Calibration for Radiography of the Equine Hoof

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Introduction

We discuss the general issues involved in calibration in order to make accurate physical measurements in radiographic images. We do this with a focus on images of the equine hoof and discuss best practices for taking radiographs of the hoof that support accurate measurements [Craig, M].

Concepts and Definitions

An ***x-ray generator*** emits radiation from a very small spot inside the apparatus. The radiation spreads out in a diverging pattern from this ***point source***. A ***collimator*** at the front end of the generator blocks most of the radiation, so that only a pyramid shaped volume is bathed in radiation. The ***central generator beam*** is the pointing direction of the generator and defines the center of the pyramid of radiation coming out of the device. When we talk about positioning the x-ray source, we are generally talking about pointing this ***central generator beam*** in some particular direction. In the old days film was used, but these days an electronic detector, sometimes called the ***detector panel***, or simply the ***panel***, receives the radiation and forms an image of whatever object was placed between it and the generator. We will often find it helpful to imagine a ***plane of interest*** which passes through the object that we are imaging. This article is about how to ***calibrate*** so that we can make accurate physical length measurements which we will understand to be in this ***plane of interest***. Due to the diverging nature of the radiation, it turns out that the distance between the panel and the plane of interest (sometimes called ***OFD*** for **O**bject **F**ilm **D**istance) affects the calibration process. Also, the distance from the generator's point source and the panel (sometimes called the ***FFD*** for **F**ilm **F**ocal **D**istance, or ***SID*** for **S**ource **I**mage **D**istance) affects the calibration (figure 1.)

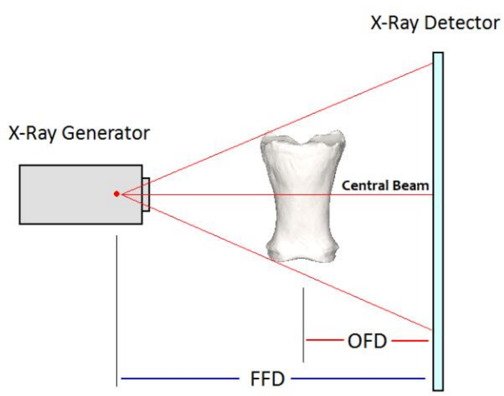

Figure 1: The basic geometry of radiographic imaging. It is apparent that the image will be a larger, or magnified, version of the object being imaged.

Keep it Simple

In most practical uses of radiographic imaging, the geometry of the physical positioning of the x-ray generator, the object to be radiographed, and the detector panel are controlled to keep things simple. Namely, we generally restrict ourselves to situations in which the central beam is perpendicular to both the detector panel and the plane of interest. In this article we will generally assume that this simple setup is adhered to – although in one case study we will consider the errors introduced when misalignment from this ideal occurs. We will focus on radiographs of the equine hoof, although nearly everything we will discuss applies to radiographic calibration for any anatomical view of any animal.

In intraoral dental radiography, the constraints of the mouth usually make this simple setup impossible, so other techniques are brought to bear to align images and to interpret them – but this is beyond the scope of this paper.

Scale Marker

In the case of radiography, a scale marker is generally something metal (nearly radio-opaque) that is of known size and is placed in the image, often on the subject being imaged, in order to be able to calibrate the image so accurate measurements can be made. The use of a scale marker is generally the easiest and most accurate way to achieve calibration, but it's not the only way – it is possible to calibrate without a scale marker, but it is more tedious – one has to take careful measurements of the physical distances involved in the setup, namely the OFD and the FFD, and then perform a simple calculation [Franken]. Intuitively, if you place a scale marker of known size right next to the thing you wish to accurately measure, it will allow a good measurement -- but let's look at a few details.

The Two-Ball Scale Marker

A good way to calibrate radiographs is with a ***two-ball scale marker***. This is a simple device consisting of two metal spheres whose centers are a known distance apart (generally 5 to 10 cm). Properly used, it must be placed so that both balls lie in the plane of interest, and the generator central beam is directed perpendicular to the plane of interest.

Figure 2: A two-ball scale marker. Left: photograph; Right: radiograph.

In an attempt to ease the required geometrical setup, some have suggested the use of a single metal sphere to set the calibration [Schropp et al]. With a single sphere it is guaranteed that a plane exists that is both perpendicular to the central generator beam and which contains the ball center (you might have to think about this statement to fully understand it).

Figure 3: A one-ball scale marker (on a flexible positioner)

There are 3 reasons why we argue that **the two-ball scale marker is superior**:

1) To increase accuracy that may be limited by the pixilation of the image, a scale marker should not be too small – otherwise the size of pixels limits accuracy of measuring the scale marker. Finding the edges of a 2.5 cm sphere may not yield that same accuracy of finding the centers of two balls spaced 10.0 cm apart. Increasing the size of the sphere becomes too intrusive as it blocks more and more of the image.
2) Depending on the energy of the radiation used, the outer surface of any metallic sphere is partially 'burned off' making the sphere image slightly smaller than it really is. This affects a single-ball calibration scheme, but does not affect a measurement between two ball centers.
3) Most importantly: If one wishes to make accurate measurements, one must know where the calibrated plane of interest lies. The single sphere gives the illusion of ease of use, but it hasn't helped the practitioner understand in which plane measures will be valid. One must know the anatomical plane one is measuring in, and therefore, its very feasible to position the two-ball marker in that plane.

Regarding placement of the scale marker: because we will see (below) that magnification is uniform everywhere in the plane of interest, the scale marker can be located anywhere in that plane. That is, it need not necessarily be close to the anatomical structure of interest, nor is it necessary to be near the central beam location, as long as it is in the same plane.

Magnification and Distortion

The nature of the diverging beam of radiation explains why radiographs always exhibit ***magnification***. Whatever anatomical structure they pass through, by the time they travel to the detector panel, they have further diverged, and so they image the structure in magnified form (figure 1). This magnification can be expressed as a multiplicative factor with the formula:

$$M = FFD / (FFD - OFD)$$

An interesting and sometimes misunderstood fact is that this magnification is ***uniform*** over the entire plane of interest. The magnification exhibited by the image is unrelated to the location of the central generator beam. From the formula above, one can see that to reduce magnification one should decrease **OFD** and/or increase **FFD**. But there is no particular reason to decrease magnification, as long as we know what it is.

Many practitioners have been taught to minimize the value of **OFD** by positioning the panel as directly as possible against the anatomy being imaged. One reason is to minimize magnification, but that is not really a good reason, as magnification should be known and accounted for, not just minimized. But there is a second reason to minimize **OFD**: the "point source" of x-rays inside the generator is not truly a mathematical point, rather, it is a small surface with finite area called the ***spot size***. A full discussion is beyond the scope of this paper, but the finite spot size leads to increasing blurriness of the image as **OFD** is increased. Modern generators have quite small spot sizes and so moderate increases in ***OFD*** are no longer an issue.

Along with magnification, there is a second attribute of radiographic images that stems from the basic geometry of the setup that we have been discussing. Radiographs display a certain kind of ***distortion*** due to the thickness of the anatomy being imaged. If the subject being imaged were infinitely thin – say a piece of paper with small metal dots affixed to it – it would be perfectly rendered in a radiograph with a uniform amount of magnification. But as the anatomy being imaged becomes thicker, there is a distortion which is minimized near the central generator beam and increased near the edges of the image. For this reason, the central generator beam is often directed at the particular anatomical structure of interest.

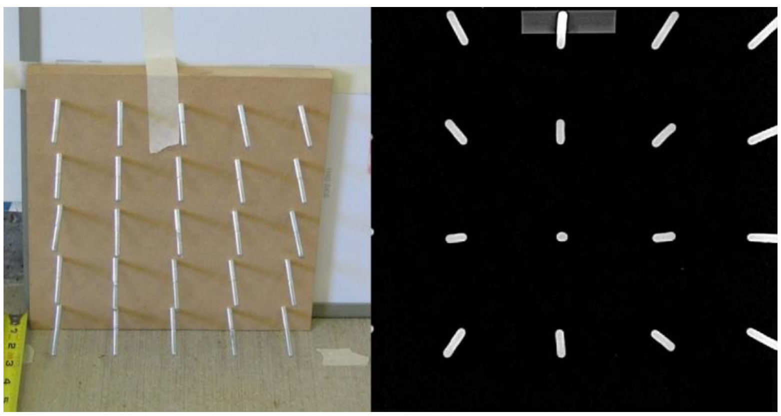

Figure 4: Distortion apparent when radiographing a thick subject. Distortion is minimized in the region near the generator central beam.

One way to think about it: thick anatomy can be thought of as having a sequence of planes of interest stacked on top of each other, each with a different OFD, and therefore with a different effective magnification for structures in that plane. So, the image is an overlay of multiple images each with a different magnification – and this leads to the distortion.

There are many other sources of distortion in radiographic images – poor detector calibration, missing pixels, image processing artifacts, the generator heel effect, and other issues. However, these factors primarily affect the luminance of the pixels in the image, and do not affect the location of image features within the image, and therefore, do not affect the issue of calibration for accurate physical measures.

Why is the Hoof on a Block?

The hoof must be placed on a block because the diverging x-ray beam that images the lower lateral wall of the hoof would be below the surface of the floor when it gets to the detector. See the red lines in figure 5 – to properly image the very bottom of the foot, it must be elevated off the floor so that the detector panel can be lowered below the level of the bottom of the foot.

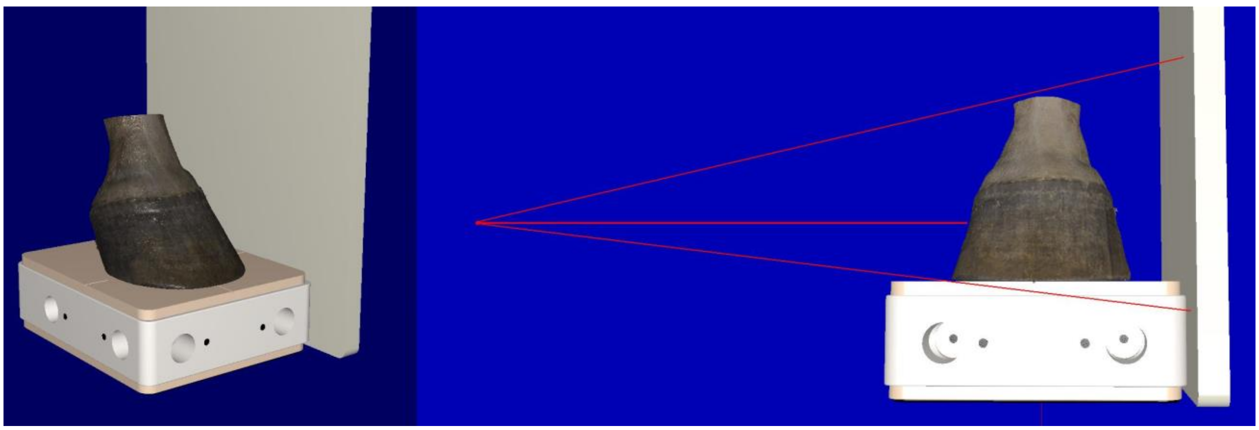

Figure 5: The left image shows a typical situation showing the hoof, the block, and the detector panel; the right image (DP view) shows the diverging x-ray beams and the central generator beam.

Hoof Radiography: Best Practices

We feel that because the hoof must be on a block for a quality radiograph, the best work-flow around the horse is achieved if the radiographic scale marker is built into the block. This way, there is one less item to handle when working around the horse and preparing the setup.

An alternative is to use a simple block (no scale marker) and then place a scale marker near the toe of the hoof or elsewhere in the plane of interest (figure 2). Some suggest this is easier than getting the horse to stand well-aligned on the block, which may be true, but even with the independent scale marker, *measurements will be accurate only in one plane*, it is just that this plane is not so easily visualized (as compared to the top block surface which has the line scribed). So, a practitioner may sacrifice accuracy of measurement for ease of use. Admittedly, it is sometimes difficult to stand a horse properly on the block, but we find it to be the best and simplest way to achieve high quality measures.

The hoof is positioned on the block with its centerline aligned with a line scribed down the center of the block. This line is exactly above the scale marker, so measurements will be accurate in that plane. A second scale marked is placed at 90-degrees to the first, so that the same block, without re-positioning the horse, can be used to take a scaled DP image of the hoof. In that case, the widest part of the foot is placed at a scribed line so that it is above the scale marker for that plane. The detector panel is up against the edge of the block, quite close, but generally not touching the hoof.

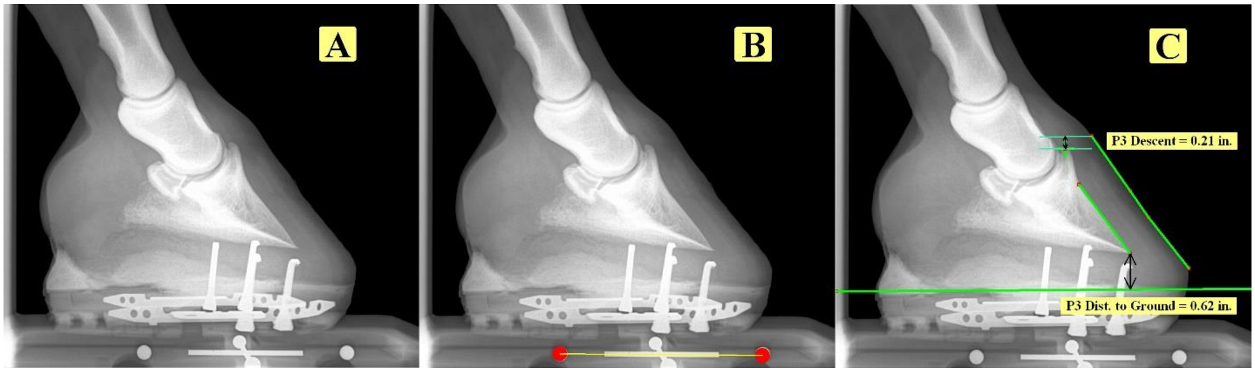

Figure 6: A hoof block with an internal two-ball scale marker. There is a second two-ball scale marker that is used for the DP view of the hoof. The Digital radiography software auto-detects the scale marker, and then all length measurements made are accurate in the central plane of the block.

We stand the opposite leg on a block of same height. Ideally, all four legs are on blocks of equal height, or perhaps the hind feet are on a simple raised platform of equivalent height.

Horses shift weight back and forth on their legs. A more uniform foot radiograph might be achieved by lifting the opposite leg to reduce this shifting. However, this is not standard practice, and the resulting radiograph of the more fully loaded foot may be misinterpreted, so we do not do this. We stand the horse as evenly as possible on two blocks.

To maximize the quality of a radiograph for the purposes of making measurements in it, we highly recommend using a larger value of **FFD** – that is, set the generator farther away from the hoof. This helps to minimize the distortion effect that was described earlier. Whereas some practitioners routinely use a stand-off of 26" (66 cm) we prefer to use about 36" (91 cm). As the **FFD** gets longer, the exact location of the generator central beam becomes somewhat less important, because the distortion effect is lower. Some practitioners debate whether (on a lateral hoof radiograph) to point the beam at the navicular bone, or at the top of the hoof block. Figure 10 below suggests that it doesn't matter greatly as long as a larger **FFD** is used. A larger FFD will require a higher technique setting on the generator, and the collimator to be closed a bit further – but the patient receives the same dose.

An extremely helpful feature of the software within the digital radiography system is the ability to automatically locate the scale marker. This increases ease of use for the practitioner and helps to ensure that all images are calibrated [Metron].

Complications due to 3-D Geometry

Measurement concepts are most easily understood when considering well-defined 3D points in the anatomy. But measures are usually made between 2D image points which may be complicated functions of how the 3D structure projects to 2D. In the first case study in the following section, we place a small metal sphere at the tip of the pedal bone to investigate calibration. But the point in a 2D radiograph that images as the "tip of the pedal bone" depends on positioning, because there isn't really a well-defined 3D point – it depends on the vantage point. A simple abstract example: if you want to measure the width of a cylinder standing vertically – you can pick points on the two opposite edges of the cylinder and measure its width. But those points that were picked don't actually correspond to any 3D feature point; rather, they are dependent on the viewing direction of the cylinder – they are points on the *limbs* of the 3D shape. In the case of the cylinder, you will get a good measurement, because the shape is simple and regular. Similarly, but more complex, are 3D shapes of bones, so we must keep in mind that our major source of error is not an issue of calibration per se, but of how measurement points are chosen and how those points may be influenced by the exact alignment of anatomical structures and our imaging apparatus.

Independent groups have used our system for real-world hoof measurements and have reported accurate results [Kummer], [Vargas].

Case Study #1: Accuracy in the Plane of Interest and Uniform Magnification

In a cadaver leg which is split in half according to the plane of interest, we place a small metal sphere at the tip of the pedal bone, and place a second metal sphere at the center of rotation of the coffin-joint (figure 7a). A physical ruler measures these points as being 3.125" (7.94 cm) apart (figure 7b).

Figure 7: Left: Small metal spheres placed at tip of the pedal bone and at the center of rotation of the coffin-joint. These are located in a plane that slices the leg in half, and will be considered as our plane of interest. Right: A ruler measures the distance between the two spheres.

We then stood this cadaver leg on a block containing the two-ball scale marker and radiographed it. We then lifted the block higher (on a second block) and took a second radiograph in order to study the effect of the generator central beam having been pointed differently relative to the anatomy and the desired measurement. The results are shown in figure 8.

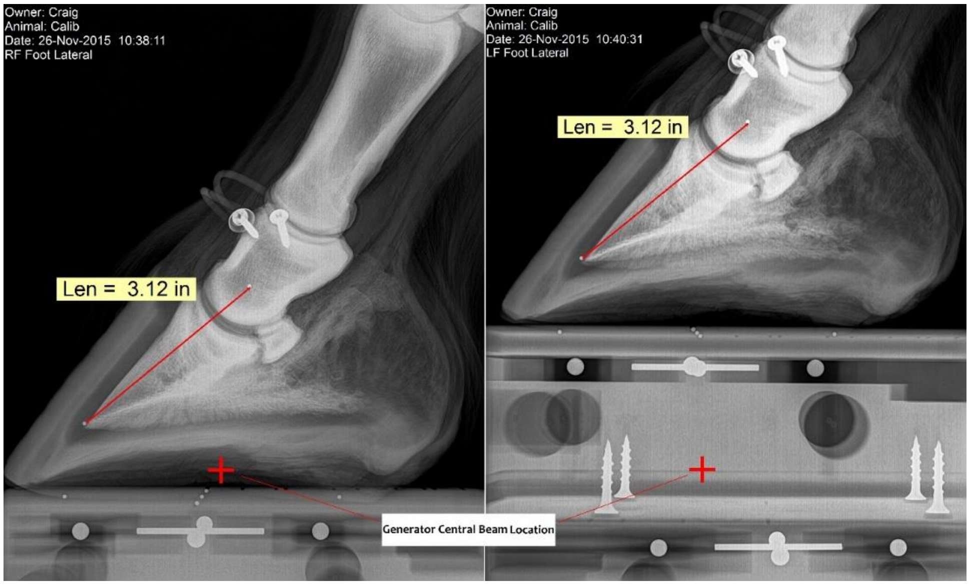

Figure 8: The measurement is of high accuracy, because the desired measurement lies in the same plane as the two-ball scale marker, and the generator central beam is directed perpendicular to this plane. The measurement is unaffected by the location of the generator central beam (indicated here by a red cross), because the magnification is uniform over this entire plane.

Finally, the same cadaver limb was imaged while varying the physical values of OFD and FFD which introduced varying amounts of magnification in the image. But due to use of the two-ball scale marker, this is perfectly compensated for, and the measurement remains accurate (figure 9).

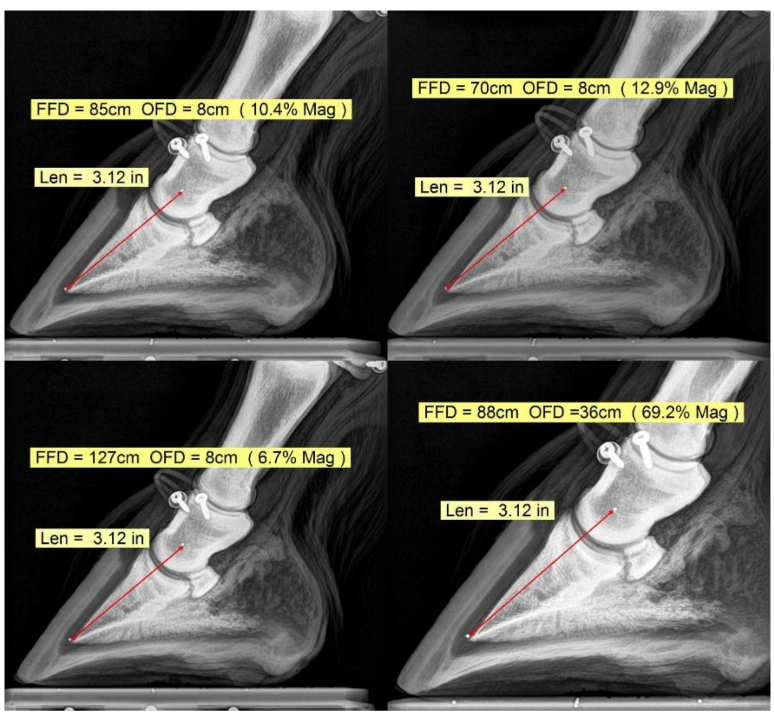

Figure 9: For any physical setup, with various values of OFD and FFD, accurate measurements are made due to the use of the two-ball scale marker.

Case Study #2: Robustness of Palmar Angle Measurement

This study is a bit different than most of the topics of this paper as it considers an angular measurement and not the calibration of a physical length measurement.   The ***Palmar Angle*** is a popular measurement made in a lateral hoof radiograph. It measures the shallow angle between the palmar surface of the pedal bone (as it projects in the lateral radiograph) and the ground or top of the hoof block. It is interesting to study the robustness of this measure: how sensitive is it to location of the generator central beam, and how sensitive is it to minor misalignment of the hoof, block, generator, and panel?

In Figure 10 the same (cadaver) leg was radiographed with the only change being the height of the hoof block. The large red cross shows the location of the generator central beam for each image. This is a very wide variation: from top of block all the way up to the approximate location of the center of rotation of the coffin-joint. The palmar angle measurement only varies by about one half of a degree. In this case, the FFD was 36" (91 cm) and this larger value aided in keeping the variation of the measurement low.

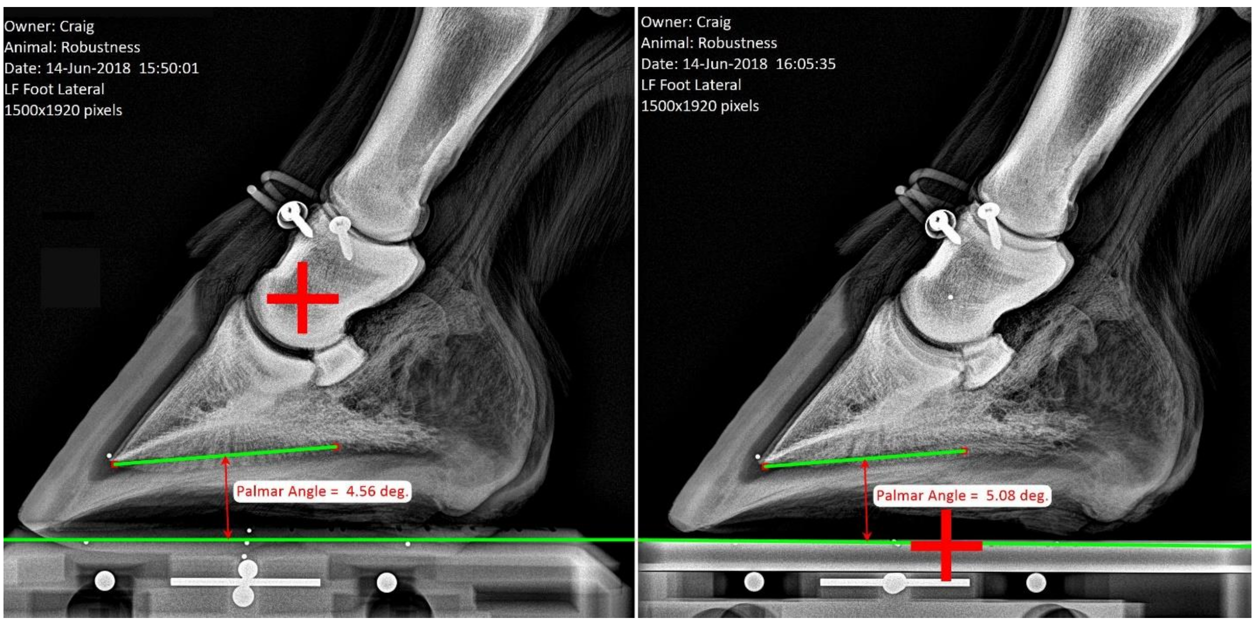

Figure 10: Effect of vertical positioning of the generator central beam. The palmar angle measurement is fairly robust to this variation if the generator is placed at 36" (91 cm) or farther from the panel. A video showing the full sweep of the beam center and the resulting Palmar Angle measures is available at [EponaMind].

Next, we study errors in Palmar Angle measurement that are introduced when the block and hoof are not well-aligned with the generator pointing direction and panel. Figure 11 summarizes the result as we vary the alignment by +/- 8 degrees from perfect alignment. It is quite easy for a practitioner to visually notice even a 5-degree misalignment without special tools – so we expect that a careful practitioner can always align within 5 degrees.   The value of the Palmar Angle varies over a range of about one degree for these misalignments.

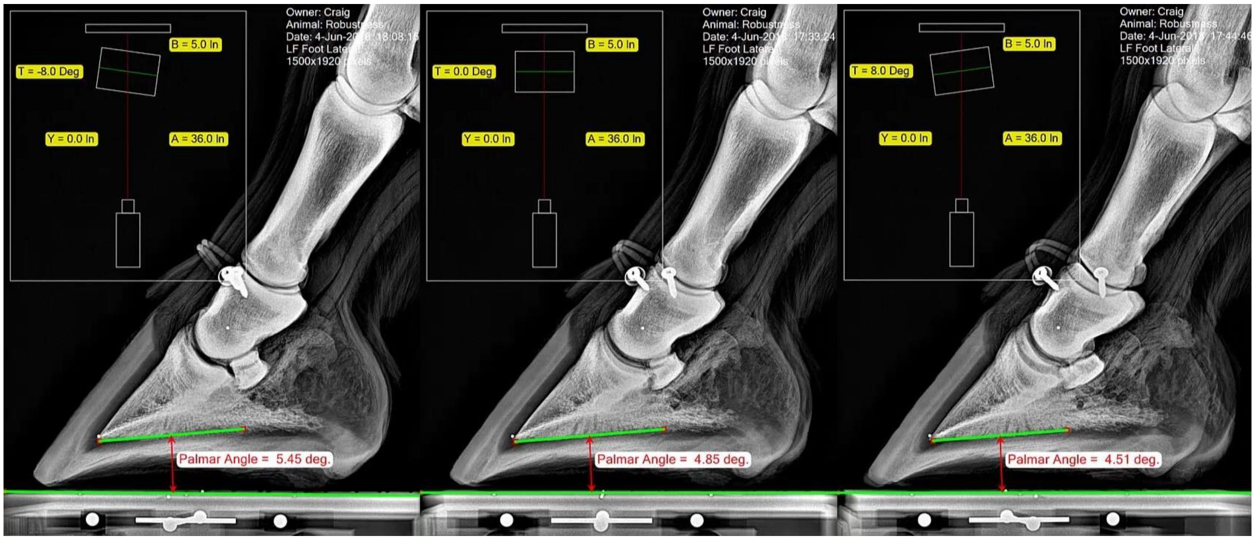

Figure 11: Robustness to alignment errors when aligning the hoof, block, and generator. Palmar angle ranges between 4.51 degrees and 5.45 degrees as misalignment is varied over a 16-degree range. The scale marker in the block, intended for use for the DP view, gives you a good visual indication of how the block is misaligned with the imaging equipment. A video showing a sweep of +/- 15 degrees is available at [EponaMind].

Case Study #3: A Full Set of Measurements Done Automatically by AI

Leveraging recent results from the field of deep learning and artificial intelligence, it is now possible to have a digital radiography system which automatically locates and uses the scale marker, and also automatically places points on the image to measure various angles, thicknesses, ratios, etc. Figure 12 is an example of an image that was measured in a fully automatic way with no input from the human practitioner [Metron]. The system likewise measures for medial-lateral balance in a DP radiograph of the foot. Further, the system can voice announce to the practitioner when the shot was not well-aligned, so the shot can be re-taken.

Figure 12: Recently the use of Deep Learning techniques has allowed development of a system which automatically calibrates the image and measures 10 or more different length or angle measures. The mark-up on this image was done without human intervention [Metron]. Only 4 of the 10 measurements made are shown in this example.

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