Can three-dimensional imaging be utilised to quantify morphology of the equine hoof

T M Smith

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Abstract

Introduction

Morphology assessment of feet currently mostly relies on anecdotal descriptions, sometimes enhanced by linear measurements. Farriers and vets often rely on memory and unquantifiable descriptions when comparing feet at different time points. The aim of this study was to explore if a mobile 3D structured light imaging system could be used to observe and document foot morphology accurately and repeatedly.

Hypothesis

It was hypothesised that a 3D mobile imaging system would result in an accuracy and repeatability similar to Computed Tomography (CT).

Methods

The study design was an experimental method validation. Eight cadavers of varying sizes, four front and four hind feet, were imaged before and after trimming with a mobile 3D system and a CT and additionally manual measurements taken; three parameters were measured on each foot, two linear and one angular and these measurements were repeated twice for each foot.The widths of agreement (WOA) were calculated.

Results

WOA results were varied; 26.42mm 3D-CT for dorsal wall (DW), 10.26mm intra-method 3D. Toe-heel (TH) measurements WOA 3D-CT 13.04mm, 5.94mm intra-method 3D. Hoof angle (HA) WOA 3D-CT was 7.6°, intra-method 3D 5.93°.

Conclusion

The results highlighted issues associated with data processing rather than image acquisition. Measurements where anatomical reference points were hard to distinguish on screen provided the largest WOA’s. Taking operator limitations into account the system provides comparable results to CT, and intra method results demonstrate repeatability.

Declaration

I hereby declare that the work within this Fellowship dissertation is my own. Any sources have been duly referenced and any illustrations or diagrams that are not mine are used with permission of the owner.

Contents

Content	Page Number
Acknowledgements	i
Abstract	ii
Declaration	iii
Contents	iv
Abbreviations	v
Introduction	1
Three-Dimensional Imaging Techniques	2
Aims and Objectives	5
Hypothesis	6
Materials and Methods	6
Results	12
Discussion	14
Conclusion	20
Manufacturers	21
References	21
Appendix	I

Abbreviations

3D	Three-Dimensional imaging system
CT	Computed Tomography
DW	Dorsal Wall Measurement (mm)
HA	Hoof angle at the dorsal wall (°)
LLOA	Lower Limit of Agreement
MAN	Manual measurement process
TH	Toe to Heel measurement (mm)
ULOA	Upper Limit of Agreement
WOA	Width of Limits of Agreement

Introduction

Over a five year period approximately nine out of ten horse owners in the UK will experience hoof based issues (Thirkel and Hyland, 2017). Despite the possibility of a statistical skew from this survey, largely due to the method of respondent recruitment, the magnitude of results shows hoof based problems are a real issue and very relevant, posing both a welfare issue and a financial burden to the owners. The correlation between many external structures of the equine hoof and corresponding internal structures is acknowledged (Dyson et al., 2011); although this correlation is reportedly modest, it is nonetheless relevant and useful to allow hoof care professionals, particularly farriers, to make educated assumptions based on the external hoof dimensions.

Hoof Morphology

Many factors including external stresses (van Heel et al., 2006), breed and type (Gordon et al., 2013), conformation (of both limb and hoof) and pathology (Thomason et al., 2008) affect hoof morphology. Lameness and pathology have been proven to distort the hoof capsule, yet can also be caused by distortion. Horses are able to compensate for changes in hoof balance due to growth by altering movement during an eight-week shoeing cycle (van Heel et al., 2006). Therefore, it may be acceptable to presume subtle morphology over a more protracted period results in a significant influence (positive or negative) on movement and soundness of the horse. It is accepted that the more information available to the farrier, the greater the likelihood of maintaining and improving the athletic ability of the horse (Moore, 2016). Hoof wall thickness was observed by Moore (2016), his study made measurements one quarter of the hoof length distally from the coronary band. Farriers generally concentrate trimming efforts on the distal half of the foot, yet the hoof wall is produced at the coronary band. It could therefore be rationalised that once produced, the wall grows distally and is increasingly influenced by external factors such as loading, wear and compression; resulting in changes in morphology. The ability to quantifiably measure and communicate morphology between farriers has the potential to improve understanding and analysis.

Improved understanding of the hoof capsule as a ‘fluid' structure that undergoes morphology, or changes shape, over time in response to many factors can only be desirable (Clayton et al., 2001). Clayton et al (2001), demonstrated that by altering stresses on the horny capsule through trimming, hoof morphology was evidenced.

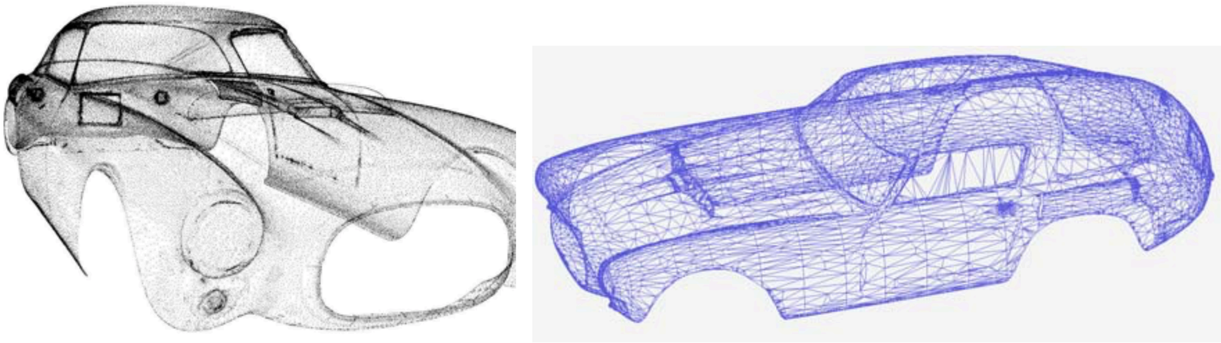
Three-dimensional imaging techniques

To aid understanding of hoof morphology, an accurate and quantifiable way of measuring feet over time is attractive. Two-dimensional measurements have been used for this, but in doing so, the analysis necessarily disregards shape, or limits it to a description creating a subjective and qualitative measurement open to interpretation, particularly between practitioners (Adams et al., 2004). Geometric morphometrics is a technique that applies co-ordinated landmarks on to a shape in a three-dimensional (3D) grid pattern (Adams et al., 2012), which has allowed changes in both shape and size to be quantified and analogies such as ‘flared toe, under-run heels’ to be moved away from (Zelditch et al., 2012). Often, 3D imaging is restricted to cadaver studies and those in laboratory settings due to the unpredictability of animals and the environment, plus the expense and sensitivity of equipment used (Chiari et al., 2008).

Three-dimensional imaging techniques have been developing at an increasing rate since the 1970's, offering numerous contactless methods to measure and recreate size and shapes of objects to precise accuracy as required (Sassoni et al., 2009). It is beyond the scope of this review to detail every technique, but as the ability to use the process ‘in the field' is being explored appropriate methods include:

Photogrammetry

Photogrammetry is the non-destructive process of capturing several photographic images of a structure and then ‘merging' them using ‘landmarks' placed on the images to form a three-dimensional structure (Arias et al., 2007), creating a ‘point cloud’. There are two main phases in photogrammetry - 1) Image acquisition and 2) Image measurements, including the mathematical relationship between image and object space (often computer-based) (Figure. 1.1).



(a) (b)

Figure 1.1 (Sassoni et al., 2009)

(a) demonstrates a 'point cloud' of a vintage car
(b) The triangle mesh created from the point cloud by software.

The accuracy of photogrammetry has been tested and proven using laboratory subjects, comparing photogrammetry data to results obtained using both traditional (Chiari et al., 2008) and modern techniques (Labens et al., 2013). Labens et al. (2013) contrasted the volume of cadaver hoof capsules using computed tomography (CT) following accepted methods and compared this to the volume calculated from images of the same hoof obtained through photogrammetry. The use of volume to validate the method may appear useful and certainly has its merits, although with further consideration it may give the correct answer, but with two or more measurements being incorrect, one higher and one lower for example, yet totalling the true volume.
The relative ease of access to the hardware required for photogrammetry makes it attractive to a farrier operating in 'the field'. Purchasing sufficiently high-quality camera(s) for the task is relatively cheap (compared to a CT scanner for example). The drawback seems to be the software used to compute the images. It can be time-consuming (Malone et al., 2014); the sheer amount of computing that the software does may cause the operator to misunderstand the complicated mathematics and algorithms that are used to create the final image (James et al., 2017). Computing power and time after image capture may be a sizeable drawback to this method. This technique has been proven accurate and versatile enough however for fieldwork in archaeology (Arias et al., 2007). The ease of set up and image capture does appear to suggest this method may be useful for the intended application of capturing hoof shape and therefore morphology. The processing time however may prevent the information from being immediately useful to the farrier.

Laser and Structured Light Scanners

These similar techniques use radiation (laser or structured light) triangulation to scan and image an object. Both require the scanner to emit radiation (light or laser) towards the object. A sensor then gathers the reflection and measures the location of the radiation, including the time taken from emitting to receiving (Figure. 1.2). Data collected are then used immediately to create a point cloud (Vozikis et al., 2004); this may be considered a definite advantage to the farrier. The computing power necessary to operate this equipment is often large and therefore expensive but both size and price are decreasing rapidly as technology improves.

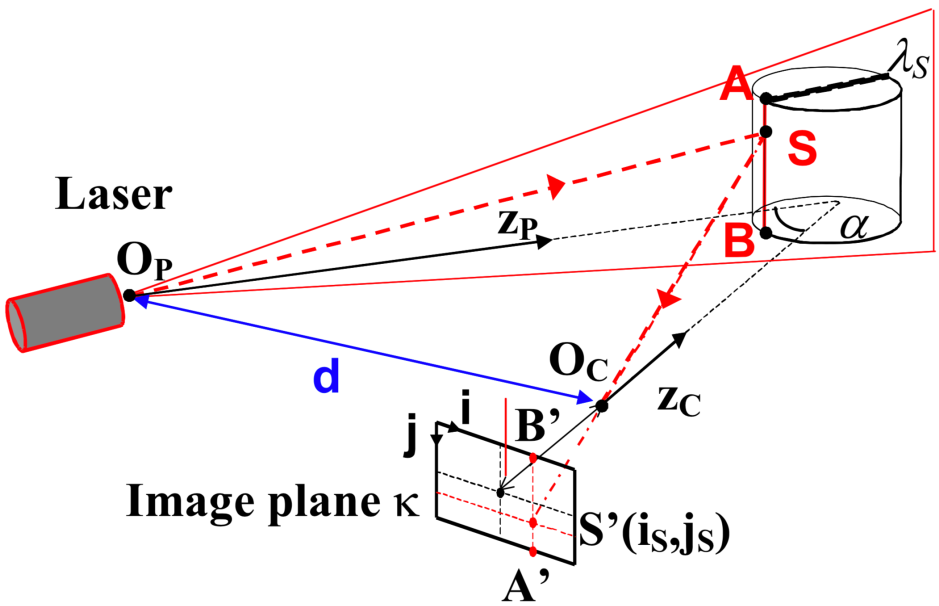


Figure 1.2
Image created to illustrate laser triangulation (Sansoni et al., 2009). This is the same principle also for structured light scanning. Radiation is emitted (Laser) and reflected from the object, passes through a lens and the image is captured by a sensor.

Medical applications of these techniques are increasing; including the ability to scan a limb stump and opposing limb to produce a prosthesis of accurate fit, the same size and proportion to the opposing healthy limb (Ryniewicz et al., 2017). The equipment used for this specific application would not be practical for horses ‘in the field' as it requires significant, expensive and fragile machinery and a perfectly motionless patient. It does, however, prove concept. Scanning accuracy is significant (Li et al., 2017). Utilising a miniaturised version of this equipment (in both size and cost) may enable quick and accurate 3D images to be obtained ‘in the field’, vastly reducing operator computer time. Because of the ease of image capture and the improvement in miniaturisation, including the costs and mobility after trialing several structured light systems, it was decided that this investigation would utilise a structured light system to reduce the computing time in creating the image after data capture.

Aims, Objectives and Hypotheses

Aim

To create a scanning system that can be used ‘in the field’ to enable the farrier to capture three-dimensional images of the horse’s hoof. If proven that these images are accurate it is envisaged that they may be utilised so that hoof morphology can be accurately and quantifiably observed. The system, to be effective, should:

1. Image the intended hoof capsule to scale.
2. Measure lengths and angles on three dimensional images taken as a baseline for quantifiable future comparison.
3. Allow the user to move away from qualitative methods such as using descriptions of shapes.

Objectives

- To design an imaging system that can accurately obtain 3D data to create an image/ model that can be used for future comparison, allowing the user to assess hoof morphology.
- To assess, and therefore validate, if the system is capable of giving accurate measurements by comparison with the current ‘gold standard’ system of Computed Tomography (CT) scanning.
- To understand the time taken to both obtain data and create an image digitally, using the system to see if it would be deemed practical on a standing horse.

For a method to be practical and cost-effective, it appears it will require the following properties:

1. Practical in most conditions
    1. Weather and environment resistant - able to be taken outside of the laboratory.
    2. Mobile.
    3. Not reliant on mains power.

    4. Able to work in most standard lighting conditions.
2. Easily used
    1. Hardware is able to be used repeatably by different operators.
    2. Software and image interpretation must be repeatable.
    3. Time taken to process images needs to be minimal - ideally available immediately, although to form a baseline this is not entirely necessary.
    4. Hoof surface and dressings should not interfere with the image collection (e.g. shiny surfaces from hoof oil).
3. Safe to use around horses:
    1. Ideally not require the horse to stand motionless for a prolonged period.
    2. Should not worry or scare the horse easily, for example, there should be no flashing lights or loud, abrupt noises.
    3. Should be able to be withdrawn quickly in case of animal danger and robust enough to resist damage.
    4. Will not cause damage or suffering to the horse.
4. Automation - Eliminating as many variables during collection and analysis by automation could be useful (Vozikis et al., 2004), complete automation is not necessarily possible ‘in the field'. However, a degree of it could improve repeatability and usefulness of results.

Hypothesis

It was hypothesised that the use of a 3D system ‘in the field’ would:

- Have a comparable level of error to CT measurements when imaging the equine hoof capsule.
- Be repeatable.

Materials and Methods

Measurement descriptions

The limbs were both manually measured in three parameters (below) and imaged prior to trimming and subsequently after trimming. Therefore, each limb provided three parameter measurements twice - before and after trimming, resulting in a total of six measurements. The measurements from each parameter were calculated manually once on the cadaver, twice using the CT images and three times using the 3D images. The parameters were:

1) Dorsal Toe (DT)- the dorsal wall measurement was taken at the centre of the hoof, from coronary band to termination of the distal wall (Figure. 2.1).

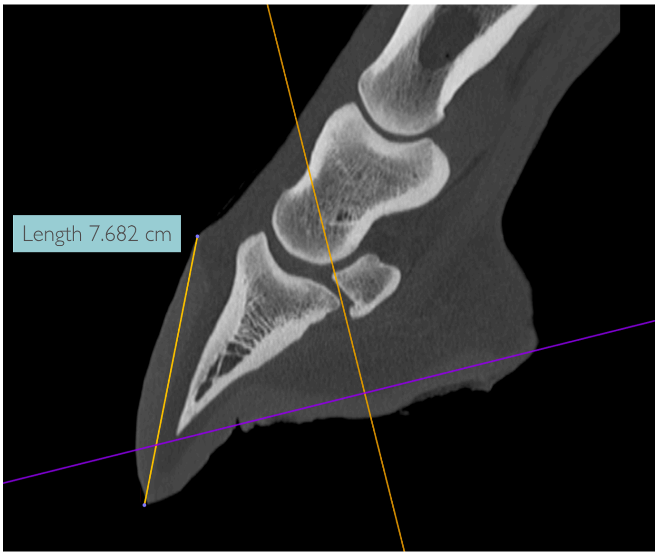


Figure 2.1: Image captured of DW measurement being taken from CT data using HOROS software.

2) Toe to heel (TH)- the solar aspect of the hoof was measured from the centre of the hoof wall at the toe to the outside heel diagonally. If it was unclear which side was the outside, one heel was selected and used in each measurement to ensure the same measurement was being taken each time (Figure 2.2).

Figure 2.2: Manual TH measurement being taken using digital vernier callipers.

3) Hoof angle (HA)- the dorsal hoof angle was taken from the centre of the hoof (Figure 2.3).

Figure 2.3: HA measurements being collected using 3D data using Blender software (left) and manual measurements with a modified angle gauge (right).

Data Collection

1) Cadaver feet were selected in accordance with the hoof grading system created for this system (Table 2.1), the intention being to select one front and hind foot from each grade. Hoof size selection was as varied as store availability made possible, and feet ranged from small to large. Eight cadaver limbs were used for this study, four front and four hinds (n=8). Based on angles; four limbs were grade 4 (50%), two were grade 3 (25%) and two were grade 2 (25%). Availability dictated that there were no grade 1 feet.

Table 2.1: Hoof grading system created to ensure a broad selection of foot types for both front and hind feet and prevent investigation bias.

Grade	Description
1	Dorsal wall angle of greater than 55º (front) and 60º (hind). The foot is often small for the size of limb and horse. The foot would be considered very upright. The solar surface will be very concave, with deep bilateral frog clefts. The foot will be longer than it is wide.
2	Dorsal wall angle of 51 to 55º (front), 56-60º (hind). The foot would be considered upright to normal spectrum. The foot will be longer than it is wide.
3	Dorsal wall angle of between 47-50º (front), 52-55º (hind). The foot would be considered towards the ‘flatter’ side of normal conformation. The concavity of the sole will be reduced and relatively flat. The foot will be as wide as is long, or nearly so.
4	Dorsal wall angle of less than 47º (front), 52º (hind). The foot would be considered very ‘flat’. Concavity of the sole is negligible. The heels will be under run, the width of the foot will be greater than the length.

2) Feet were cleaned and the hairline trimmed to reveal the coronary band and skin at bulbs of heel. All surface mud and detritus was removed and the feet brushed well with a wire brush. Solar surfaces were subjected to the same procedure once shoes were removed, any loose/partly exfoliated frog was removed. This process ensured that no foreign objects would influence the imaging for either method and prevent inaccuracies assisting in the prevention of poor data collection.

3) Cadaver feet were labelled securely (numerical labelling of fronts and hinds, i.e. 1f, 2f,1h 2h etc.). A linear measurement was taken from centre of the toe to the lateral heel on the solar surface (TH) and centre of the distal toe to the centre of the coronary band on the dorsal wall (DW) (both in mm, to one decimal place). Hoof angles (HA) were measured using a digital angle gauge. All measurements were manually recorded on the data collection sheet. This formed the manual measurements column.

4) Feet were imaged using both modalities (CT and 3D) at this point. Each data set was carefully labelled to correspond to their cadaver. The time taken for the acquisition of the data was recorded (seconds) for each stage and entered into the data collection spreadsheet. All feet were placed with the left side of the hoof on the bed of the CT scanner to ensure side was easily identified and all images were consistent. The CT images were acquired in a helical fashion at 120 kVp, 255mAs and a slice thickness of 0.65 mm (Model: LightSpeed RT 16, Manufacture: GE Medical Systems). Images were acquired in a matrix 512 x 512 and a field of view of approximately 200mm. Three-dimensional reconstructions and measurements were performed in HOROS ver 3.3.5 software. Three dimensional (3D) images were taken using an iPadPro (Apple Inc.) equipped with a Structure Sensor (Occipital Inc, CO, US: Model ST01) using the M3DScan app created for the sensor (Mirage 3D NY, available on the apple app store).

5) The feet were then trimmed. The trimming was conducted to the mapping protocol utilised by Nunn (2017) and performed by the same farrier on all feet to minimise trimming variation. All loose trimmings were removed, linear points and hoof angles were measured again and recorded, entering results onto the data capture table in the manual column against the trimmed feet.

6) Both imaging modalities were then repeated (same format as step 4), and datasets recorded post trim against their identity label. Time was measured for data acquisition as before. All data was entered into the data capture sheet.

7) The data collected was analysed. CT Images taken were exported into HOROS ver 3.3.5 software and measurements taken using the 3D MPR view, using the tools available to make linear and angular measurements. 3D images were exported into blender (Version 2.79b 2018-03-22, Blender Foundation) in an stl. format. The tools available under the ‘grease pencil’ tab include a ruler and protractor and were used to calculate linear and angular measurements. To compare the accuracy and repeatability of these results, measurements were taken on two separate occasions by the same operator, a third time by 3D to assess repeatability.

8) Time taken (seconds) to acquire data, and form the images from it, was collected to ensure data collection was within the time scale that would be available to a farrier working on an unsedated horse comfortably .

N.b. All results were recorded on a pre-planned data collection sheet.

Statistical Analysis

Data distribution was assessed using histograms and found to be not normally distributed. Inter-method agreement between CT, MAN and 3D measurements was assessed by calculating the limits of agreement, agreement between repeat 3D and CT measurements (intra-method) was also calculated using the same statistical analysis (Bland and Altman 1986). For this the average and standard deviation of the differences between measurements were calculated. The distribution of the differences in relation to the magnitude of the measurements was assessed by plotting them against each other in a scatter graph and there was no apparent correlation. All data analysis was performed in Numbers version 5.3 (5989), Apple Inc. US.

Bland-Altman plots were created to visualise the agreement between 3D and CT measurements, 3D and manual and 3D to 3D measurements. 3D measurements were performed three times and CT measurements were performed twice. The mean average for 3D was calculated from the second and third repeats. For the intra-method agreements, the second and third measurements were also used.

Technical issues dictated one CT image could not be used for either DW or TH measurements. One 3D image was not useable for DW measurements. On both occasions the data recorded excluded part of the foot being imaged.

Results

Overview of absolute measurements

Table 3.1 Median, inter-quartile range, minimum and maximum values across the three imaging modalities.

Parameter		Manual	CT	3D
DW (mm)	Number	n=16 (100%)	n=15 (93.75%)	n=15 (93.75%)
	Median (IQR)	95 (25)	91 (31)	99 (31)
	Min - Max	73 - 118	73 - 121	72 - 115
TH (mm)	Number	n=16 (100%)	n=15 (93.75%)	n=16 (100%)
	Median (IQR)	133 (31)	136 (26)	133 (31)
	Min - Max	95 - 171	98 - 173	99 - 170
HA (°)	Number	n=16 (100%)	n=16 (100%)	n=16 (100%)
	Median (IQR)	49.5 (5.0)	49.9 (4.5)	49.4 (4.4)
	Min - Max	44.0 - 57.8	43.3 - 56.4	44.9 - 58.1

Table 3.2 Bland-Altman Limits and widths of agreement DW measurements (mm)

	3D to CT DW	Manual to 3D DW	CT to Manual DW	3D to 3D DW	CT to CT DW
Mean of difference	1.61	-0.50	-1.93	0.87	2.80
Standard Deviation of Difference	6.74	5.09	4.28	2.62	2.62
Lower Limit of Agreement	-11.6	-10.48	-10.38	-4.26	-2.34
Upper Limit of agreement	14.82	9.49	6.46	6.00	7.94
Width of limits of agreement	26.42	19.97	16.84	10.26	10.28

Table 3.3 Bland-Altman Limits and widths of agreement TH measurements (mm)

	3D to CT TH	Manual to 3D TH	CT to Manual TH	3D to 3D TH	CT to CT TH
Mean of difference	-0.77	-0.59	0.03	0.19	-0.33
Standard Deviation of Difference	3.33	3.09	3.98	1.52	3.52
Lower Limit of Agreement	-7.29	-6.65	-7.77	-2.78	-7.23
Upper Limit of agreement	5.75	5.46	7.83	3.16	6.56
Width of limits of agreement	13.04	12.11	15.6	5.94	13.79

Table 3.4 Bland-Altman Limits and widths of agreement HA measurements (°)

	3D to CT HA	Manual to 3D HA	CT to Manual HA	3D to 3D HA	CT to CT HA
Mean of difference	-0.04	0.13	0.17	-0.51	2.21
Standard Deviation of Difference	1.94	1.11	1.73	1.51	2.58
Lower Limit of Agreement	-3.84	-2.05	-3.22	-3.47	-2.84
Upper Limit of agreement	3.76	2.31	3.56	2.46	7.27
Width of limits of agreement	7.6	4.36	6.78	5.93	10.11

The DW measurements provided the largest WOA, particularly in the 3D to CT measurements. The inter-method analysis showed the smallest WOA. The TH measurements demonstrated much smaller WOA. The 3D intra-method analysis showed a very tight WOA comparatively. HA measurements inter-method gave comparable WOA between the modalities. Intra-CT HA WOA was substantially larger than any other result in observed in HA analysis.

Discussion

The majority of WOA's of the 3D-CT methods were larger than anticipated, particularly given the level of accuracy described by the manufacturer of the imaging hardware. At the range and size of object in this application it is claimed that the level of error is around 0.12%. WOA's may, however, be explained with further investigation of the results and, in particular, the way in which they were obtained.

The DW 3D-CT measurements were the most variable and provide the largest WOA's (Table 3.2), therefore leading to the summary that there was the largest margin of error in this measurement. There are numerous reasons for this which include using computer software. Taking digital measurements from the coronary band to the termination of the distal toe poses several difficulties; the most obvious is identifying a clearly definable location of the coronary band, this results in two issues when trying to assess accuracy:

1) The true location of the coronary band and hoof wall junction is not known and therefore cannot be selected.
2) The accuracy with which the area that is 'presumed' to be the junction is selected based on the operator's interpretation.

The WOA between manual and the two imaging techniques are comparable, suggesting that one method may have averaged higher than manual and the other lower. Upon examination CT DW median measurement is 4mm lower than the manual measurement, whilst the 3D DW median measurement is 4mm higher; another factor that may aid in understanding the larger WOA between CT and 3D DW. The lower DW LOA inter-method are all within 1.2mm, yet the upper LOA has a much greater spread of 8.4mm. Given the difficulties in accurately defining the physical junction between the coronary band and hoof capsule (Figure 4.1) the DW measurement may not be as useful in assessing the accuracy of the system although it has highlighted issues that require further consideration.

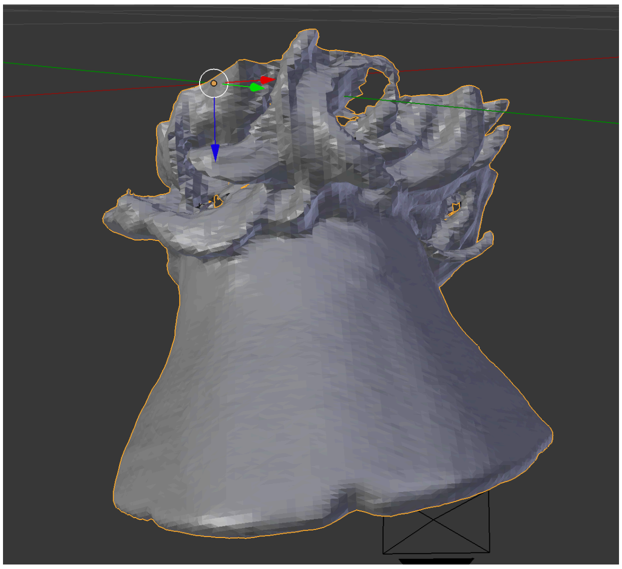


Figure 4.1: 3D image illustrating the difficulty in accurately locating the coronary band for DW measurements.

The TH measurement limits of agreements are much smaller and more comparable in WOA (Table 3.3). 3D imaging is more in agreement with CT imaging and manual measurement more accurately than CT is with manual. The intra-method 3D TH imaging comparison presents a very small WOA comparatively, in fact the tightest agreement noted in this investigation; the CT intra-method TH WOA is more than double that of the 3D TH. The decrease in size of the TH WOA is almost certainly attributable to the easier definition of the toe and heel on the hoof in both 3D and CT imaging. Despite the degree of agreement of TH compared to the DW measurements, there were limitations that the author believes would certainly increase the WOA. The TH measurement for the CT imaging proved difficult to conclusively find the exact plane for the solar surface of the hoof capsule. Moving the plane of view slightly produces differing measurements, and if the plane was slightly oblique or not in perfect alignment to the plane of the hoof the measurements could differ (Figure 4.2); therefore, increasing the WOA for the TH CT measurements.

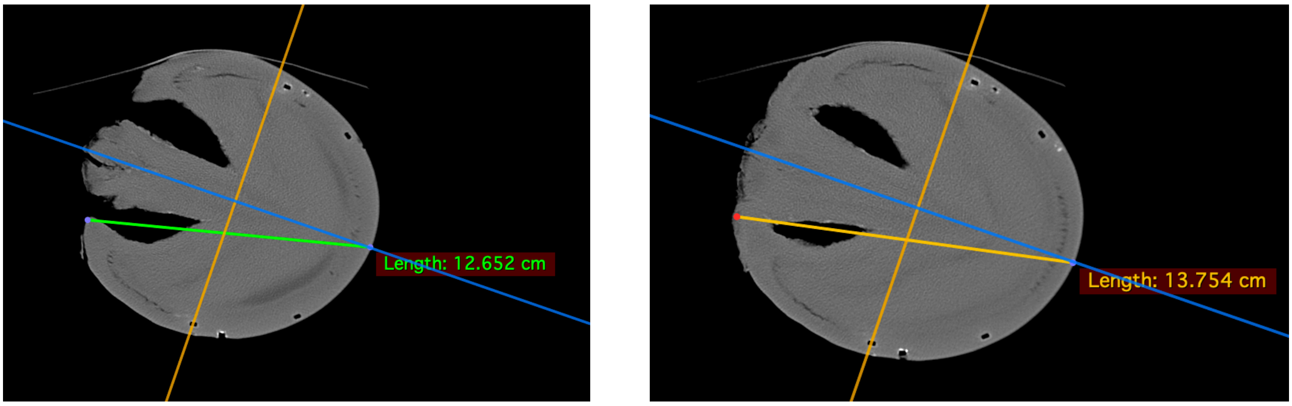


Figure 4.2: CT scans of the same hoof. TH measurements taken with the hoof on view at differing planes. This indicates the difficulty in deciding a conclusive measurement and may help explain the larger intra-method CT TH WOA.

Hoof angles (HA) WOA were, in the opinion of the author, very comparable between all inter-method measurements (Table 3.4). Of note is the intra-method 3D WOA, this presents as nearly half the agreement width of the CT - CT analysis measurements. A major complication in obtaining accurate and completely repeatable hoof angles on both CT and 3D imaging is the hoof wall is rarely a perfectly straight line. Operator interpretation is required to decide from which part of the dorsal wall the measurement is taken. A domed shape dorsal wall can present several different justifiable angles (Figure 4.3). The creation of a uniform way, or place, to measure the angle of dorsal walls may reduce the WOA.

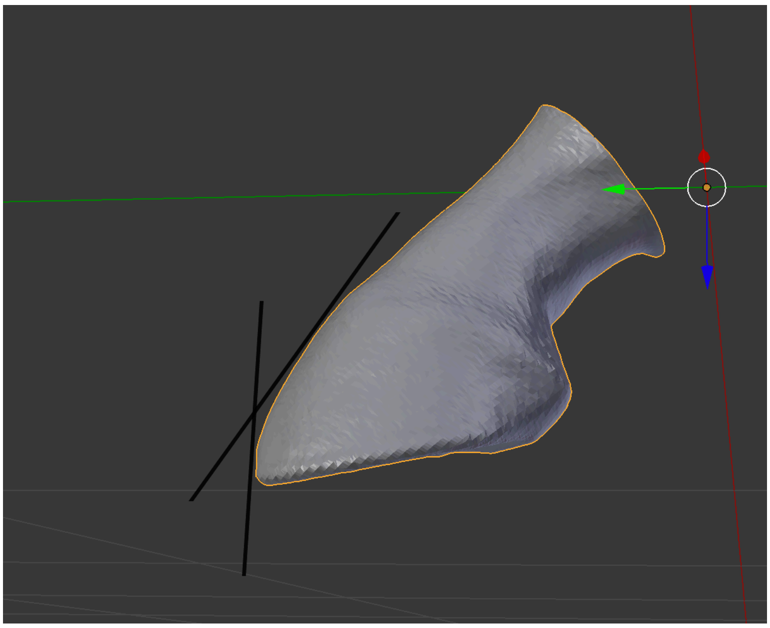


Figure 4.3: Two lines that represent the differing angle that could be taken when measuring the HA on a domes dorsal wall. This ambiguity leaves a large amount of operator interpretation on both CT and 3D analysis and could explain why the WOA were significantly larger than one may expect.

It does appear that a large proportion of the WOA’s are directly attributable to the precision with which the operator is able to select two accurate points between which, or choose an angle, to measure. This compares directly with an investigation into operator precision conducted on hoof angles both manually and digitally obtained (Moleman et al., 2005). A variability of results were recorded of up to 37% difference. Once this is taken into consideration the accuracy of the actual scanned image does appear to be much increased (Li et al., 2017). The accuracy level described by the manufacturer of the 3D imaging system is claimed to be around 0.12% when imaging structures of a similar size to the horses’ hoof. With WOA of up to 26mm this figure was obviously impossible to confirm. Anecdotally, tests using the system on very regular, clearly defined objects have previously confirmed the system to be certainly accurate to within one millimetre which again supports the theory of operator point selection precision being a large factor in increased WOAs.

The time taken to obtain the data was recorded during the study with the intention of comparison to CT and also to ensure the system is practical for use in the field. It soon became apparent to the author that this measurement was not usefully comparable to CT imaging as every horse would need to be anaesthetised to use a CT imaging system. It was considered that a farrier can comfortably hold most horse’s feet up for around two minutes, and the imaging was taking substantially less than this so although not confirmed statistically, it was deemed practical in this respect.

Study Limitations

The study was conducted on eight limbs, although the variation in both size, shape and front or hind mitigated this somewhat, and by repeating the test following trimming effectively doubled the sample size. Imaging issues dictated that one measurement was lost from 3D results and two from CT. This slightly reduced the data set subjected to statistical analysis. Image processing for 3D images was conducted on open source software that was not designed for this purpose but was capable of satisfying the requirements. The author was unable to find software specifically created for this intention, the cost of creating such a system has been quoted between £30,000 and £120,000; which before proof of concept represented a substantial risk.

Future Recommendations

This study was to prove the concept of a small sized imaging system that can be used in the field. The use of cadavers was necessary to allow the use of CT. Using the system on live horses in a baseline study would enable the testing of the system 'in the field' as ultimately this is the intended use.

The system should be assessed for results obtained by different operators, this would allow the repeatability to be tested and any operational guidelines to be created from this. The addition of colour scans may greatly assist in the narrowing of the WOAs, particularly when anatomical landmarks are to be measured. Previous studies have suggested that the repeatability is high when using different operators comparing first and second measurements, but that they may obtain slightly differing results from one another (Labens et al., 2013).

Future System Improvements

This investigation has indicated areas of the 3D system that could possibly be improved. Of particular interest, the ability of the following proposed additions to the 3D imaging and analysis system on their effect on the WOAs should be investigated:

- Imaging in colour on the 3D imaging system. This should allow areas such as the coronary band to be identified more easily. This will require a change from .stl file type to .obj and a substantial increase in memory used for the operation but it is possible with the current imaging system and software.
- Automation of the measurements. Artificial Intelligence (AI) based programming may be required for this but the removal of the 'human element' in selecting points may be a useful tool in reducing the level of error.
- Being able to keep all imaging 'in-house' with regards to the software. The use of HOROS for CT limited programme changes, yet with 3D one app was used to obtain the data and another programme (blender) was used once the file had been sent via email to obtain measurements. It is questioned if file conversions etc., may cause a slight loss of fidelity between each step? If the 3D imaging system could offer data in .dicom format HOROS could be used for all analysis for example.
- Purpose built software may make taking accurate measurements easier. Blender is actually designed for use in creating 3D animations. It did however prove the most adequate amongst the open-source programmes that the author was able to use.
- The size and quality of the screen being used to visualise images.

The results from this study cannot compare directly to the study comparing hoof volume calculated from photogrammetry and CT methods (Labens et al., 2013), mainly as the compared measurement for agreement were in cubic cm. The WOAs are not provided but the LLOA and ULOA are in the study by Labens et al., (2013). The WOAs are reasonably wide when the difference is calculated and comparable. It is concluded in that study also that the value of any digital assessment method is dependent on the person analysing the data, also in keeping with this study. Of interest in this study is that when assessing the accuracy of photogrammetry in calculating hoof volume when compared to CT showed that the hoof volume calculated by CT data was consistently larger than that of photogrammetry methods.

Future uses of the system

The ability to quantifiably document and record hoof shape, and from comparisons of subsequent scans morphology, could allow the farrier to undertake many exercises that without such a system could prove difficult or impossible. Some examples of these exercises may include:

- Aiding with research - any in-vivo research that wishes to measure or quantify hoof changes currently utilises linear measurements and two-dimensional images such as photos, this system would enable accurate measurements and comparisons to be made. An example is if a farrier wished to understand the effect a shoeing system may have on the hoof capsule over time (such as quarter clips) this system could be used to take a baseline and then comparisons to this at regular intervals throughout a given time period.

- Move away from anecdotal and qualitative descriptions (such as flared, long, flat, etc.) and move towards quantifiable descriptions. Communications between farriers and veterinary professionals could move from these descriptions to sending a scan of the hoof capsule to allow the recipient to draw their own conclusions from the same image as the farrier saw on the horse.

- Refine the programming and information achieved from finite element analysis, and validate the results. This mechanical programming has, in the author’s opinion, at times not reflected the practical (and therefore anecdotal) observations in the field. Data captured and processed by a 3D imaging system could either remove the necessity for finite element analysis at times, or improve the algorithms that dictate the information output.

- Better understand small and subtle changes to hoof shape, and possibly use these as an early warning of pathologies. With research and study this may help slow or prevent certain pathologies from causing issues on horses by earlier changes in shoeing systems.

- Shoeing system design and fit improvement; a better understanding of hoof morphology and the factors affecting it could give the farrier a more educated and measured approach to shoe selection and its application. The effect of the shoeing system could also be monitored and measured.

Conclusion

In conclusion, in the opinion of the author, an acceptable WOA is evidenced to validate the method of taking 3D images for making accurate measurements and therefore prove the first hypothesis. The second element of the hypothesis can also, in the author's opinion, be considered proven as the method is repeatable. Further research is required to allow the user to reduce the accuracy limitations. For accuracy to be tested there necessarily needs to be comparison, it is the comparison of two slightly differing techniques, along with the limitations of operator precision, that appears to increase the WOA obtained.

Manufacturers

iPad Pro, Apple Inc. (Cupertino, CA 95014, USA)

CT: LightSpeed RT 16, GE Medical Systems (Chalfont St. Giles, Buckinghamshire, UK, HP8 4SP)

Occipital Structure Sensor, Occipital Inc. (Boulder, CO 80302, USA)

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Appendix I

Ethical approval letter

Dear Xxxxxx,

URN: M2017 0142 - Project Title: *Experimental Method Validation of a Three-Dimensional Imaging system for the Equine Hoof*
Duration: from May 2018 for 6 months

I am pleased to advise that this project has been ethically reviewed by the Clinical Research Ethical Review Board (CRERB) and that ethical approval has been granted.
Please ensure that you put your reference (URN) number on any documentation relating to the study and indicate that ethics approval has been given by the Clinical Research and Ethical Review Board at the Royal Veterinary College. You also need to keep a copy of this letter in the study file.

If you need to make any changes to the project, then please contact me for an amendment form.

All the best,

Maria Johnson

Programme Support Co-ordinator
Academic Registry
Royal Veterinary College
Royal College Street
London NW1 0TU

Tel: +44 (0)20 7468 5157