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Photogrammetric measurement of deformations of horse hoof horn capsules

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ABSTRACT

In a coorperation of the Department of Veterinary Surgery at the University of Zurich and the Institute of Geodesy and Photogrammetry at ETH Zurich, a system for the measurement of three-dimensional deformations of horse hooves under different load conditions has been developed. The system consists of a force sensor panel and three Sony XC75CE CCD cameras mounted on a trolley which can be moved on a circular rail around the hoof. To achieve a reliable photogrammetric network and to ensure the full coverage of the hoof, triplets of images are acquired at three different positions of the trolley. The nine images are processed separately for each single experiment to determine discrete marked points mounted on the horn capsule of the hoof. Prior to the experiment, the horse was sedated to reduce its movement to a minimum. The force sensor panel is used to assure a more or less constant load condition of the hoof during the image acquisition. To increase the accuracy of the object point determination, a calibration of the three cameras is performed before the experiment. For the definition of the reference system, 84 points were milled into the anodized surface of an aluminium plate. From the specifications of the controlled manufacturing machine, the coordinates of the reference points can be expected to be milled with a precision in the order of a few micrometers. The aluminium plate has a size of 0.5x0.5 meters and in its center a notch for the force sensor panel upon which the hoof is placed. For a good visibility of the reference points a diameter of 8 mm was chosen and to improve the contrast on the images the milled position was covered with retro-reflective sheeting. The circular rail for the camera trolley has a diameter of 75 cm and 6 mm objectives are used to get a suitable field of view. Using nine images distributed regularly around the hoof, each marked object point is visible and can be measured on three images. The reference points on the aluminium plate might even appear on more images and provide for a well-defined photogrammetric network. To analyse the deformation of the horn capsule, another set of nine images is acquired after changing the load conditions by remaining the horseshoe or placing a wedge pad under the hoof. After image acquisition the data is processed with the commercial software PhotoModeler® from EOS Systems Inc. to determine the 3-D coordinates of the marked points on the hoof. The estimated precision of the 3-D points positions is in the order of 0.1 - 0.2 mm, which is sufficient for this application. The two resulting 3-D point clouds can then be used for a deformation analysis. The paper describes the basic design of the system, discusses a calibration strategy and presents first results.

Key words: Measurement System, CCD Camera, Veterinary Surgery, Deformation Analysis

1. INTRODUCTION

Many equine foot problems, from foot bruising and quarter cracks to laminitis and navicular disease are either caused or worsened by the severe loads the feet experience during locomotion. In addition some phalangeal joint problems may be caused through inadequate trimming of the hooves, the inability of the hoof capsule to compensate distortional movements and through high frequency vibrations occurring at the beginning of the stance phase. Description of the hoof mechanism has occupied scientists for a long time (see references from Harders[13]). Many studies have been published during the last century. All of those works reported the movement of the hoof wall in the horizontal plane. The vertical component of this mechanism is still poorly described. The goal of this project is to describe the vertical deformation and to explain the role and the importance of this mechanism for the soundness of hooves and limbs of horses.

The hoof works as a blood pump and shock absorber[9]. The last mentioned characteristics determine the mechanical loads on joints. If unshod, the vertical adaptability of the hoof is responsible for a part of the compensation of joint distortion. Traditional horse shoeing has proven its value for a long time, but more and more its efficiency and effect on the soundness of the equine limb is questioned. Reasons for this include that the high frequency impact is higher when shod[9] and that shoeing can restrict parts of the hoof mechanism. Many horses develop narrow heels with time; the quality of horn suffers and the vertical movement is totally restrained. Understanding the normal mechanical function of the healthy hoof is a prerequisite to understand how loading causes or exacerbates these conditions. Furthermore, it will allow a more efficient progression in the development of novel horse shoe alternatives. Up to now, the movements of the hoof wall were described only in the horizontal plane (2-D hoof mechanism). But if the horse is unshod, deformation of the hoof capsule in the vertical axis can be observed when the heel is elevated on the medial or lateral side. This vertical movement (3-D hoof mechanism) could only be poorly assessed until now.

In the last century development of several techniques helped to understand part of the movements of the hoof capsule and confirm or brought new findings about this interesting subject. Akerblom[1] confirmed the results of Lungwitz[17] by using a mechanical recording system mounted on the hoof capsule and recording the movements on a tracing paper. More recently Knesevic[16], Bayer[3] and Bein[4] investigated the deformation of the hoof capsule using strain gauges. The photoelastic method to show distribution of strain within the hoof wall of a living horse was applied by Davies[8]. Harders[13] developed an other method. He covered the surface of the hoof with sodium tera-cilicilate and alabaster. During weight bearing this coat cracked at several locations. By evaluating the characteristic "crack pictures" he could therefore optically visualise but not quantify the elasticity of the hoof.

Some scientists used radiographic techniques to study the effects of the middle and distal phalanx and the navicular bone in relation to the hoof wall[11]. An other radiographic study assessed this interphalangeal rotation in relation to changes in equine digital conformations[6]. Because of the difficulty to establish those studies on horses in vivo, Hinterhofer[14] programmed a computer model of the equine hoof capsule. Based on this computer model these authors could simulate different limb positions during weight bearing.

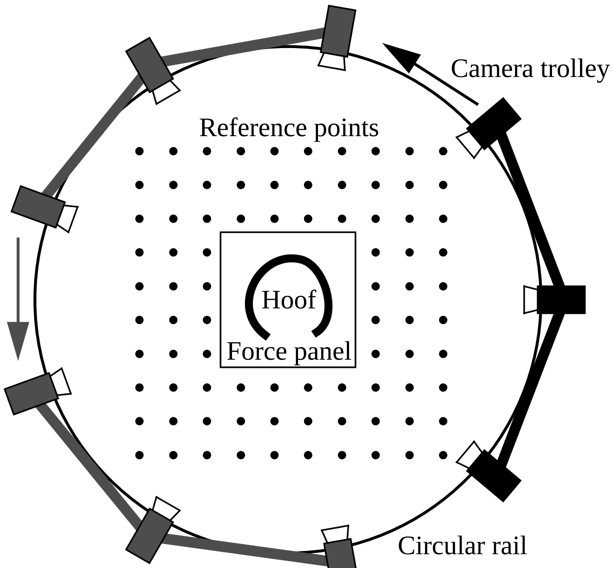
Optical 3D measurement techniques are used in an increasing number of applications. This novel technique for the measurements of hoof capsule movements has been used in humans for measuring parts of the human body as early as 1863 and the first measurements on horses where made in the 1880's[22]. This technique is currently used in facial surgery[5, 23, 15], dentistery and orthopaedics[22]. In the literature different methods are described: (1.) Video-photogrammetry[20, 24, 10], (2.) a laser system for three dimensional surface measurements[19] and (3.) "conventional" photogrammetry with photo-cameras[5, 23, 15]. The measurement accuracy of the above mentioned methods are reported to be accurate down to 1 mm[15, 24, 10]. Because the measured horizontal expansion of the hoof during weight bearing is between two and four millimetres[3, 16, 18], the accuracy of these methods is sufficient to be applied in our study. Even in veterinary surgery these techniques have the potential to deliver a suitable solution in precise measurement tasks. Both hard- as well as software have reached a development standard that commercial systems can be used without adapting them for the special application.

2. SYSTEM REQUIREMENTS

The designed measurement system had to fulfil the following requirements. It should be capable to measure the 3D coordinates of marked points on the horn capsule of living horses. The horses can be tranquilized for a while but data aquisition time should be minimized to avoid displacement of the limb and therefore displacement of the hoof and to reduce physical and psychic strain to the animal as human operators as well. Due to this, the image acquisition should be carried out in a rather short time. Regarding the aspect that the image evaluation is performed by 'non-photogrammetrist' user, the system should be easy to handle. As software package Photomodeler[12, 21] was choosen which on the one hand offers the possibility to calibrate the cameras, triangulate multiple images in a convergent block arrangement and to create 3D models quickly and reliably. On the other hand the system can be used by non-experts concerning photogrammetry knowledge.

2.1. Hardware setup

The acquisition of all the images in one instant of time would take 9 CCD cameras for full coverage. This increases hardware costs significantly. Using three Sony XC75CE CCD cameras mounted on a trolley which can be moved around the hoof on a circular rail, is a good practical solution, regarding tolerable costs and time needed for the image acquistion. The cameras capture 8 bit grey value images with a resolution of 768 x 576 pixels. The image acquisition procedure is made with a Matrox Meteor RGB card which allows the storage of the three images of the three cameras simultaneously in one composite image. The cameras are synchronised and each camera has one canal (Red; Green; Blue). The single canals of the composite image are separated to get grey value images of each camera. The Adobe® Photoshop® software is used to separate the images. The different images are saved and imported in the PhotoModeler®. To standardise the position of the limb a 3D measurement system (Kistler force plate) is used to assess the ground reaction force (GRF). The force plate consists on an aluminium top plate, mounted on four 3-component piezo-electric force sensors. The output of the four sensors is internally reduced to 8 channels to allow force measurements in the tree orthogonal axes (vertical Fz; horizontal lateral, Fx; horizontal fore-aft, Fy). The vertical GRF is a sensible parameter to monitor weight distribution within the four limbs in a quitely standing horse. This allows the standardisation of the measurement series where the different photogrammetry image-trials are sampled at different moments.
To reduce the risk of damage of the cameras, the trolley can be removed quickly when the horse reacts in an unexpected way. To provide suitable lighting conditions in total of four neon lamps are attached to the camera trolley. During the positioning of the horse the camera trolley is taken away and the aluminium plate is covered by a rubber blanket. Instead of moving the cameras exactly to fixed positions with known exterior orientation these parameters are determined for every single image, using a well-defined reference system which is described later in this paper. The circular rail has a diameter of 75 cm, the approximate distance to the measured object results from its radius. This distance in combination with 6 mm objectives leads to a suitable field of view. A graphic representation of the three camera positions around the hoof and the actual set up as shown in Figure 1.



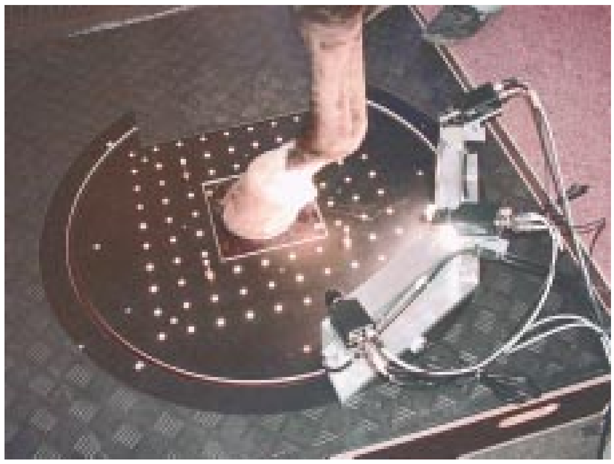


Figure 1: Configuration of the measurement system and image acquisition setup

3. CALIBRATION

To increase accuracy, a calibration procedure is performed to obtain information about the internal orientation of each of the 3 CCD cameras. The Photomodeler is accompanied by the camera calibration tool Calibrator which includes not only the software but also a simple 2D target field, making it very easy to get calibration values from the cameras used. This target field is included in the Photomodeler package as a 35 mm slide which can be projected on a wall or can be printed on paper of a suitable size (Figure 2). At the best the calibration pattern and the typical measured objects have approximately the same size. The used calibration method is semi-automated, after measuring four points on each of the images the corners of the triangles on the pattern are located automatically. Using homologous points and one additionally measured distance on the pattern the numerical values of the camera parameters are determined. To avoid changes of the interior orientation the focus and aperture of the lens can be fixed with screws. For each camera a set of at least 8 images with a good photogrammetric network configuration has to be acquired. Rotating the camera for some of the calibration images serves to eliminate existing correlations between exterior and interior orientation[25]. This procedure has to be performed for every camera and repeated from time to time or after changes in the setup. The arrangement of the cameras in the photogrammetric network used for the calibration is shown in Figure 3.

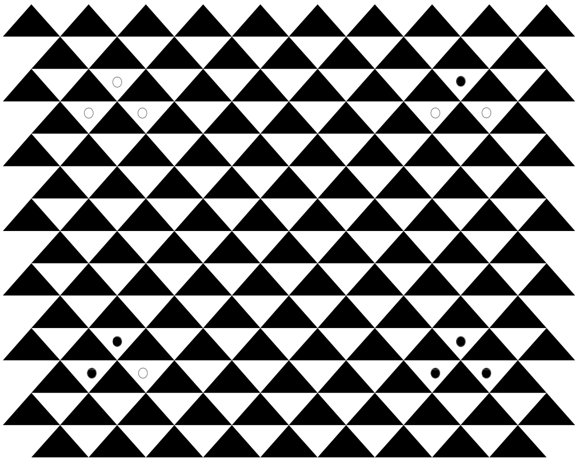


Figure 2: 2D Target pattern

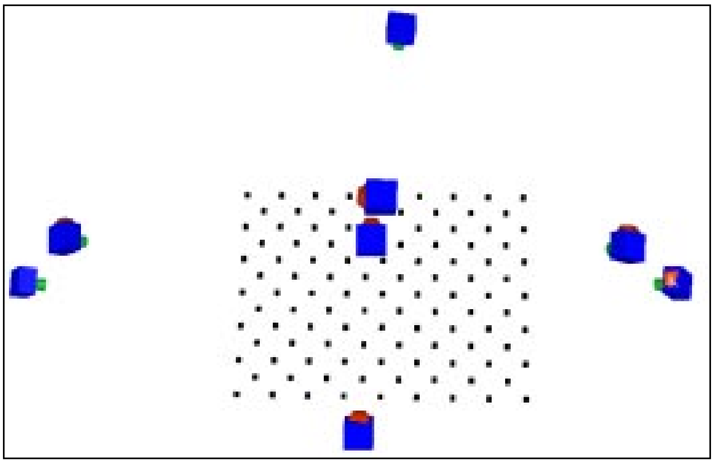


Figure 3: Calibration network

4. DATA PROCESSING

For this study, the movement of the hoof capsule is measured with and without conventional horse shoes. In attempt to standardise the measurements, only healthy hooves will be used to establish normal values. The hoof shape will be scored and selected according to the guidelines reviewed in[2]. Five positions will be measured for each shod and unshod hoof. The first position without wedge, the second with a wedge of 5 mm, the third with a wedge of 10 mm, the forth with a wedge of 15 mm and the last one with a wedge of 20 mm. The horse will be slightly sedated according the recommendation of Colahan[7]. For each position a set of nine images are captured for the deformation analysis. Best point of time for the data capture is when hoof care anyway becomes necessary. The different demanded states of interest with and without horseshoes can then be observed with a minimium of effort. For each set of images the marked points on the hoof have to be reconstructed. The image data sets are processed with PhotoModeler®.

4.1. Definition of the reference system

For the definition of the reference system, 84 points were milled into the anodized surface of an aluminium plate and 8 points were milled to place small spheres in the vertical plane (z-plane). From the specifications of the controlled manufacturing machine, the coordinates of the reference points were milled with a precision in the order of a few micrometers. The aluminium plate has a size of 0.5x0.5 meters with a notch in its center for the force sensor panel where upon the hoof is placed. For a good visibility of the reference points a diameter of 8 mm was chosen and to improve the contrast on the images the milled position was covered with retro-reflective sheeting. In image space the reference points have a diameter of around 10 to 20 pixels, depending on the distance and viewing angle of the recording camera (see Figure 7a) . The white matt spheres made of a synthetic material have a diameter of eight mm and are placed four and eight cm above the aluminium plate. Under the assumption of more or less constant temperature conditions during the data capture, the influence of the coefficient of expansion of the aluminium plate can be neglected.

4.2. Marking of the hoof points

The structure of the hoof capsule delivers not enough contrast to work with natural points. To ensure a good visibility of the points in the different demanded positions they are marked artificially. The distribution of the hoof points is chosen according to the present knowledge of hoof mechanics. Because of the greater movement of the heels - horizontal 2 to 4 mm (Figure 4)

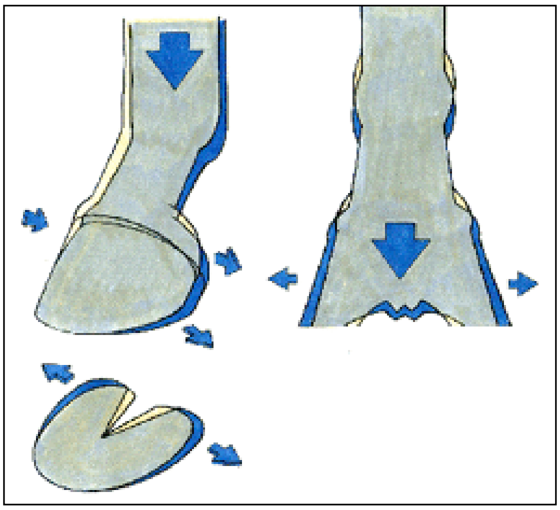


Figure 4: Application of a vertical force running down the leg causes a horizontal outward movement of the walls at the heels (blue) of 2 to 4 mm and a backward movement of the dorsal wall (yellow) at the level of the coronary band.

Figure 5: Palmar side of a front hoof with the 2 balls on the heels

a)

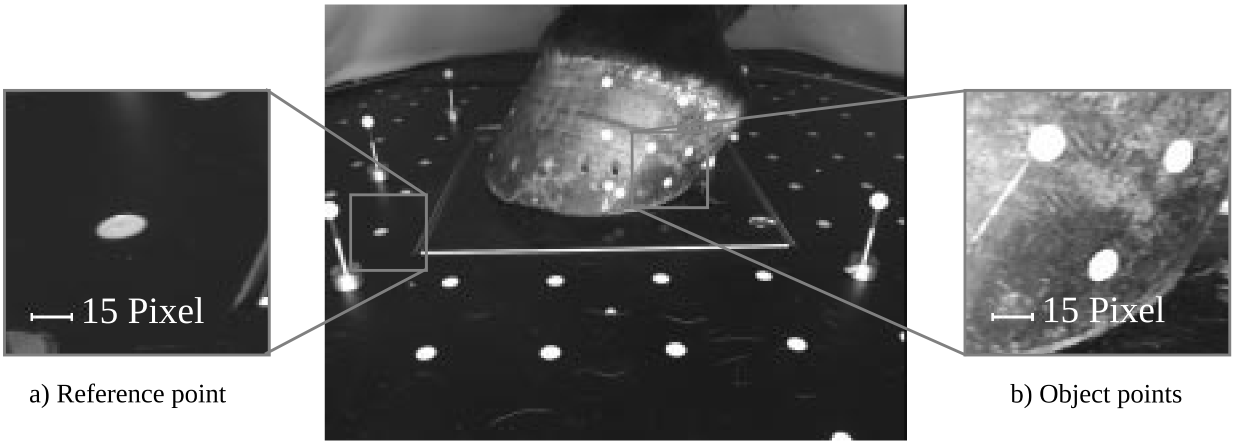
b)

Figure 6: Points arranged perpendicular to the ground on the widest part of the hoof, two rows along the horn tubules (a) and one row on the dorsal wall along the horn tubules (b)

- the points were mainly distributed on the palmar/plantar part of the hoof. One row of 3 points on the widest part of the hoof vertical to the ground, one row halfway between the widest part of the hoof along the horn tubules, one row in the middle between the widest part of the hoof and the heels along the horn tubules (Figure 6a), one row of 3 points was placed on the dorsal wall (Figure 6b) and two small balls of 6 mm diameter each on both heels (Figure 5). With a single perforator circular targets are punched out of retro-reflective sheeting and stuck to the hoof. The fixation should resist the necessary manipulations on the hoof as the removal of the horse shoe. Figure 7 shows a typical image used for the measurement. The points have a diameter of approximately 6 mm which results to approximately 10 pixels in image space (Figure 7b).

4.3. Image coordinate measurement and block triangulation

The interior orientation of the cameras derived from the former calibration is used to model the sensors. Besides of a number of measured tie points with a proper image coverage, the Photomodeler normally needs no approximate values for exterior orientations or object points. But using only the marked points on the hoof which are mostly visible on three images would lead to an unstable photogrammetric block. The photo coverage would be to low and the connection of the images would fail due to a insufficient tie point distribution. Not only the hoof itself but also some of the surrounding reference points have to be visible to allow a reliable calculation of the exterior orientation. To be able to perform a bundle adjustment with all nine



a) Reference point b) Object points

Figure 7: Image used for measurement

images simultanously additional points have to be measured to tie the images together to a common circular block. A smart way to assume enough tie points is to use the points on the aluminium plate for the triangulation. These well-defined points on the aluminium plate with known 3D coordinates are also serving as control points. This leads to a high redundancy and a reliability. The points on the hoof and on the aluminium plate are measured manually or supported by a so-called subpixel target mode which calculates the image coordinates as the center of an imaged circular object automatically. Working with this subpixel target mode requires a good image quality regarding contrast and noise but also the suitable dimension of the imaged point. This is not always the case and the resulting image coordinate should be checked carefully and remeasuring the point might be necessary. This was especially necessary when the markers had an oval shape. In such cases the markers had to be measurement manually which represents a potential source of error because the precise positioning is not possible in a reliable way.
After the measurement of the image coordinates the correspendences between homologous points have to be established. It is advisable to triangulate sequentially starting from a triplet of adjoining images and then to continue by adding one after the other. When an image is oriented once the display of epipolar lines can be helpful to find further corresponding points in the other images. For the rather small number of object points on the hoof this is not as important as for the reference points because reliable assignment of these points is sometimes, due to their similar appearence only possible when they are seen in a wider image context. Moreover the possibility to merge point pairs that correspond to the identical object point is given.

4.4. Photogrammetric network design and results of the 3D modeling

Optimally the nine images are arranged regularly around the hoof. The resulting camera arrangement is shown in Figure 9, including the calculated 3D points. Due to the fact that most hoof points can be measured on three images the resulting intersection angle of the homologous rays is around 60 degrees which allows a good determinability in object space.
After optimising the experimental set-up, a first trial was conducted, testing the reproducibility of the 3D coordinate determination of the object points. Therefore 9 images of the same hoof were recorded and subsequently four models of the hoof capsule reconstructed. At the same time the coordinates of five calibration points within the reference system were calculated.
For each marker on the hoof capsule the mean value (n=4) of the x/y/z coordinates and for the calibration points the mean difference (n=4) between the known reference values and the measured coordinates were calculated.

Hoof capsule marker points:

The precision of marker detection was considered as "very precise" if the divergence to the mean values of all three marker coordinates was ≤ 0.1 mm; as "precise" if the divergence to the means was between 0.1 and 0.2 mm; and as "moderately precise" if the divergence was > 0.2 mm. Out of the 22 hoof markers 11 were reconstructed with a precision of 0.1 mm ("very precise"). 9 points were reconstructed "precisely" and 2 points were reconstructed with a precision between 0.2 and 0.3 mm ("moderately precise"). From the distribution of the "very precise" and the "moderately precise" points the following statements can be made: The coordinates of a marker can be reconstructed the more precisely

- 1. the more images are available depicting the marker.
- 2. the more perpendicular the images are taken from a specific marker.

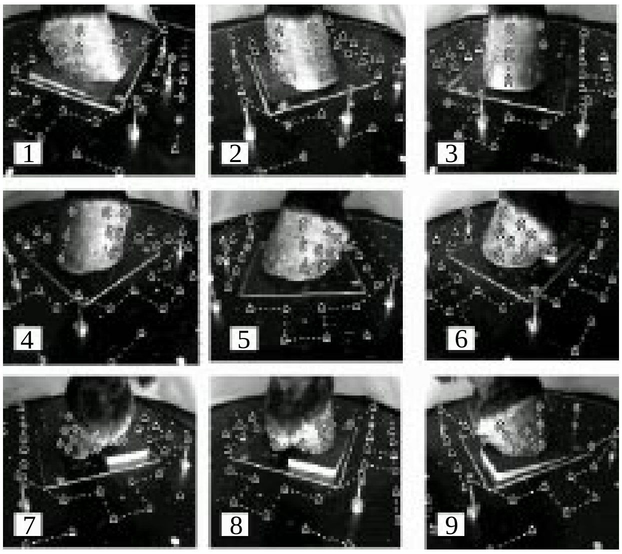


Figure 8: Set of nine measurment images

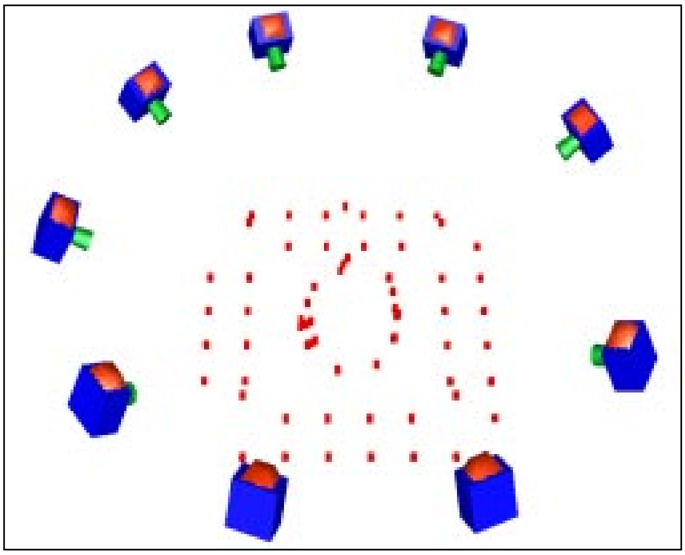


Figure 9: Camera arrangement with 3D points

Oblique shots, where the markers are portrayed as an oval or even as a line, limit the precision of reconstruction. The resulting camera arrangement calculated from the nine images shows some lack in the overlap of the inner medial hoof part lying between the front limbs (see Figure 8 and Figure 9). The hoof markers of the inner medial hoof wall are displayed optimally on images N˚1 and 9 (see Figure 8) and adequately on images N˚ 2 and 8. In contrast, the markers of the outer lateral hoof wall are displayed optimally on 4 images (N˚4, 5, 6, 7) and partly on image N˚3 and could be therefore reconstructed by a majority "very precisely". To further increase the accuracy, the camera and trolley positions have to be improved. Because of safety reasons this is associated with considerable risks, as the trolley has to be positioned very closely to the opposite front limb. However, only after optimising the camera positions the needed accuracy of <0.2 mm can be guaranteed for any point on the hoof capsule.

Control points:

The precision of reference point detection was considered as "very precise" if the differences to the reference values of all three axes were ≤ 0.1 mm; as "precise" if the differences were between 0.1 and 0.2 mm; and as "moderately precise" if the differences were > 0.2 mm. The differences to the reference values were either "very precise" or "precise" with the exception of one reference point where the difference in the y-axis exceeded the acceptable 0.2 mm. After inspection of the plate it was noticed, that this point was not precisely milled. Therefore, the reference coordinates of this point had to be corrected. In a first preliminary trial the effect of a 10 mm wedge under an unshod hoof was assessed and compared to the non-wedged condition. All coordinates of hoof markers one the wedged site differed more than 0.3 mm between wedged and non-wedged condition. Therefore it can be assumed that the present experimental set-up is of adequate precision to answer the questions raised for the study.

5. DEFORMATION ANALYSIS

As a result the photogrammetric evaluation 3D coordinates from the marked points on the hoof can be determined. The point clouds of the different load situations can then be used for a deformation analysis. The influence of the changing load condition on the deformation of the horn capsule can be investigated. After changing the load condition the horseshoe can not be placed exactly in the same position on the force sensor panel. Due to this fact the derived 3D points have to be transformed in one common coordinate system before a detailed analysis.

6. CONCLUSIONS

It has been shown that off-the-shelf hardware components as standard video cameras and a low-cost software package for the photogrammetric evaluation of the image data offer a convenient tool to measure deformations of the horn hoof capsule under different load condition with a suitable accuracy. The application of the so-called softcopy photogrammetry in the field of veterinary surgery proves the flexibility and potential of this optical 3D measurement technique.

7. ACKNOWLEDGEMENT

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