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Dynamic pressure measurements for the detailed study of hoof balance: the effect of trimming

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Summary

***Reasons for performing study*: Studies on hoof balance have, so far, only assessed the effects of strong and relatively unrealistic interventions due to technical limitations of measuring equipment. For the assessment of more subtle interventions, other techniques are necessary.**

***Objectives*: To test a sensitive pressure measurement system during locomotion and to set a standard for further studies by using the system to evaluate the effects of trimming.**

***Methods*: Eighteen horses were measured before and after trimming with an interval of 4 weeks. Trimming was standardised to a straight hoof-pastern axis. The horses trotted over a pressure/force measuring system, with a temporal resolution of 240 Hz and a spatial resolution of 0.39 cm^2.**

***Results*: The preferred way of landing was lateral, asymmetrical in both front and hind feet. The duration of landing was shorter in forelimbs than in hindlimbs with an equal decreasing trimming effect. Horses had a fixed hoof-unrollment pattern; the centre of pressure (CoP) travelled towards a maximum lateral deviation and returned towards the dorsopalmar/plantar axis of the hoof. Trimming decreased the intra-individual left/right difference in maximum lateral displacement.**

***Conclusions*: The technique used provided easily accurate data to quantify hoof balance characteristics and to measure short-term trimming effects.**

***Potential relevance*: Determination of CoP patterns has added value in gait analysis and can improve our understanding of the effects of different interventions on hoof balance.**

Introduction

Farriers balance feet to prevent horses from injuries and to improve performance. Throughout the centuries, farriery has, however, remained principally an empirical craft based on personal observations and individual interpretations rather than scientific evidence. This was to a large extent due to the lack of techniques by which the often subtle influences of various ways of shoeing on the internal structures of the digit and on locomotion could be measured. To quantify the effects of normal trimming and shoeing, sensitive measurement equipment is required. So far, most intervention studies have used rather unnatural exaggerations in the form of extreme changes in trimming or the application of wedges (Bushe *et al.* 1987; Clayton 1990; Thompson *et al.* 1993; Crevier-Denoix *et al.* 2001). Therefore, the available scientific knowledge is more about the effects of inducing imbalance than on actual balancing of the hoof.

These effects have been measured with different kinds of equipment. The effect of prolonged mediolateral imbalance is, for instance, visible to the eye and leads to cracks and sheared heels (Moyer and Anderson 1975). High frequency cinematography has been used to gain insight into the consequences of differences in hoof wall angulations on stride kinematics (Clayton 1990). The introduction of force plate and in-shoe force techniques permitted the study of the effect of imbalance on ground reaction forces (GRF) and centre of force (CoF) (Barrey 1990; Wilson *et al.* 1998, 2001; Eliashar *et al.* 2002). Radiological techniques gave information about the effects of imbalance on structures within the hoof, such as the relative alignment of the phalanges and changes in the interphalangeal joint spaces (Caudron *et al.* 1998a,b). Although the outcomes of these experiments have certainly led to an increase in the understanding of the mechanisms by which the hoof copes, the magnitude of most induced changes in hoof balance must be classified as far from realistic.

In recent years, more refined techniques have been introduced to measure pressure underneath the foot in human locomotion research. These techniques have proven to give reliable normative data for time-related changes in pressure distribution patterns while moving (de Cock *et al.* 2002). The data have been used to provide insight in to the developmental pattern of walking children (Hallemans *et al.* 2003), to improve shoe quality in patients suffering from diabetic problems (Praet and Louwerens 2003) and to gain insight in biomechanical aspects of running with and without shoes (de Wit *et al.* 2000). In other species, like bonobos (Vereecke *et al.* 2003) and cows (van der Tol *et al.* 2003), pressure measurements have also proved to be of great value for the generation of normative information in moving subjects.

The aim of this study was to describe a new technique in which pressure measurements are dynamically calibrated with force plate data to obtain detailed and accurate quantitative information about the location of the centre of pressure (CoP) and the forces exerted on the hoof while moving. Such a technique will enable detailed study of the effects brought about by subtle

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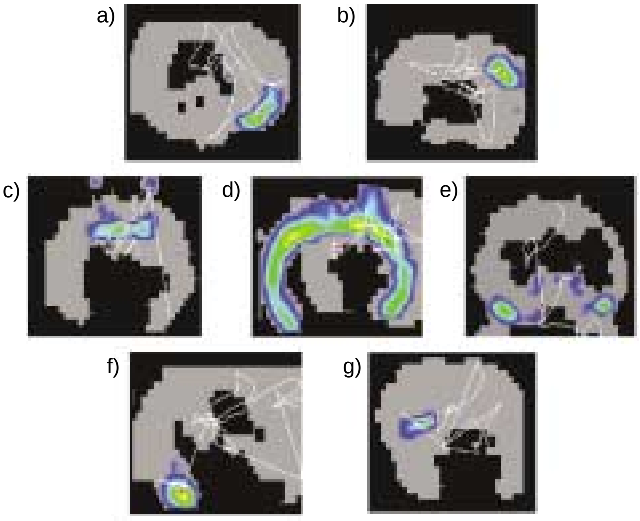

Fig 1: Different types of initial ground contact. a,b) Lateral asymmetrical ways of landing; c,d,e) symmetrical forms; and f,g) medial asymmetrical ways. a) Lateral heel; b) lateral toe; c) toe; d) flat; e) heels; f) medial heel; and g) medial toe.

changes in hoof balance. To exemplify the technique and set the standard for further studies, the technique was used to investigate the short-term effects of conventional trimming.

Materials and methods

Horses

Eighteen clinically sound Warmblood horses were used in this study. All horses were ridden under saddle and were trained daily during the experiment. Mean ± s.d. age was 4.9 ± 2.3 years and weight 569.4 ± 40.7 kg.

Trimming procedure

Two experienced farriers were assigned with 9 horses each, which they followed throughout the experiment. Four weeks prior to the first measurements, the farriers trimmed the horses. They were instructed to trim towards a static hoof balance, which refers to a geometric equilibrium of the limb and hoof in the square standing position. It aims at symmetry of the hoof with the axis of the limb perpendicular to the ground surface and the medial and lateral hoof walls equal in length (Stashak 2002). Seen from the side, the hoof-pastern axis should be straight. Four weeks after the initial trimming the horses were measured, trimmed according to the same guidelines and measured again shortly afterwards (40–60 mins).

Data collection

The horses were trotted in hand over a composite pressure-force measuring system. This system consisted of 2 synchronised measuring devices. The RSfootscan[1] is a pressure measurement plate that contains pressure-sensitive polymer sensors (0.39 cm^2). The measuring surface is 97.6 x 32.5 cm and contains 8192 conductive sensors. The RSfootscan plate was embedded in an aluminium plate on top of a Kistler force plate (Type z4852/c^2, 60 x 90 cm), which dynamically calibrated the RSfootscan plate.

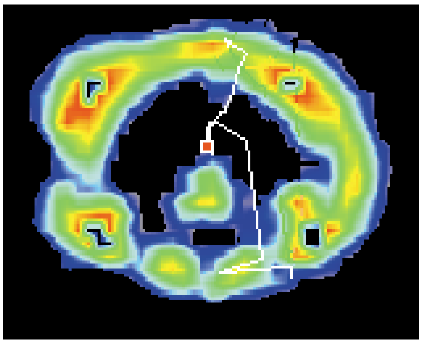

Fig 2: The location of the centre of pressure (CoP) at midstance (red dot) in a right front foot. The white line represents the trajectory of the CoP in the palmar (bottom of figure) to dorsal (top of figure) direction of the hoof and shows the hoof-unrollment pattern.

The sum of the vertical forces applied to all loaded sensors of the pressure plate was adjusted to the vertical component of the GRF of the force plate. The threshold level of the RSfootscan was 3 N/cm^2 to discard noise-related information. Pressures above 3 N/cm^2 were registered and colour-coded with one of the 256 available colours between blue (threshold) and red (maximum). The measurement frequency was 240 Hz and a total of 500 frames were collected. The whole system was placed in a concrete pathway of 20 m covered with a 5 mm thick rubber mat. The systems were triggered by an infrared gate, which also started the time measurement. There were 2 infrared gates 5 m apart, with the measurement equipment halfway between the gates. A measurement was defined as valid when the horse trotted at a constant velocity in a straight line, was looking straight forward not distracted by anything, and hit the measurement systems with a forelimb and an ipsilateral hindlimb. A measurement session was completed when 5 valid paired measurements of a fore- and ipsilateral hindlimb had been collected of both sides for the horse.

Data analysis

To define initial contact or landing, the first loaded frame in the RSfootscan software was coded. To achieve this, the hoof was divided into quadrants, which resulted in 3 different ways of landing, subdivided into 7 possibilities: 1) lateral heel; 2) lateral toe, both lateral asymmetrical ways; 3) toe; 4) flat; 5) heels, 3 symmetrical ways; 6) medial heel; and 7) medial toe, 2 medial asymmetrical ways (Fig 1).

The duration of landing was defined as the number of frames where 2 quadrants of the foot, corresponding with 50%, were loaded, multiplied by the duration of each frame, 4.2 msecs. Which quadrants were loaded was dependent on initial contact, which could be 50% of the foot in craniocaudal direction or 50% in mediolateral direction. In each measurement a total amount of 500 frames were collected. To define the stance time, the number of measurement frames filled with data was multiplied by 4.2 msec. Subject velocity was calculated by dividing the covered distance of 5 m by the time of one measurement.

To describe hoof-unrollment during breakover, the pattern of the CoP was followed from midstance to toe-off. The maximum vertical component of the GRF was defined as midstance. The location of the CoP (Fig 2) at midstance was placed on the origin of an x/y axis, (0,0). To compare left and right feet, the data on the x-axis of the left foot were mirrored. Therefore, the maximum

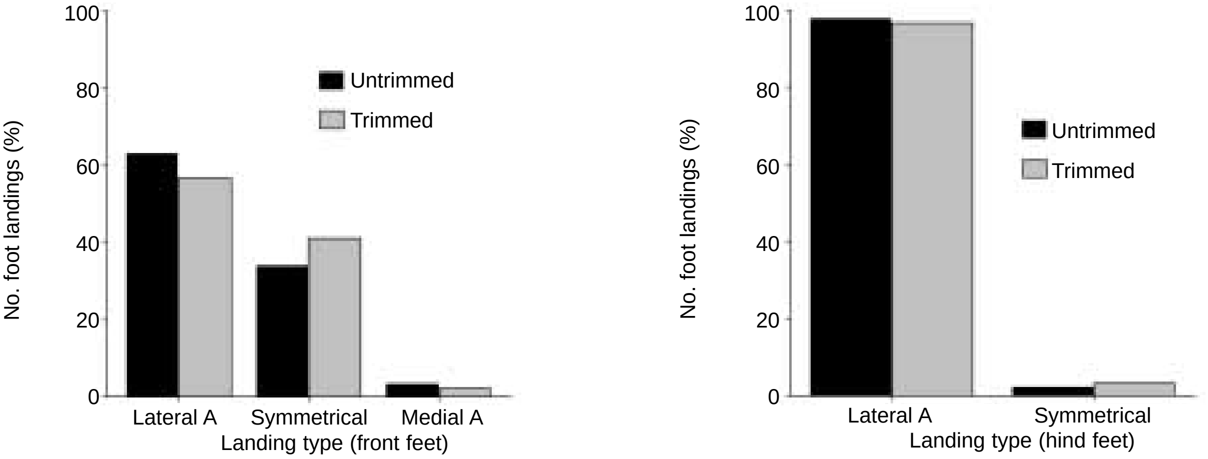

Fig 3: Distribution of landing per landing score in the untrimmed and trimmed situation for the a) front and b) hind feet. A = asymmetrical.

positive x-value was the maximum lateral deviation of the CoP during breakover. The end-x value is the deviation at toe-off. To calculate the intra-individual left/right difference between the untrimmed and trimmed conditions, the absolute difference, delta-x, between the left and right limbs within one individual was calculated for the maximum-x (delta-x-max) and the end-x value (delta-x-end).

Statistics

To describe the way of landing, a relative frequency analysis was used to test all measurements of the horses. The other variables were tested for significance in a GLM repeated measures test with, if applicable (P<0.05), a Bonferroni *post hoc* test (performed with the statistical package SPSS)[3]. In the test, the mean values were used from 5 sequential measurements of each limb.

Results

Lateral asymmetrical landing was the preferred way of landing in front feet and especially in hind feet of trotting horses (Fig 3). Trimming, aimed at complete symmetry under static conditions, did not change this preference. In the front feet, 63.3% of all measured untrimmed landings were located on the lateral side of the foot. After trimming, 57.8% of all landings were lateral asymmetrical. In the hind feet the way of landing was more specific, as 97.8% of all untrimmed landings were located laterally; after trimming this figure was still 96.7%.

The duration of landing was significantly different (P<0.001) between front and hind feet. In the front feet the mean duration was 6.7 msec and in the hind feet 16.7 msec (Table 1). Trimming significantly influenced the duration of landing (P<0.001). The effect was equal for fore- and hindlimbs; in both the duration was shortened with mean 2.2 msec. Because of the difference in duration of landing, the trimming effect was much larger in front feet (33.0%) than in hind feet (13.2%). The stance time was not changed significantly after trimming, nor was the difference between fore- and hindlimbs (295.6 vs. 289.7 msec) affected.

The maximum vertical component of the GRF was found to be different in fore- and hindlimbs (P<0.001). The mean of this value was 115.7% of the bodyweight in the forelimbs and 94.3% in the hindlimbs. Trimming had no effect on these parameters.

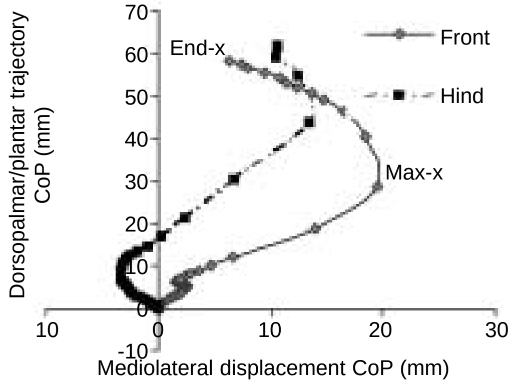

Fig 4: A typical example of a hoof-unrollment pattern from the front and the hind feet. Unrollment starts at the origin and ends at end-x. Note the disparity in the scale of the axes that was introduced for the purpose of clarity.

TABLE 1: Mean (s.e.) values of relevant kinetic and kinematic variables of 18 horses at the trot before and after foot trimming

	Front		Hind	
Variable	U	T	U	T
D of landing (msec)	6.7 (0.71)^{a}	5.5 (1.95)^{b}	16.7 (1.95)^{c}	13.4 (1.34)^{d}
GRF (% of bwt)	116.3 (1.52)^{a}	115.1 (1.85)^{a}	95.2 (0.92)^{b}	93.9 (1.17)^{b}
Stance time (msec)	294.9 (3.53)^{a}	296.3 (4.50)^{a}	288.2 (4.32)^{b}	291.2 (4.01)^{b}
Subject V (m/sec)	3.54 (0.04)^{a}	3.46 (0.02)^{b}	3.54 (0.04)^{a}	3.46 (0.02)^{b}
Max-x (mm)	20.4 (1.56)^{a}	19.9 (1.70)^{a}	12.3 (0.89)^{b}	10.5 (1.02)^{b}
End-x (mm)	14.5 (1.72)^{a}	14.4 (1.75)^{a}	7.9 (1.07)^{b}	6.0 (1.11)^{b}
Δ x-max (mm) |L–R|	10.3 (1.05)^{a}	6.8 (0.80)^{b}	10.2 (1.17)^{a}	7.2 (1.07)^{b}
Δ x-end (mm) |L–R|	8.0 (1.63)^{a}	8.3 (1.92)^{a}	4.6 (0.62)^{b}	3.0 (0.60)^{b}

T = trimmed; U = untrimmed; D = duration; GRF = ground reaction force; V = velocity; |L–R| = absolute difference between left and right. Means in the same row with a different superscript are significantly different (P<0.05).

The mean velocity was slightly decreased, 0.08 m/sec, but significantly different between the 2 sets of measurements (P = 0.031).

The pattern of hoof-unrollment was different between front and hind feet (P = 0.003), with mean maximum lateral displacement of the CoP 20.2 mm in front feet and 11.4 mm in hind feet (Fig 4). The end-x value was positive and again different for front and hind feet (P = 0.001); in front feet mean end-x value was 14.5 mm and in hind feet 7.0 mm. There was no effect of trimming on the maximum lateral displacement of the CoP or on the end-x value.

When comparing left and right feet of one individual, there was an effect of trimming on the symmetry of hoof-unrollment in both front and hind feet. With respect to the maximum lateral deviation, the intra-individual difference between left and right, delta-x-max, was smaller after trimming (P = 0.015). The mean delta-x-max for front and hind feet was 10.3 mm before trimming and 7.0 mm after trimming, a trimming effect of 33.3%. With regard to the end-x values before toe-off, delta-x-end, trimming did not induce significant changes in intra-individual left/right differences, although there was a trend towards a decrease of difference for the hindlimbs (Table 1).

Discussion

In this study, a new application of a pressure measurement technique was evaluated. The system features a high resolution, with 2.6 sensors per cm^2, which provides a high spatial accuracy. The density of sensors is equally distributed all over the pressure plate so, in contrast to force plate measurements (Bobbert and Schamhardt 1990), the location of the measurement does not interfere with the accuracy of determination of the CoP. The temporal accuracy of the force plate is higher compared with the RSfootscan and the piezoelectric sensors of the force plate are very precise for force measurements. Therefore, the combination of the 2 measurement systems increases the validity of the pressure measurements and accuracy of the location of the CoP. Further, the combination of RSfootscan and force plate obviously allows for detailed analyses of various regions of the contact area between hoof and surface, which the force plate alone does not. Due to its ease of use and resolutional limits, the system provides the opportunity to describe different characteristics of normal loading and unloading of the hoof during movement.

It has been stated, based on previous research, that a well balanced hoof should land flat or symmetrically (Balch *et al.* 1997; Grady and Poupard 2001). This may be true when observations are made with the human eye. However, studies with more sophisticated kinematic equipment have already shown tendencies towards different kinds of initial ground contact such as toe first, heel first, or both heels first (Lindfort 1994; Back *et al.* 1995a), and were able to show the influence of changes in hoof angulation on the way of landing (Clayton 1990, 1998). In this study, it was shown that lateral asymmetrical landing should be considered standard in Warmblood horses, certainly in hind feet where symmetrical landing is an exception. In other horse breeds the landing might differ, although Eliashar *et al.* (2002) also measured only lateral landings in Irish Draught horses, independent of the shoes they were wearing. There were no effects of trimming on the way of landing. This is in contrast to findings in previous studies (Barrey 1990; Clayton 1990; Wilson *et al.* 1998). However, in those trials very large differences were induced so effects of imbalance, rather than balance, were measured.

Whereas there were no effects on the way of landing, there were changes in the duration of landing, and on loading and unloading characteristics after trimming. The duration of landing decreased significantly after trimming, which means that the horses had faster complete foot support during the impact phase of landing. This implies that the CoP moves faster towards the centre of the foot, which at least theoretically should have a positive influence on load distribution over the structures within the hoof. Faster full support will also increase the bearing surface available for damping of the high frequency vibrations that occur during impact (Balch *et al.* 1988; Benoit *et al.* 1993). The relative effects of trimming on landing duration were larger in the front feet compared to the hind feet. It therefore appears to be easier for farriers to change landing and thus loading conditions in the front rather than in the hind feet. The differences in duration of landing in front and hind feet can be explained by a different hoof/ground angle in front and hind feet at the moment of initial ground contact. The hoof/ground angle at impact is larger in the hind feet than in the front (Merkens and Schamhardt 1994; Back *et al.* 1995a). Another explanation can be found in the different accelerations at impact; it has been shown that in the forelimbs the vertical acceleration is higher during impact, while in the hindlimbs the horizontal acceleration is higher (Back *et al.* 1995b).

The lateral landing of horses is not visible to the human eye. The temporal resolution of the human eye is about 24 Hz, which means that the eye is able to discriminate between events that are <40 msecs apart; therefore, the lateral landing, which is normally shorter than 40 msecs, cannot be detected. The normal landing of a sound horse trotting in a straight line, observed with the human eye, should therefore be flat. If a lateral, medial or toe landing can be seen, this is abnormal and suggests that the horse is poorly balanced or has other problems.

The effect of subject velocity on the GRF is known (McLaughlin *et al.* 1996); therefore, in this study the velocity was standardised for each individual. All measurements had to be within a range of ± 0.1 sec of the average time obtained from the first measurement set. Surprisingly, there was a significant effect of trimming on subject velocity; the horses significantly decreased trotting velocity by 0.08 m/sec. Although this change was small, it could have been a result of the alterations in conformation and an ensuing change in proprioception after trimming. Other correlated variables, such as vertical GRF and stance time (McLaughlin *et al.* 1996), did not change.

Previous studies noted a complex pathway of the CoF during the stance phase while moving (Barrey 1990). That this pattern can be affected with wedges has also been shown (Wilson *et al.* 1998). Another study described the effects of different shoes on the breakover point underneath the shoe (Eliashar *et al.* 2002). There have been some pressure measurement studies that aimed at localising the CoP underneath the hoof (Colahan *et al.* 1991, 1993). However, the methods used in these studies were relatively complicated and the applicability of the outcome limited, as horses often had to be tranquilised before they could be measured. Furthermore, the horses could not be measured while moving. More recently, the RSfootscan system was used to localise the CoP underneath the hoof (Rogers and Back 2003), but only in horses standing square. In the present study, the RSfootscan system was used to measure the trajectory of the CoP under dynamic conditions. The outcome was a distinct hoof-unrollment pattern, with slight individual differences. The patterns were similar for fore- and hindlimbs, although the magnitude of lateral displacement in CoP was larger in fore- than in hindlimbs. In man there is a very typical path of foot-unrollment (de Cock *et al.* 2002), and CoP patterns serve as a guide to make in-shoe adaptations when the path is not optimal, or when people suffer from specific foot-related ailments. In horses, there are several ways to influence the location of the CoP (Caudron *et al.* 1998b; Wilson *et al.* 1998; Eliashar *et al.* 2002). CoP pattern analysis may provide a better insight into how we can influence and optimise hoof-unrollment. Trimming did not affect the hoof-unrollment pattern itself, but enhanced the intra-individual left/right symmetry by decreasing delta-x-max. Trimming therefore leads to a more equal load distribution within the individual. Such a distribution over the internal structures of the feet is, at least theoretically, advantageous.

In conclusion, the RSfootscan system appears to be a reliable tool to measure and quantify hoof balance characteristics and to detect changes, even if they are subtle, such as those induced by normal trimming. The obtained data can serve as a good basis for further detailed studies of interventions with respect to the horse's feet, including different ways of trimming and shoeing and differences in trimming intervals. Lateral asymmetrical landing is most common in the front feet and by far the predominant way of landing in the hind feet of Warmblood horses. Lateral landing should therefore be regarded as the physiological standard for these horses, rather than symmetrical landing. Trimming does not have much influence on way of landing, but decreases landing duration, especially in the front feet, and enhances left/right symmetry. Both effects are potentially beneficial with respect to loading of the internal structures of the foot.

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Manufacturers' addresses

[1]RSscan International, Olen, Belgium.
[2]Kistler Corporation, Winterthur, Switzerland.
[3]SPSS Inc., Chicago, Illinois, USA.

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