two rotation centers. The value of the pastern-joint angle is the geometric angle formed between this constructed line and the line representing the 'centerline of P1'. In the example of figure 4, this value is 7.61 degrees. The positive sense is defined such that a positive rotation of the pastern-joint makes the axis of P1 become more upright in the image.

Examples of Use

Regarding the coffin and pastern joint angles as measured in figure 4, there is an oft-quoted "rule of thumb" that these angles should be near zero for good bone alignment[4]. Using the method of measuring developed in this paper provides a way to study a population of horses and see if these angles are typically near zero. We measured the lateral radiographs of 151 hooves from a mixed population of horses in California and found that the average coffin-joint angle is 8.27 degrees (with a standard deviation of 9.04 degrees), and the average pastern-joint angle is 5.78 degrees (with a standard deviation of 5.18 degrees). The population was mixed; mostly sound horses, but some partially lame as well. The population contained horses maintained by various farriers employing varyious shoeing techniques. We attempted to be very non-selective in choosing the horses in the study, simply using all the radiographic images we had available at the time.

These numeric results mean that the bones to not align in a straight line, but are slightly more 'upright' than that. Of course, this data is dependent on how the horse was stood during radiography, shoeing details, and other influences. Generally we tried to have both feet on equal height blocks and stand the horse with the cannon bone vertical. It is our opinion that our study is representative, and that a similar study on any group of horses would show that the "perfect alignment" of the bones so often shown in farrier publications is not reflective of how horses are conformed.

Figures 5 and 6 show the data from our study, with the "zero" degree (aligned) position marked with a heavy line, and the average marked with a dashed line.

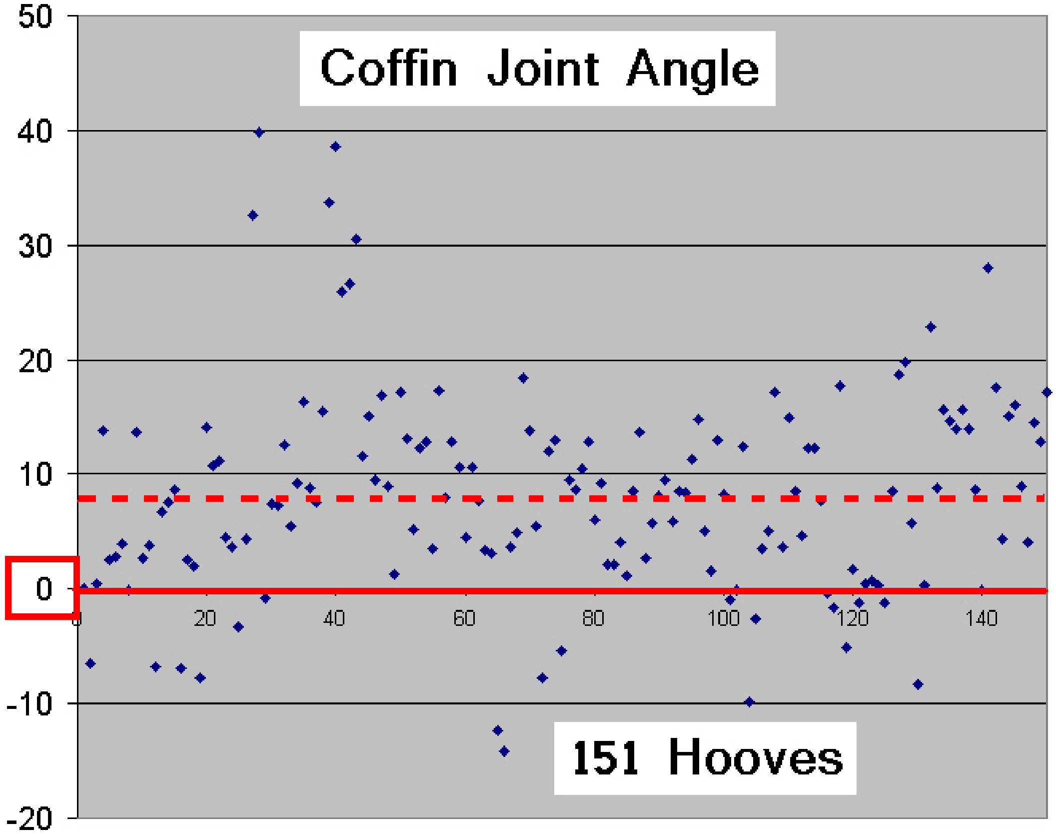

Figure 5 The average coffin-joint angle was 8.27 degrees (dashed line) with a standard deviation of 9.04 degrees.

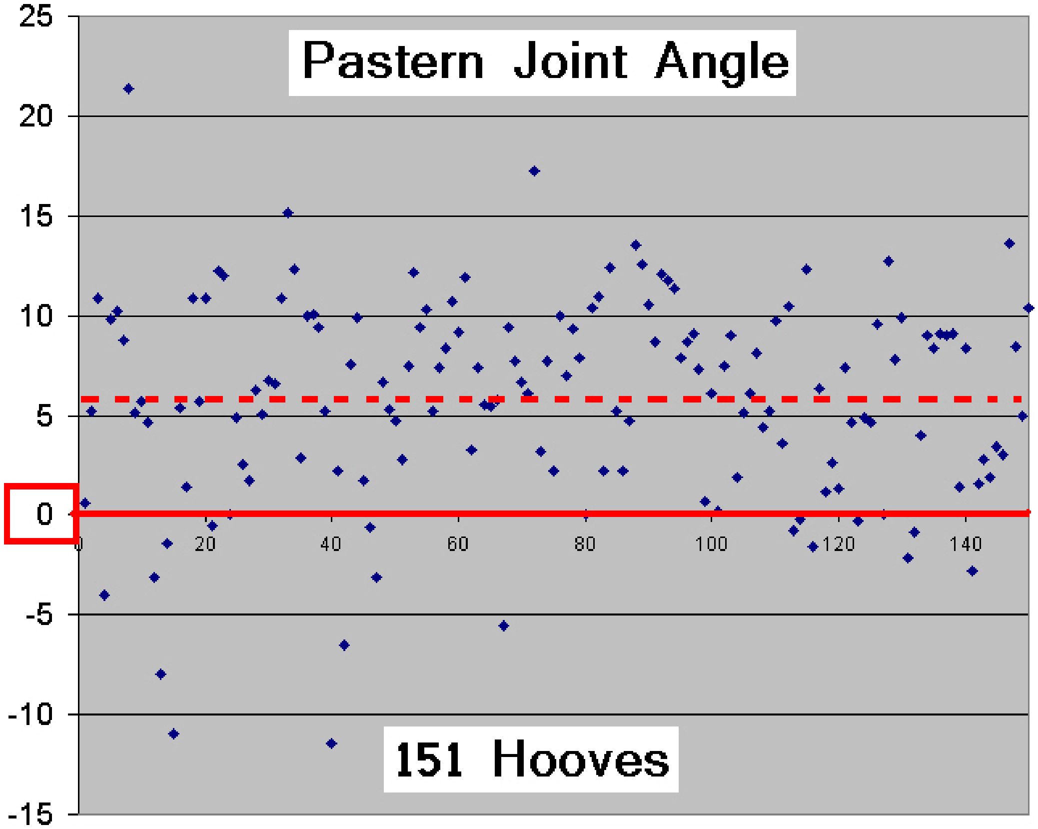

Figure 6 The average pastern-joint angle was 5.78 degrees (dashed line) with a standard deviation of 5.18 degrees.

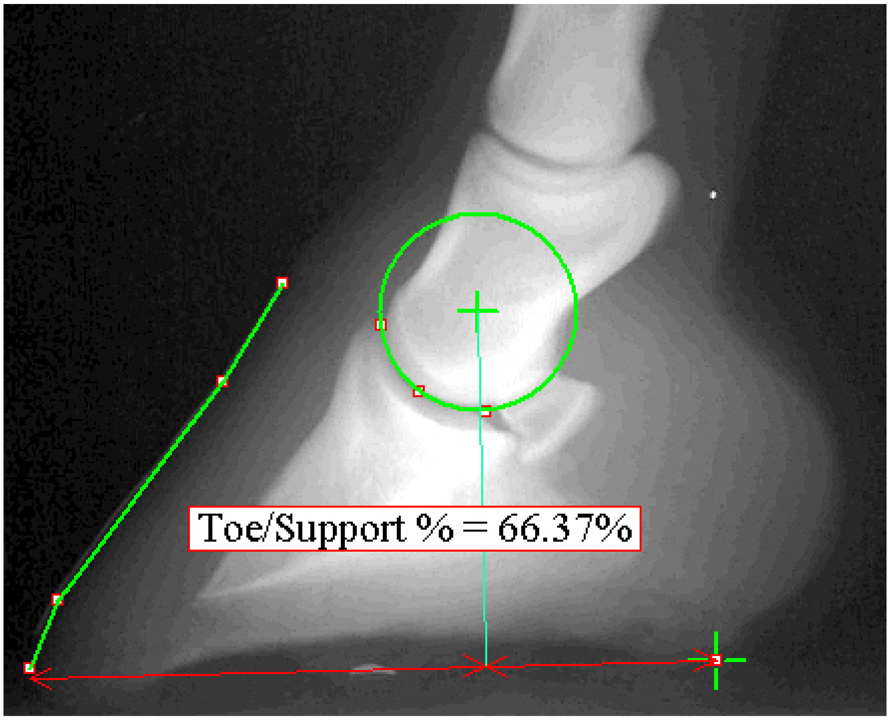

Figure 7 The "Toe/Support %" measures the percentage of the foot's support that is "ahead of" the coffin-joints center of articulation (COA).

In another study, we looked at the position of the center of articulation of the coffin-joint with regard to the support length of the foot. As shown in figure 7, dropping a perpendicular line down from the coffin-joint's COA, we computed the distance from this point to the toe as a percent of the length from toe to heel at the ground level. A recent publication[5] (among others) suggests that this percentage be 50%, but the data in our study do not support this, with the average found for 131 hooves as 67.06 degrees with a standard deviation of 5.41 degrees. For example, the digit shown in figure 7 would be very close to "normal" in our study. The population was the same as for the data in figures 5 & 6 (although some had to be removed due to inability to see needed features in some radiographs). Figure 8 shows the data, with the average shown as a dashed line.

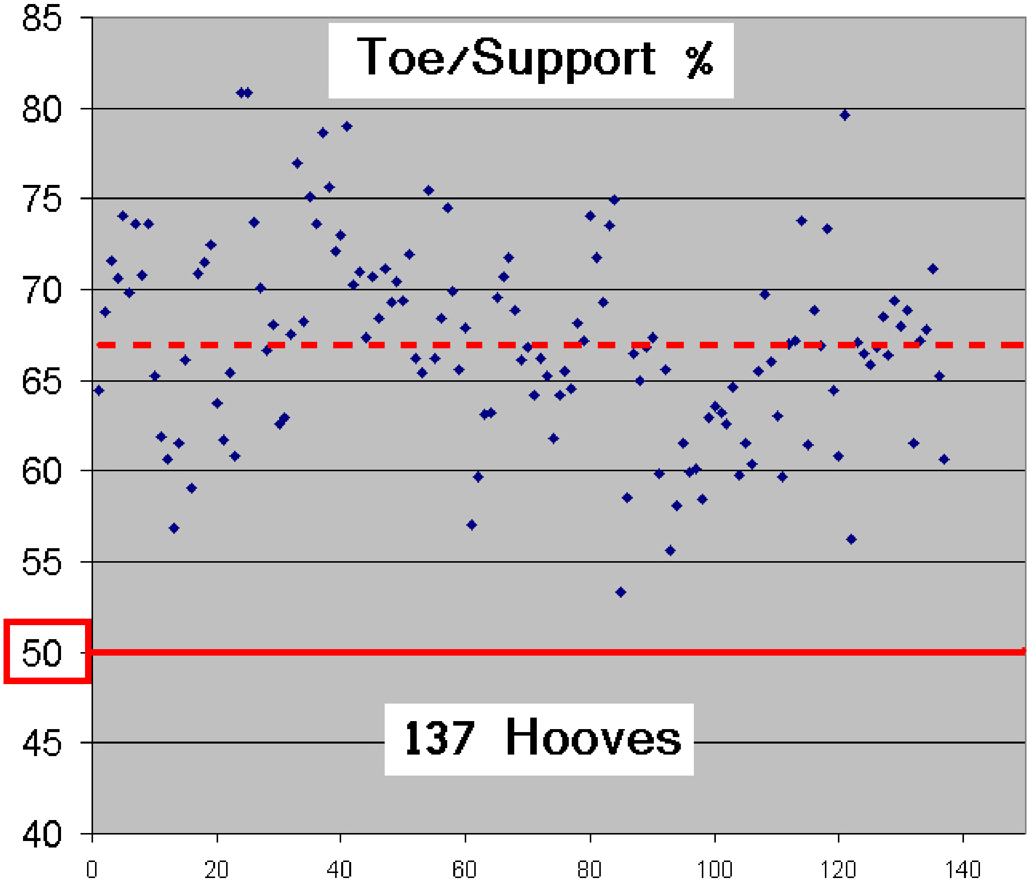

Figure 8 The "Toe/Support %" is the percentage of the ground support line that is forward of the coffin-joints center of articulation as viewed in a lateral radiograph.

Conclusion

Fitting circles to the distal ends of P1 and P2 in radiographic images provides a good way to locate the centers of articulation for these joints. Using the located points allows a well-defined way of measuring the angulation of the bone column, and other aspects of conformation[1]. Following such a methodology would help give meaning to oft-used but poorly defined terms such as 'broken-back pastern', 'sloping pastern', 'aligned phalanges', etc. We presented some examples of the use of such a measurement system in quantifying aspects of the bone alignment and location within the hoof capsule which are regularly discussed in the veterinary and farriery literature.

References and Footnotes

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5. Williams, G, and Deacon, M. *No Hoof, No Horse*, The Kenilworth Press Ltd, 1999, Figure 3.1

[a]Metron, EponaTech, P.O. Box 361, Creston, CA 93432, USA. www.eponatech.com

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