EQUINE VETERINARY JOURNAL
*Equine vet. J.* (2006) **38** (7) 610-615
doi: 10.2746/042516406X150367

# Reliability of conformational measurements in the horse using a three-dimensional motion analysis system

**R. WELLER*, T. PFAU†, D. BABBAGE, E. BRITTIN, S. A. MAY** and **A. M. WILSON†‡**

*Department of Veterinary Clinical Sciences and †Structure and Motion Laboratory, Department of Veterinary Basic Sciences, The Royal Veterinary College, Hawkshead Lane, North Mymms, Hatfield, Hertfordshire AL9 7TA; and ‡Institute of Human Performance, University College London, The Royal National Orthopaedic Hospital, Brockley Hill, Stanmore, Middlesex HA7 4LP, UK.*

**Keywords:** horse; conformation; motion analysis; 3D; photography

## Summary

*Reasons for performing study:* **The importance of a reliable method for conformation studies is generally acknowledged, but there are only limited data on the accuracy and precision of current assessment methods.**

*Objectives:* **To assess (1) the accuracy and repeatability of marker placement, (2) influence of stance of the horse on conformational parameters, (3) practicality of a computerised motion analysis system and (4) to compare the computerised motion analysis system to photographic systems of assessment.**

*Methods:* **Twenty-eight reflective markers placed over anatomical landmarks were located in 3D using a computerised motion analysis system and their coordinates used to calculate segment lengths and joint angles. Four experiments, involving a cadaver study, a series of repeated measures on a single Thoroughbred and repeat measurements on 108 racehorses were performed.**

*Results:* **Identification of anatomical landmarks was found to introduce the biggest variation in the measurements for proximal conformation parameters with the interoperator being larger than intraoperator variation. Length measurements were least influenced by stance, with distal interphalangeal and metacarpo/metatarsophalangeal joint angles being the most variable. In some measurements, the variation between stances within a horse proved to be almost as large as between horses, rendering these parameters less useful as predictors of performance or orthopaedic health.**

*Conclusions:* **A computerised motion analysis system allows 3D assessment of conformation with high accuracy and precision. It eliminates 3 major sources of error associated with photography-based methods and increases accuracy of conformational assessment by allowing repeat measurements in a relatively short period.**

*Potential relevance:* **Studies on conformation should be viewed in the light of the limitations of the measurement technique used. The presented method maximises accuracy and precision and is a valuable basis for future studies investigating the effect of conformation on performance or orthopaedic health.**

## Introduction

Conformation has been thought of as an indicator of performance and orthopaedic health of horses since about 360 BC (Morgan 2002) and there has been a constant supply of publications in this area over the last few centuries (Holmström 2001). 'Conformation' describes the shape of a horse (Stashak 1987) and conformational traits comprise segment lengths, joint angles and deviations of segments from the vertical. These parameters are usually measured from the external appearance of an animal or, less commonly, on radiographs (Barr 1994; Eksell *et al*. 1998). In early studies, measurements were performed with a tape measure and a goniometer, a time-consuming process eventually replaced by photography (Kronacher and Ogrizek 1931; Magnusson 1985; Holmström *et al*. 1990) or video-recorded images (Hunt *et al*. 1999). In most recent studies, digital photography was employed with (Dressel 2002) or without (Anderson and McIlwraith 2004) a reference frame. Despite the importance of a reliable method for conformation studies (Belloy and Bathe 1996), there are few studies evaluating their accuracy and precision (Magnusson 1985; Hunt *et al*. 1999).

Marker placement and stance of the horse are 2 main sources of error. To be able to measure length of segments and joint angles the ends of these segments and the centre of rotation of the joint have to be identified in a repeatable manner. This is usually done by placing markers over palpable skeletal landmarks. Some landmarks are easily palpable and well defined but others are not, because of overlying muscles or the large size of the landmark, for example. In addition, if the horse moves, the location of the bony landmarks relative to the overlying skin changes. This causes errors both during marker placement and during or between the actual measurements (especially for angles).

If photographic methods are used, there are 3 additional potential sources of error: (1) deviation in the camera-horse angle distorts measurements, (2) geometrical errors when a 3D object is reduced to a 2D image and (3) limited accuracy achieved in measuring conformational parameters from photographs by hand.

A passive motion analysis system consists of a set of video cameras that send out and detect infrared light and are used in conjunction with reflective markers. A multiple camera system can locate each marker within a predefined 3D volume to an accuracy better than 0.6 mm (Pfau *et al*. 2005) and the distance

*Author to whom correspondence should be addressed.
*[Paper received for publication 07.07.05; Accepted 03.04.06]*

between markers can than be calculated from the output coordinates. While still susceptible to marker placement and stance related errors, the 3D computerised motion analysis system enables repeated measurements in 3D, with high accuracy and removes the potential distortions from 2D photography.

We hypothesised that a 3D motion analysis system would be a repeatable, quick and practical method for conformation measurement in the horse. To test the hypothesis 4 experiments were undertaken to assess: a) accuracy of marker placement, b) interoperator agreement of marker placement, c) intraoperator repeatability of marker placement, d) stance related measurement error, e) agreement between photography and motion analysis measurements; and f) practicality of a motion analysis system in the measurement of conformation with regard to time and space requirements.

## Materials and methods

### Experiment 1: *Accuracy of marker placement*

The whole cadaver of a horse killed for reasons unrelated to this study was used to identify bony landmarks used in the main part of the study. The horse was placed in right lateral recumbency. Hypodermic needles were placed at the end of segment lengths and over the centre of rotation of joints, using landmarks as proposed by Holmström (2001). After placement, the position of the needle in relation to the underlying bony landmark was evaluated by radiography and dissection. Lateromedial and craniocaudal (dorsopalmar/plantar) radiographs were obtained of the markers placed including and distal to the elbow and stifle joint. The radiographs were acquired with a mobile x-ray unit (Hunter X-ograph Imaging System GOP 1000G)[1] and digital cassettes (CR MD 4.0)[2], which were digitised (CR 25 digitiser)[2] and exported as bitmap images for further analysis in Image Tool (v.3)[3]. The distance of the needles to the centre of the landmark was measured on the radiographs. Needle placement proximal to the elbow and stifle was assessed qualitatively by carefully removing the soft tissue around the needle and identifying the position of the needle in relation to the underlying bone.

### Experiment 2: *Interoperator repeatability and distribution of conformation parameters*

An unshod 8-year-old Thoroughbred mare owned by the Royal Veterinary College was used. A passive motion analysis system with 4 cameras (ProReflex MCU 500)[4] was set up in a covered area with a flat, level concrete surface to view one side of the horse at a time and calibrated for 3D acquisition. Polystyrene hemispheres with a diameter of 2.5 cm, covered with reflective tape (Scotchlite 8850)[5] were used as markers. These were fixed to 28 bony landmarks using heavy-duty double-sided tape (R370)[6] on the left side of the horse (Table 1). The horse was led into the calibrated area and positioned so that it was equally weightbearing on each leg, and both front and hindlegs were at the same level. Images were acquired over 3 sec at a frame rate of 50 frames/sec. Data were discarded and the acquisition repeated if the horse moved. The position of each marker in space was determined by the motion analysis cameras and described by its x, y and z coordinates. The axes were defined employing a right-handed coordinate system with the x-axis denoting the craniocaudal, the y-axis denoting the lateromedial and the z-axis the proximodistal direction. To avoid the effect of outliers caused by erroneous markers, the median coordinates for each marker of the 150 frames/image acquisition was used for the consequent calculations. Segment lengths equal the length of the vector between markers, joint angles equal the angles enclosed by those vectors and were calculated using a custom-written programme within the software package MATLAB[7]. Angles were defined in a mathematical positive sense. To mimic angles commonly used in subjective assessment of conformation, the inclination (angle between segment and horizontal plane) was calculated for the scapula, humerus, pelvis, femur and hoofs. The deviation of the leg from the median plane (resembling a view from cranial) and the deviation from the transverse plane (resembling a view from lateral) were calculated at the level of each joint. The median plane was defined as the plane through the markers on the withers and tail root, orientated orthogonal to the floor. The transverse plane was defined orthogonal to the median plane.

Segment lengths and joint angles were also calculated in 2D in the median (xz plane, resembling a lateral photographic view) and in the transverse plane (yz plane, resembling a cranial photographic view) to enable comparison with conventional conformation assessment methods.

Three operators (E.B., D.B. and R.W.) repeated the marking process 3 times each. For each marking the acquisition process was repeated 5 times, except for operator 3 for whom the acquisition process was repeated 25 times for the third marking. Between each acquisition the horse was led out of the calibration area, returned and repositioned.

### Experiment 3: *Stance dependent repeatability and comparison between motion analysis and photography based measurements*

Conformational measurements were acquired repeatedly of 108 Thoroughbred racehorses from one National Hunt racing yard.

**TABLE 1: Names of markers and their anatomical location**

| Marker name | Location |
|---|---|
| atlas | Most cranial point of wing of atlas |
| scapula | Tuber of spine of scapula, proximal end |
| dsp | Highest dorsal spinous process |
| humerus | Between cranial and caudal part of greater tubercle |
| elbow | Caudal edge of lateral collateral ligament of elbow joint |
| radius | Lateral styloid process of radius, most prominent point |
| carpus | Midpoint of dorsal aspect of antebrachiocarpal joint |
| mc4 | Base of 4th metacarpal bone |
| mcp lat | Midpoint of lateral aspect of metacarpophalangeal joint |
| mcp dors | Midpoint of dorsal aspect of metacarpophalangeal joint |
| coronet fore | Midpoint of dorsal aspect of coronet forelimb |
| hoof fore | Midpoint of dorsal aspect of toe forelimb |
| heel fore | Heel bulb forelimb, dorsal |
| *tubercoxae* | Most cranial part of *tuber coxae* |
| *tubersacrale* | Middle of *tuber sacrale* |
| tailroot | Tail root |
| ischialtuber | Lateral aspect of most caudal point of ischial tuber |
| greater trochanter | Most cranial part of greater trochanter of femur |
| stifle | Distal end of patella |
| tibia | Lateral malleolus of tibia, most prominent point |
| tarsus | Midpoint of dorsal aspect of tarsocrural joint |
| calcaneus | Highest point of calcaneal tuber |
| mt4 | Base of 4th metatarsal bone, most prominent point |
| mtp lat | Midpoint of lateral aspect of metatarsophalangeal joint |
| mtp dors | Midpoint of dorsal aspect of metatarsophalangeal joint |
| coronet hind | Midpoint of dorsal aspect of coronet hindlimb |
| hoof hind | Midpoint of dorsal aspect of toe hindlimb |
| heel hind | Heel bulb hindlimb, dorsal |

The same experimental set-up was used as described for *Experiment 2*. Thirty-two segment lengths and 11 joint angles were calculated (for complete list of conformational parameters and the anatomical landmarks used for their calculation see supplementary online information, www.evj.co.uk/suppinfo, Table 2). The same operator put the markers on the left side of each horse and 3 repeat acquisitions were performed. Between each acquisition, the horse was led out of the calibration area, in again and repositioned. After the acquisitions for the left side were completed the same process was performed on the right side. Time needed for marking and for acquisition was recorded for the first 20 horses. Left and right sides were treated as separate samples to avoid the asymmetry of the horse itself (Manning and Ockenden 1994) and in marker placement (Audigie *et al*. 1998) influencing the assessment of repeatability of the method.

A digital camera (Cybershot DSC-P5, 3.4 million pixels)[8] was set up on a tripod equipped with a water level. Pictures were taken of both sides of each horse with the camera parallel to the ground and aimed at the *tuber olecrani*. A rod with 2 markers at a distance of 150 cm was used for spatial calibration. Images were analysed in Image Tool and all images were viewed at 50% of the original image size (72.25 x 54.19 cm, 2048 x 1536 pixels) on a 19 inch monitor (J Vision Master 1451-LS902UTG)[9]. Segment lengths and joint angles were measured by identifying the markers using a graphics tablet with a stylus (Digitizer2, UD1212R)[10].

Experiment 4

A subset of 12 horses from the cohort used in *Experiment 3* was used to evaluate intraoperator repeatability. The set-up remained the same as in *Experiments 2* and *3*. One operator (D.B.) repeated the marking process twice on these horses (left side) on the same day, but not consecutively. The acquisition process was repeated twice for each marker placement.

*Data analysis*

*Interoperator repeatability:* Data from *Experiment 2* were used to assess interoperator agreement. The measurements obtained from the 15 repeated acquisitions (3 markings x 5 repeats) were averaged for each conformation parameter. For the third marking of operator 3, only the first 5 repeated acquisitions were used. The average value of each conformation parameter was then used to calculate the differences between each pair of operators and expressed as percentage of the measurement mean (coefficient of variation, CoV). The differences between each pair of operators are displayed as bar charts for selected length and angle measurements (Fig 1).

*Intraoperator repeatability*

Data from *Experiment 4* were used to assess intraoperator repeatability. The 2 acquisitions per marking were averaged for each conformation parameter. These averages were then used to calculate the differences between each marking for each conformation parameter. The distribution of the differences was evaluated graphically by plotting histograms and the relationship between the differences and the mean by plotting scatterplots. Once the assumptions of normality and independency of the mean for the differences were checked graphically and found to be satisfactory, the mean and s.d. of these differences ($s_d$) were determined. The 95% limits of agreement were calculated as mean difference ± 1.96 x $s_d$ (Bland and Altman 1986). The precision of the estimated limits of agreement was determined by calculating their s.e.= $(3\ s_d\ 2/n)^{1/2}$ where n = number of subjects).

*Stance related measurement error:* Magnitude and distribution of measurements were assessed graphically and descriptively for each conformation parameter from the 25 repeated acquisitions in experiment 2. Data from *Experiment 3* were used to calculate the within-subject s.d. ($s_w$) as a measure of repeatability (Bland and Altman 1986). The variances of repeated measures on the same subject were calculated and $s_w$ determined for each conformation parameter by averaging the variances and taking the square root (sqrt). The difference between 2 measurements for the same subject is expected to be less than 1.96 x $s_w$ on either side for 95% of observations. $S_w$ was calculated separately for the left and right side and then averaged for each conformation parameter. $S_w$ as percentage of the population mean and the ratio between $s_w$ and the between-subject standard deviation ($s_b$) was also calculated.

The precision with which $s_w$ can be estimated depends on the number of subjects and the number of observation per subject and expressed as the s.e. = $s_w/(2n[m-1])^{1/2}$, where n = number of subjects and m = number of measurements.

*Comparison between motion analysis and photography*

*Repeatability of measuring parameters from photographs:* Nine conformation parameters were measured on the photographs of the left side of 70 horses obtained in *Experiment 3*. The selected parameters were neck, withers, humerus, heel fore, shoulder, mcp and tarsal joint, scapula incline and deviation of the forelimb viewed from lateral. The measurement process was repeated 3 times per photograph and $s_w$ determined as described above (Bland and Altman 1986). Repeatability of the photographing process itself was not assessed in this study, but was reported by other authors to be largely influenced by the angle of the lens with regards to the horse and the distance between the camera and the horse (Magnusson 1985; Hunt *et al*. 1999).

*Magnitude of the geometrical error:* The projection of a 3D structure onto a 2D plane results in a geometrical error. The magnitude of the geometrical error depends on the angle of the segments to the median plane ($\alpha$), where the 2D length is $\cos(\alpha)$ x 3D length. Alpha was determined for the data obtained in *Experiment 3* and the geometrical error calculated.

*Agreement between motion analysis and photography based measurements:* The 9 parameters measured from photographs in 70 horses were compared to the same measurements obtained in 3D with the motion analysis system in *Experiment 3*. These were the same 70 horses as used for the assessment of repeatability of measuring conformational parameters from photographs. Agreement between photography and motion analysis was assessed by determining the 95% limits of agreement as described above (Bland and Altman 1986).

**TABLE 2: Conformation parameters and the markers used for their calculation**

Refer to www.evj.co.uk/suppinfo for details.

## Results

### *Times for procedure*

Data for *Experiment 3* were collected over 7 days, mean working time 9 h/day, involving 6 personnel, camera set-up and calibration took about 30 min, positioning of horse for marking and marking process 10 min, range 8–16 min/side. One horse could not be used, since it was not possible to place markers on its hindlegs. Time for 3 repeat acquisitions for each horse side was 2–8 min, mean 4 min. Post processing involved identification of the markers within Qualisys track manager[4] and exporting the 3D coordinates of these markers to Matlab[7]. Identification of markers took about 4 min/horse side, exporting the data to Matlab was performed as batch process and the programme took about 2 h for computation of all conformation parameters in 216 horse sides.

### *Marker placement*

*Accuracy:* In *Experiment 1* on the cadaver, the accuracy was found to be excellent for all landmarks distal to the elbow and stifle respectively (<0.5 cm), but less accurate for proximal landmarks. This was due largely to proximal landmarks being bigger, especially the greater trochanter, *tuber coxae*, greater tubercle, *tuber sacrale*. For subsequent experiments, the list of landmarks was revised and landmarks described in more detail, (e.g. cranioproximal border of the greater trochanter or the middle of the *tuber sacrale)* or landmarks that are easier to identify were used (Table 1).

*Interoperator comparison:* For length measurements the mean ± s.d. difference between all 3 operators in absolute values was 2.13 cm ± 2.60 cm. The CoV ranged from 0.62 % (withers) to 19.25% (carpus), mean CoV 6.15 ± 6.08%.

For angle measurements mean ± s.d. difference between 3 operators in absolute values was 2.96 ± 1.57°. The biggest differences in absolute values were observed for pelvis, back and hindlimb (all 3 associated with the *tuber sacrale* marker), shoulder and elbow joint in front (both defined over humerus marker) and stifle and tarsal joint in the hindlimb (both defined over stifle marker). The large difference between operators observed for the parameter 'pelvis' was due to a misidentification of the *tuber coxae* marker by operator 1. The differences in segment lengths and joint angles between operators are illustrated in Figure 1.

*Intraoperator repeatability:* Mean difference between markings for segment length measurements was 1.13 cm with a maximum difference of 2.53 cm for the back length. Mean differences over 2 cm were found in neck, trunk length, croup length and tibia. Back, trunk and croup length measurements were all based on the *tuber sacrale* marker. Lengths measurements distal to the carpus and tarsus showed average differences under 1 cm. The width of the 95% limits of agreement (difference between upper and lower 95% limit of agreement) was mean ± s.d. 3.81 ± 2.42 cm. Mean s.e. of the limits of agreement for length measurements was 0.63 ± 0.22 cm.

For angle measurements, mean difference between markings was 3.2°. The width of the 95% limits of agreement was mean ± s.d 11.72 ± 7.43°, s.e. of the limits of agreement for angle measurements was 1.18 ± 0.38 cm.

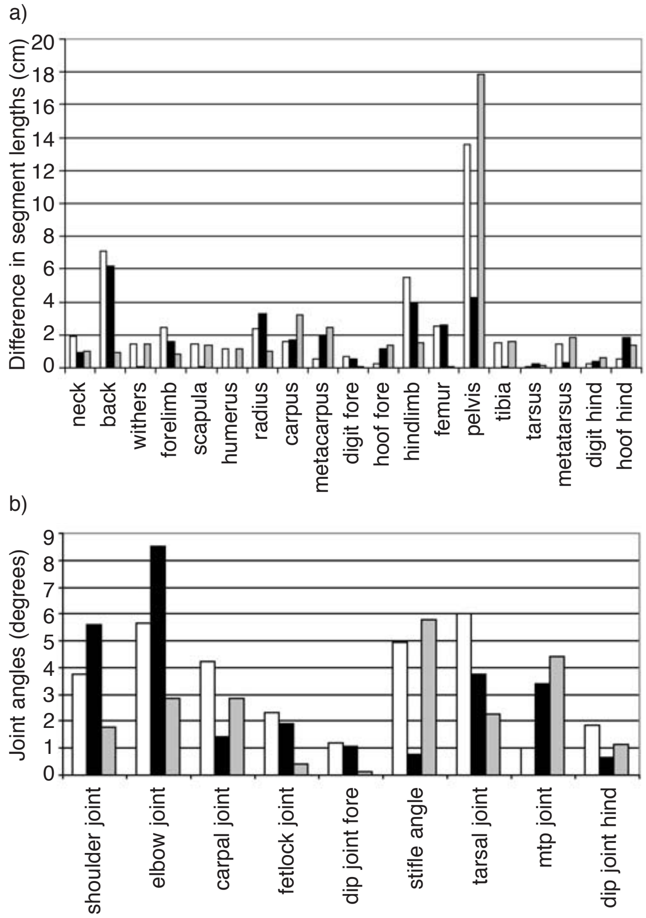


*Fig 1: Interoperator comparison: the columns represent the differences in segment lengths in cm (a) and joint angles in degrees (b) between operator 1 and 2 (white), operator 2 and 3 (black) and operator 1 and 3 (grey).*

Some of the biggest differences for 3D and lateral 2D angles were associated with the coxal, hip and stifle angles, all of which are associated with the greater trochanter marker. For cranial angles the biggest differences were associated with the metacarpophalangeal joint (mcp), the distal interphalangeal joint (dip) in the forelimb and both hoof angles. The marker common to these joints was the coronet marker (Table 3, see www.evj.co.uk/suppinfo).

### *Stance related repeatability*

For the 25 acquisition repeats in the single horse used in experiment 2, CoV was 0.13 (carpus angle) to 5.23% (dip angle), mean 1.45%. All conformation measurements were normally distributed.

Figure 2 illustrates the ratio between $s_w$ and $s_b$. $S_w$, $s_b$ and the population mean (mp) for each conformation parameter are provided as supplementary online information, (Table 3, see

**TABLE 3: Intraoperator repeatability of marker placement: mean (mean diff) and s.d. (s.d. diff) of the differences between markings for each conformation parameter based on 2 repeated marker placements in 12 horses. Stance-related repeatability: within-subject standard deviation ($s_w$), between-subject s.d. ($s_b$), study population mean (mp) for each conformation parameter based on three repeated acquisitions in 108 horses. Lengths in cm, angles in degrees**

For full table see www.evj.co.uk/suppinfo

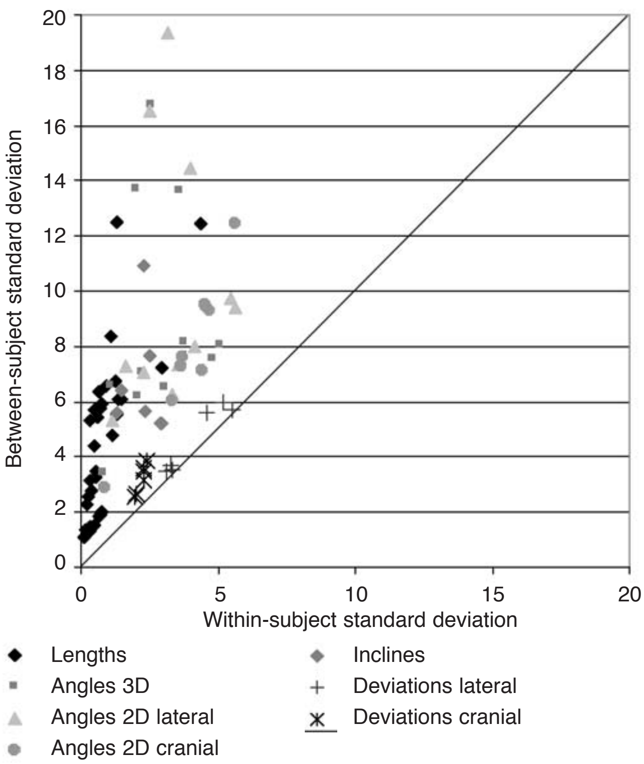


*Fig 2: Stance related repeatability, within-subject standard deviation vs. between-subject standard deviation for each parameter, categorised in lengths, 3D angles, 2D angles, inclines and deviations. While for the majority of measurements the ratio between the within-subject standard deviation and between-subject s.d. is well above 1, for deviations it is just above 1, indicating that the differences between horses are in the same order of magnitude as the differences between different stances within one horse.*

www.evj.co.uk/suppinfo). For length measurements the highest $s_w$ were found for horse length and neck. $S_w$ expressed as percentage of mp was highest for heel measurements, due to the relative effect of a small variation on a small measurement. The lowest ratios of $s_w$ and $s_b$ (<3) were found for the neck, front and hind digits and the tarsus.

For joint angles, the highest $s_w$ were found for the front and hind dip joints, mcp and mtp joints. The lowest ratio of $s_w$ and $s_b$ was also found for the front and hind dip joints.

For deviations, the ratio between $s_w$ and $s_b$ was 1.06 to 1.56, with a mean of 1.28 ± 0.20, indicating that the between-subject variation was only slightly higher than the within-subject variation. The standard error $s_e$ was below 0.10 cm for length measurements and below 0.11° for angle measurements.

*Comparison between motion analysis and photography*

*Repeatability of measuring segment lengths and joint angles from photographs:* $S_w$ was between 0.03 and 0.06 cm for length measurements and between 0.02 and 0.12° (mcp joint) for angles. When expressed as percentage of the population mean this corresponds to values below 1% for all measurements, except for the height of the heels where it was 1.5% and deviation of the foreleg from the vertical where it was 9.5%. This is caused by the small population mean of 2.2° for this parameter. The standard error $s_c$ was below 0.53 cm for length measurements and below 0.05° for angles.

*Magnitude of geometrical error:* Mean α for all segment measurements was 10° with the scapula showing the highest degree of deviation from the median plane (20.25° on average with a maximum of 27.1° and a minimum of 10.3° of deviation). This resulted in an average geometrical error of 2 cm with a maximum average error for the scapula length of 5 cm.

If α does not vary between horses, the geometrical error could be corrected by multiplying the 2D measurements by a constant factor. However in this study the length measurements with the biggest α also showed the biggest ranges in α. In the example of the scapula this would lead to a 10% error.

*Comparison of photography and motion analysis based measurements:* For the selected length measurements, mean differences were 1.25 cm (heel forelimb) to 4.0 cm (withers) with the width of the limits of agreement 2.99 cm (heel front) to 12.69 cm (withers). For the selected angles mean differences were 1.69° (tarsal joint) to 3.89° (mcp) with width of limits of agreement 4.42° (shoulder) to 13.21° (mcp). The s.e. of the limits of agreement was below 0.54 for all parameters.

**Discussion**

A computerised motion analysis system enables measurement of conformational parameters in 3D, thereby enhancing accuracy of conformation assessment by eliminating 3 sources of error encountered when using photography. It is independent of camera position relative to the horses, which is crucial when using photography (Magnusson 1985; Hunt *et al*. 1999). It also takes away error caused by reduction of a 3D structure onto a 2D image, which is found to result in an average error of 2 cm for length measurements in this study. Correction for this geometrical error requires knowledge of the angle of the segment to the median and would require an additional photograph from the cranial or caudal aspect of the horse. Computerised motion analysis does not rely on the post acquisition identification of markers by an operator as required when using photography. The repeatability of identifying markers on photographs performed by a single operator was found to be below 1% for all length measurements, but increased to 10% for deviations, therefore adding another source of error.

All conformation measurements proved to vary with the stance of the horse, as reported by others (Magnusson 1985; Dressel 2002). Twenty-five repeat measurements in a single horse, with the same set of markers showed that the majority of conformation parameters followed a normal distribution and, therefore, 95% of repeats would be within 2 s.e. of the mean. Few extreme outliers were observed. Since s.e. is defined as s.d. of the parent distribution divided by the square root of the sample size, repeat measurements lead to a smaller s.e. The use of a motion analysis system enables the repetition of acquisitions in a relatively short period leading to an increase in the accuracy of the measurement. There is a trade-off, however, between the benefit of increasing the number of repeats and the period necessary for each horse. Three acquisition repeats lead to a decrease of the s.e. by about a factor of 2, while, at the same time, keeping average acquisition time under 10 min/horse. This would be difficult to achieve with photography based systems since it requires a minimum of 4 photographs to assess the whole animal (left and right lateral, cranial and caudal aspects) and these would have to be performed without the horse moving during recording and repositioning.

In this study, a 4-camera motion analysis system was used, which enabled assessment of the conformation of one side of a horse with one acquisition. With the use of 8 cameras the conformation of a whole horse could be assessed in a single acquisition. This however increases the demand for space to an area of 10 x 6 m, which may prove difficult to find in a racing yard, especially when the weather requires the use of an indoor barn. Motion analysis systems are designed for indoor use. Passive motion analysis cameras not only pick up the light reflected back from the markers, but are also sensitive to the infrared part of daylight. The system was set up outdoors in full sunlight, in the shade and in a partially covered barn. The system can be used outside as long as there is no direct sunshine and no reflective surfaces, which result in aberrant markers.

In some conformation measurements, namely deviations of the limb from the vertical, the variation between stances within one horse proved to be almost as wide as the variation between horses, hence rendering these parameters less useful as predictors of performance or orthopaedic health.

Identification of anatomical landmarks forms the basis of all conformation measurement methods and this was found to introduce the widest variation in the measurements for proximal conformation parameters. The variation is caused by the difficulties arising from palpating the more proximal landmarks through overlying muscle layers and by the bigger and less well defined nature of these landmarks. To circumvent variability introduced by different operators, one operator only should apply the markers. However, agreement between operators might improve with training. Marking each horse several times improves the accuracy of the measurements, but each additional marking requires an extra 20 min/horse on average. This may be difficult when a large number of horses in a busy racing yard are to be measured and access time to the horses is limited.

In conclusion a computerised motion analysis system allows the 3D assessment of conformation with high accuracy and precision. It eliminates 3 major sources of error associated with photography-based methods and increases accuracy of the measurements by allowing repeat acquisition in a relatively short period. The biggest source of error in conformational measurement is marker placement over skeletal landmarks, especially on the proximal skeleton, followed by the way a horse stands.

## Acknowledgements

We would like to thank the participating racing stable for use of their horses, Dr. Aviva Petrie for advice on statistics, Marta Ferrari and Glen Lichtwark for help with data collection, Anna Wilson for help with the manuscript, and the BBSRC and the German Science Foundation for funding (DFG Emmy Noether Program WE 2180/1-1).

## Manufacturers' addresses

[1]Philips Medical Systems, Reigate, Surrey, UK.
[2]Agfa-Gevaert Ltd, Brentford, Middlesex, UK.
[3]The University of Texas Health Science Center, San Antonio, Texas, USA.
[4]Qualisys Medical AB, Gothenburg, Sweden.
[5]3M Personal Safety Products, Manchester, UK.
[6]ANCA Industrial supplies, Halesowen, West Midlands, UK.
[7]The MathWorks, Inc., Natick, Massachusetts, USA.
[8]Sony Corporation, Weybridge, Surrey, UK.
[9]New Monitors, Continental Limited, Cheltenham, UK.
[10]WACOM Europe GmbH, Krefeld, Germany.

## References

Anderson, T.M. and McIlwraith, C.W. (2004) Longitudinal development of equine conformation from weanling to age 3 years in the Thoroughbred. *Equine vet. J.* **36**, 563-570.

Audigie, F., Pourcelot, P., Degueurce, C., Denoix, J.M., Geiger, D. and Bortolussi, C. (1998) Asymmetry in placement of bilateral skin markers on horses and effects of asymmetric skin marker placement on kinematic variables. *Am. J. vet. Res.* **59**, 938-944.

Barr, A.R.S. (1994) Carpal conformation in relation to carpal chip fracture. *Vet. Rec.* **134**, 646-650.

Belloy, E. and Bathe, A.P. (1996) The importance of standardising the evaluation of conformation in the horse. *Equine vet. J.* **28**, 429-430.

Bland, J.M. and Altman, D.G. (1986) Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* **1**, 307-310.

Dressel, C. (2002) *Die objektive Messung der Gliedmassenstellung beim Pferd mittels Photogrammetrie: Evaluation einer neuen Methode*. PhD thesis, University of Zürich, Zürich.

Eksell, P., Axelsson, M., Brostrom, H., Roneus, B., Haggstrom, J. and Carlsten, J. (1998) Prevalence and risk factors of bone spavin in Icelandic horses in Sweden: a radiographic field study. *Acta vet. Scand.* **39**, 339-348.

Holmström, M., Magnusson, L.-E. and Philipsson, J. (1990) Variation in conformation of Swedish Warmblood horses and conformational characteristics of elite sport horses. *Equine vet. J.* **22**, 186-193.

Holmström, M. (2001) The effects of conformation. In: *Equine Locomotion,* Eds: W. Back and H. Clayton, W.B. Saunders Co, Philadelphia. pp 281-295.

Hunt, W.F., Thomas, V.G. and Stiefel, W. (1999) Analysis of video-recorded images to determine linear and angular dimensions in the growing horse. *Equine vet. J.* **31**, 402-410.

Kronacher, O. and Ogrizek, A. (1931) Exterieur und Leistungsfähigkeit des Pferdes unter besonderer Berücksichtigung der Gliedmaßenwinkelung und Schrittlängenverhältnisse. *Z. Tierzücht. Zücht Biol.* **23**, 138-228.

Magnusson, L.-E. (1985) *Studies on the Conformation and Related Traits of Standardbred Trotters in Sweden*. PhD thesis, Swedish University of Agricultural sciences, Skara.

Manning, J.T. and Ockenden, L. (1994) Fluctuating asymmetry in racehorses. *Nature* **370**, 185-186.

Morgan, M.H. (2002) The art of horsemanship. In: *Xenophon and the Art of Horsemanship*. Ed: M.H. Morgan, J.A. Allen, London. pp 13-68, 107-119.

Pfau, T., Witte, T.H. and Wilson, A.M. (2005) A method for deriving displacement data during cyclical movement using an inertial sensor. *J. expt. Biol.* **208**, 2503-2514.

Stashak, T.S. (1987) The relationship between conformation and lameness. In: *Adam's Lameness in Horses*, Ed: T.S. Stashak, Lea & Febiger, Philadelphia. pp 71-99.

**Author contributions** All authors contributed to the initiation, conception and planning of this study. Its execution was by R.W., T.P., D.B. and E.B., writing by R.W., S.A.M and A.M.W. Statistics were by R.W., T.P., S.A.M and A.M.W.