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## Use of a stand-alone pressure plate for the objective evaluation of forelimb symmetry in sound ponies at walk and trot

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### ABSTRACT

Subtle lameness in horses may be difficult to diagnose and methods to evaluate lameness objectively are useful when equine clinicians fail to reach a consensus. The aim of this study was to determine whether equine pressure plate measurements are repeatable when used to calculate forelimb loading (peak vertical pressure [PVP], peak vertical force [PVF], vertical impulse [VI]) and symmetry ratios, and to establish if these data are similar to the 'gold standard' force plate values. Since plate dimensions are relatively small, ponies were used to enable recordings to be taken from both forelimbs in one trial. Five sound ponies were walked and trotted over a pressure plate which was embedded in a custom-made runway. For each pony, five valid trials were recorded during two different days. A trial was considered valid if complete prints of both fore hooves were recorded consecutively and if velocity was within a preset range.

The PVP, PVF and VI values showed an acceptable variability ( $CV \leq 16\%$ ), with PVF (130% of bodyweight [BW],  $n = 5$ ) similar to previously reported force plate data (128% BW,  $n = 48$ ). Mean symmetry ratios appeared to be high ( $>95\%$ ) and showed a low variability ( $CV < 5\%$ ). The stand-alone pressure plate permitted adequate registration of forelimb PVF, VI and limb symmetry with a high level of precision in sound ponies.

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### Introduction

Force plates are accepted as the current 'gold standard' in the quantitative evaluation of equine lameness (Buchner, 2001; Bertone, 2003). The most relevant kinetic parameters in equine gait evaluation are peak vertical force (PVF) and vertical impulse (VI), which is the area under the force curve (Ishihara et al., 2005). However, the use of force plate technology in horses is largely limited to experimental settings, mainly because forces created by different limbs simultaneously in contact with the plate cannot be separated, and the limited force plate dimensions preclude recording consecutive strides. Therefore, gathering force plate data of all four limbs requires numerous trials or the use of an instrumented treadmill (Weishaupt et al., 2002; Weishaupt, 2008).

Pressure plates with high sensor density and high measuring frequency could provide a valuable alternative to force plate evaluation and allow analysis of simultaneous and consecutive hoof strikes. Furthermore, detailed information on the loading of the different portions of the foot during a complete stance period can be obtained. As such, these pressure plates could be useful in a clinical setting.

In dogs, lameness has been quantified using a stand-alone foot pressure-measuring system (Besançon et al., 2003) and the pressure plates have also been used successfully in horses to study hoof break-over both with concurrent force plate calibration ( $n = 18$ ; Van Heel et al., 2004) but also without this dynamic calibration technique ( $n = 6$ ; Rogers and Back, 2003, 2007). A successful preliminary test of the pressure plate system to evaluate lameness objectively in a Quarter Horse (Oosterlinck et al., 2008) encouraged us to perform a detailed evaluation of the repeatability of this equipment as a first step towards validation. Ponies were used as their conformation facilitated recording data from both forelimbs in one trial.

The aims of the study were to investigate whether pressure plate measurements and their symmetry ratios recorded on different days in a group of sound ponies using a stand-alone system were repeatable, and whether absolute values were similar to previously reported force plate data in ponies (Barr et al., 1995).

### Materials and methods

#### Ponies

Five healthy ponies were used (four geldings, one mare; mean age  $1 \pm 7$  SD years; bodyweight [BW]  $279 \pm 55$  kg; wither height  $1.19 \pm 0.05$  m). The ponies, which had no history of lameness and were clinically sound, were walked and

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trotted over a pressure plate embedded between high-density polyethylene plates on a 20 × 2 m concrete walkway and covered with a 5 mm rubber mat. Measurements were repeated at a 1 week interval. The BW of each pony was recorded before the start of each session.

The study was approved by the Ethical Committee of the Faculty of Veterinary Medicine, Ghent University (EC 2007/108).

#### Measurement system and data collection

The pressure plate consists of 16,384 force-sensitive resistors in an active measuring surface of 1.95 × 0.32 m (2.6 sensors/cm<sup>2</sup>), measuring at the maximal frequency of 500 Hz (Footscan 3D 2m-system, RsScan International) and connected to a portable computer equipped with the Gait Scientific software (RsScan International).

Calibration was initially performed following the manufacturer's instructions with a person of 83 kg. Gain and offset were subsequently adjusted manually to avoid saturation of the sensors when measuring horses with a 5–8 fold greater mass compared to the human. To assess accuracy after these adjustments, a static measurement was made with a person standing on the pressure plate on one limb. Gain and offset were fine-tuned until the vertical force measured was equivalent to the BW; this was done before each measurement session.

Centre of mass average velocity over the measuring area was computed from the time interval measured by two photocell-activated gates mounted at 2 m intervals centred over the pressure-measuring area. The sensors were mounted at the level of the pony's chest. A trial was considered valid if complete hoof prints of both forelimbs were recorded and if the velocity of the pony was within a preset range of 1.1–1.5 m/s at the walk and 2.5–3.5 m/s at the trot. A measuring session was limited to the number of trials necessary to obtain five valid measurements.

#### Data processing

Only the data from the five valid trials were analysed. The peak vertical pressure (PVP), PVF and VI were normalised to BW (N/cm<sup>2</sup>kg, N/kg and Ns/kg) for both forelimbs of each of the five ponies at walk and at trot. For each set of five trials, left fore (LF) and right fore (RF) measurements were averaged and PVP, PVF and VI symmetry was calculated as:

$$\frac{\text{lowest}}{\text{highest}} \text{ mean value} \times 100\%.$$

#### Statistical analysis

To assess variability in PVP, PVF and VI between the different LF and RF measurements, coefficients of variation ( $\frac{SD}{\text{mean}} \times 100\%$ ) (CV) were calculated 'within-session' and were also pooled for all valid measurements over both sessions. The CVs were averaged over the five ponies. The mean and CV were calculated for PVP, PVF and VI symmetry.

A linear mixed effects model with horse as random component was used to evaluate (1) the effect of measurement day, gait, LF or RF (fixed factors) and velocity (covariate) on PVP, PVF and VI, and (2) the influence of measurement day and gait (fixed factors) and velocity (covariate) on PVP, PVF and VI symmetry ratios.

Data were collated and prepared for analysis using spreadsheet software (Microsoft Office Excel 2003) and statistical analysis was performed using S-Plus 7.0 (Insightful Corporation), with statistical significance set at  $P < 0.05$ . Data is presented as means ± SD, unless otherwise stated.

## Results

At the walk,  $13 \pm 1$  trials per pony were required to obtain five valid measurements of both front limbs; at the trot,  $19 \pm 7$  trials per pony were required. The velocity of valid trials was  $1.3 \pm 0.1$  m/s at walk and  $2.9 \pm 0.2$  m/s at trot.

The vertical ground reaction force curves at the walk showed a characteristic bi-phasic pattern with the second peak being greater than the first peak, a dip at mid-stance and a little spike just before the end of the stance phase (Fig. 1). At trot, a smoothly shaped curve pattern with one maximum was seen, with a 'dimple' early in the stance phase (Fig. 2). Vertical ground reaction curves of LF and RF were similar for every pony at both gaits.

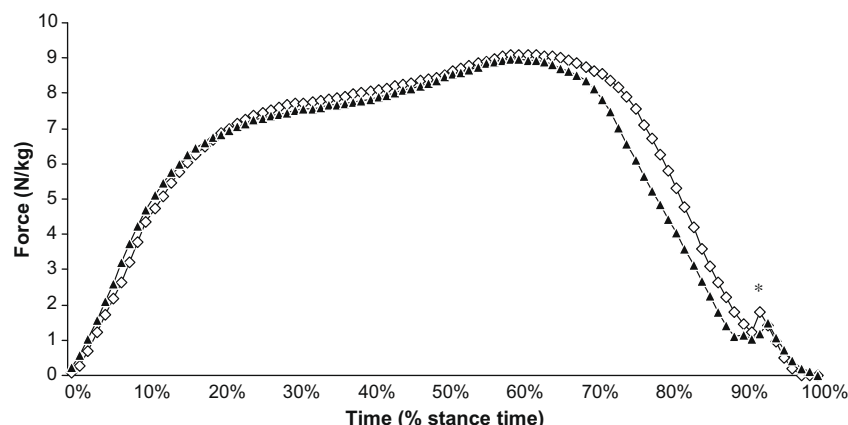
Mean left and right PVP, PVF and VI at walk and at trot for all measurements are summarised in Table 1. The average 'within-session' and pooled CV of LF and RF measurements of the five ponies are summarised in Table 2. In the univariate analysis, PVP measurements were significantly influenced by measuring day, gait and velocity ( $P < 0.05$ ). There was no significant difference between LF and RF measurements. In multivariate analysis, measuring day and velocity still had a significant effect on PVP ( $P < 0.05$ ), but the effect of gait did not reach significance. Both gait and velocity significantly influenced PVF and VI ( $P < 0.05$ ), but there was no significant difference between measuring days and between LF and RF for PVF and VI measurements.

The overall mean PVP symmetry between both forelimbs was  $97.2 \pm 0.9\%$  at walk and  $97.2 \pm 3.4\%$  at trot, while the PVF symmetry ratio was  $97.5 \pm 1.7\%$  at walk and  $98.2 \pm 1.1\%$  at trot, and finally the VI symmetry ratio between both forelimbs was  $96.7 \pm 1.8\%$  at walk and  $97.3 \pm 1.8\%$  at trot. The CV of these symmetry ratios are shown in Table 3. There was no significant effect of measuring session, gait and velocity on the symmetry ratio of PVP, PVF and VI.

## Discussion

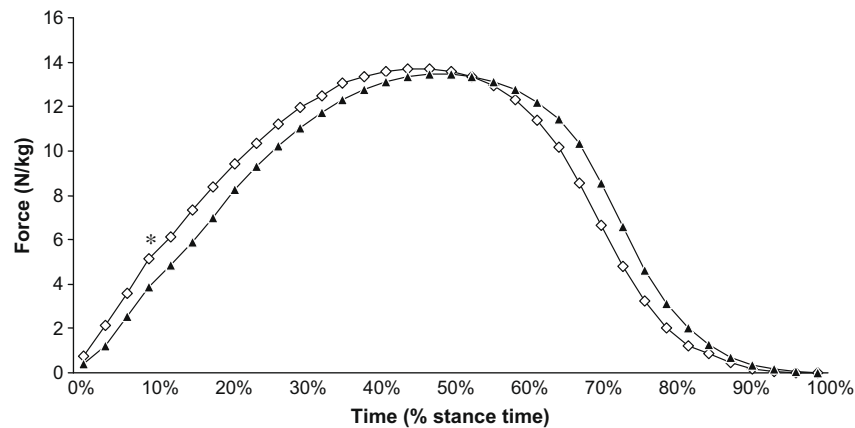
### Repeatability of measurements

The results indicate that this stand-alone turnkey pressure plate allowed adequate registration of forelimb PVP, PVF and VI and their symmetry ratios with a high level of precision in sound ponies at the walk and trot. Mean CVs of PVP, PVF and VI measurements within a session were moderate at walk ( $\leq 14\%$ ), while at trot they were small ( $\leq 10\%$ ), which suggested a moderate variability at walk and a low variability at trot. Variability between measurements over the two measuring days was slightly higher ( $\leq 16\%$  at walk and  $\leq 12\%$  at trot) than variability on one day. Mean



\* 'spike' in the vertical ground reaction force curve at the end of the stance phase

Fig. 1. Typical example of a left front (◇) and right front (▲) vertical ground reaction force (N/kg) curve as a function of time (% stance time) at walk.



\* 'dimple' in the vertical ground reaction force curve in the early stance phase

**Fig. 2.** Typical example of a left front (◇) and right front (▲) vertical ground reaction force (N/kg) curve as a function of time (% stance time) at trot.

**Table 1**

Mean  $\pm$  SD of peak vertical pressure (PVP in N/cm<sup>2</sup> kg), peak vertical force (PVF in N/kg) and vertical impulse (VI in Ns/kg) of the group of five ponies at the walk ( $1.3 \pm 0.1$  m/s) and trot ( $2.9 \pm 0.2$  m/s). LF, left front; RF, right front.

Variables	Walk		Trot	
	LF	RF	LF	RF
PVP (N/cm <sup>2</sup> kg)	0.17 $\pm$ 0.02	0.16 $\pm$ 0.02	0.21 $\pm$ 0.04	0.21 $\pm$ 0.04
PVF (N/kg)	8.84 $\pm$ 1.35	8.94 $\pm$ 1.12	12.44 $\pm$ 1.52	12.46 $\pm$ 1.58
VI (Ns/kg)	4.08 $\pm$ 0.66	4.12 $\pm$ 0.52	2.13 $\pm$ 0.27	2.10 $\pm$ 0.27

**Table 2**

Mean 'within-session' and pooled coefficient of variation (CV%) of peak vertical pressure (PVP), peak vertical force (PVF) and vertical impulse (VI) measurements of the group of five ponies at walk ( $1.3 \pm 0.1$  m/s) and trot ( $2.9 \pm 0.2$  m/s). LF, left front; RF, right front.

CV	Within session		Pooled	
	LF	RF	LF	RF
Walk				
PVP	9.9	9.2	10.8	9.4
PVF	12.3	9.9	14.1	11.9
VI	13.9	10.2	15.9	12.3
Trot				
PVP	7.0	9.1	7.8	9.9
PVF	8.9	9.7	9.1	10.3
VI	10.1	10.3	10.3	11.9

**Table 3**

Mean  $\pm$  SD symmetry ratio (SR%) and its coefficient of variation (CV%) for PVP, PVF and VI values of the group of five ponies at walk ( $1.3 \pm 0.1$  m/s) and trot ( $2.9 \pm 0.2$  m/s).

SR%	Walk		Trot	
	Mean $\pm$ SD	CV%	Mean $\pm$ SD	CV%
PVP	97.2 $\pm$ 0.9	0.9	97.2 $\pm$ 3.4	3.5
PVF	97.5 $\pm$ 1.7	1.8	98.2 $\pm$ 1.1	1.2
VI	96.7 $\pm$ 1.8	1.9	97.3 $\pm$ 1.8	1.8

CVs of the PVP, PVF and VI symmetry ratios was very low (<5%), which indicated excellent repeatability.

The significant effect of measuring session on PVP demonstrated higher variability compared to PVF and VI measurements. Although the pressure measurement in the present study had a high spatial (2.6 sensors/cm<sup>2</sup>) and temporal resolution (up to

500 Hz), this variability could be due to limitations in the dynamic response to loading and unloading of the multitude of activated sensors and is more likely to affect the calculation of pressure (which is force per unit of area) than the vertical force alone. This confirmed the higher relevance of PVF and VI in equine gait evaluation (Ishihara et al., 2005) as for routine use in a clinical setting repeatability of measurements is crucial.

#### Absolute kinetic values

Barr et al. (1995) only supplied quantitative ground reaction force data in his study on 48 ponies, whereas in the present paper, a graphical representation of the vertical ground reaction force at walk and at trot is shown. Although it was not our aim, the possibility of detailed analysis of the four individual quadrants, as quantitatively assessed by Rogers and Back (2003, 2007), is another distinct advantage of the pressure plate over a force plate, as it demonstrates the subsequent loading of the different portions of the foot during a complete stance period.

Pressure patterns in the ponies were similar to those reported for pressure plate studies in horses (Van Heel et al., 2004), whereas the curves of the vertical ground reaction force of every individual pony were similar to those reported in force plate studies in horses (Merkens et al., 1986, 1993). The slight shift between the LF and RF curves, due to small differences in timing between both forelimbs, is probably attributable to natural biological variation. In force plate and kinematic studies it is known that slight physiological locomotion asymmetries may be compatible with 'handedness' in clinically sound horses, illustrating that absolute symmetry is nearly impossible in nature (Buchner, 2001). Vertical ground reaction force curve details seen in force plate analysis, like the small spike at the end of the stance phase at walk and the 'dimple' early in the stance phase at trot, could also be distinguished in the curves obtained in the present study (Figs. 1 and 2). The small spike at the end of the stance phase at walk may be associated with 'heel lift' (Back et al., 1995) and the 'dimple' early in the stance phase at trot may be associated with rapid extension of the carpus acting as a propulsive strut (Back et al., 1995; Merkens and Schamhardt, 1994).

It is known that gait parameters are breed-specific and scaling for differences in height at the withers cannot compensate completely for important conformation-related differences in gait parameters between breeds (Back et al., 1999, 2007). The PVF values obtained by the pressure plate in the present study (mean PVF 12.5 N/kg = 130% BW) are quite similar to data previously reported in a force plate study in ponies (mean PVF 128% BW = 12.6 N/kg)

(Barr et al., 1995). Although the mean BW of the five ponies in the present study (279 kg) was higher than that of the 48 ponies (189 kg) in the study of Barr et al. (1995), the slightly higher forelimb PVF in ponies at trot compared to other breeds such as Dutch Warmbloods (118% BW) (Merkens et al., 1993), Standardbreds (113% BW) (Seeherman et al., 1987), Thoroughbreds (108% BW) (Dow et al., 1991) and Quarter Horses (101% BW) (Back et al., 2007) was confirmed.

#### Symmetry ratio

The mean PVF and VI measurements of five trials of the sound ponies in the present study had a high symmetry ratio (>95%), which is comparable to those obtained using a force plate in horses with PVF symmetry ratios of 94–99% at walk and 97% at trot (Merkens et al., 1986, 1993) and in ponies, with PVF symmetry ratios of 99–100% at trot (Barr et al., 1995). Merkens et al. (1993) used left-to-right symmetry quotients in horses, while Barr et al. (1995) calculated the symmetry ratio in ponies by dividing the value from one randomly chosen forelimb by the value from the contralateral one. In the present study, we used the  $\frac{\text{lowest}}{\text{highest}}$  mean value of five valid trials per pony  $\times 100\%$  to be independent of handedness of a leading limb and so keep values <100%.

The similarity between LF and RF vertical force curves was comparable to results obtained using a force plate in horses (Merkens et al., 1986, 1993), a combined force plate-pressure plate system in horses (Van Heel et al., 2004) and the use of a force plate in ponies (Barr et al., 1995). Graphically, forelimb symmetry is illustrated by expressing LF versus RF PVF (% BW) (Fig. 3a, and Fig. 3b). Perfect left-right symmetry coincides with the diagonal line, whereas the data point would deviate from this line in case of lameness. Data clusters of the clinically sound ponies are centred over the diagonal line.

Based on the high symmetry with low inter-individual variability in this study, calculating the mean symmetry ratio of at least five PVF and VI measurements using a pressure plate seems to be acceptably precise for clinical use. The robustness of these parameters is accentuated by the lack of any significant effect of different measuring sessions, gait, and velocity on the symmetry ratio of PVP, PVF and VI.

Detecting a decrease in symmetry can be associated with lameness (Seeherman et al., 1987; Weishaupt, 2008). It would seem promising therefore to establish reference values for symmetry ratios that can be used in evaluating lame ponies and horses. How-

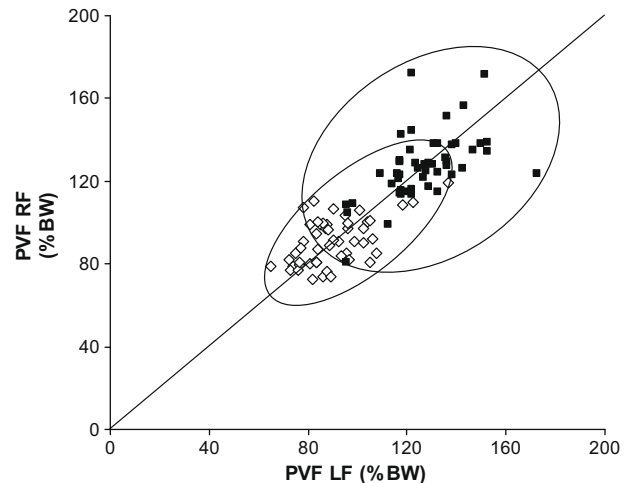


Fig. 3b. Left front (LF) versus right front (RF) PVF (% BW) of all valid measurements of the five ponies at walk ( $\diamond$ ) and at trot ( $\blacksquare$ ). The diagonal line represents 100% left-right symmetry. The two data clusters are centred around the diagonal.

ever, future research is needed to determine the relation between symmetry ratios and clinical degrees of lameness. Inevitably, the decision as to the extent that a very subtle degree of asymmetry in a subjectively sound horse is a sign of sub-clinical lameness will remain difficult, complicating the determination of cut-off values to distinguish lame horses from sound ones. Obviously, bilateral lesions would require unilateral diagnostic analgesic techniques to accentuate any asymmetry. Moreover, as it is known that load redistribution occurs between fore- and hindlimbs, a subsequent registration of fore- and hind-limb parameters would be interesting (Weishaupt, 2008).

#### Velocity and gait

The range of velocity at the trot was set similar to those used by Ishihara et al. (2005) and Perino et al. (2007). At walk, an even more narrow range was set, to minimise inter-trial variability.

As expected, PVF and VI were significantly different between the two gaits. Furthermore, even after setting a narrow range of velocity for a valid trial, velocity still significantly influenced PVF and VI measurements both at walk and at trot, in agreement with the findings of Barr et al. (1995).

It is most likely that setting more narrow ranges of velocity in the present study could have decreased variability even more. However, this would certainly have increased the number of trial repetitions and thus would complicate the application of the system in a clinical setting.

#### Number of trials

On average, less than 14 trials at the walk and 19 trials at trot were required to obtain five valid measurements of both forelimbs in the ponies, whereas in previously reported force plate studies, 44 attempts were necessary to obtain sufficient PVF data for each of the four limbs in horses (Merkens et al., 1993). The number of trials in our study would be feasible in a clinical environment.

The number of trials that are necessary is very dependent on the width of the pressure-measuring area and we only included trials in which both fore hooves made a complete strike on the pressure plate to minimise inter-trial variability between LF and RF. This is in contrast to the pony study by Barr et al. (1995) who collected data from the left and the right limbs independently on different runs, without accurate registration of velocity. In the present

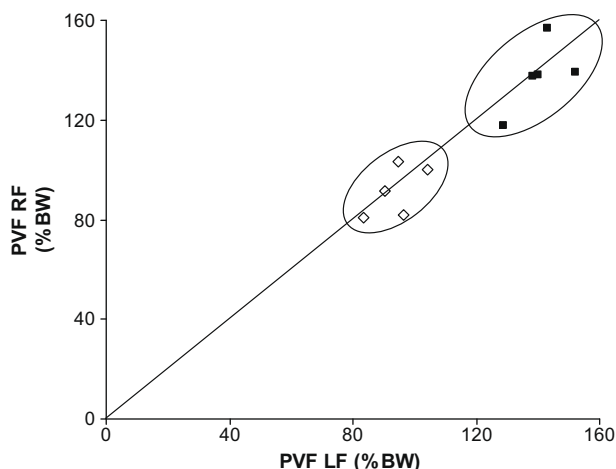


Fig. 3a. Typical example of left front (LF) versus right front (RF) PVF (% BW) of the five valid measurements at walk ( $\diamond$ ) and at trot ( $\blacksquare$ ). The diagonal line represents 100% left-right symmetry. The two data clusters are centred around the diagonal.



study, the limited height at the withers and related conformation of the ponies facilitated an acceptably low number of runs to obtain five valid trials on a  $2 \times 0.32$  m pressure plate. Warmblood horses with a height of 1.60 m or more often hit the plate with only one hoof completely on smaller force and pressure plates (Merken et al., 1986, 1993; Van Heel et al., 2004). Many more trials are therefore needed to gather sufficient hoof strikes of both forelimbs so increasing variability due to slight changes in velocity.

The development of a larger measuring surface, customised for large animals, presents technical challenges that will need to be addressed by the manufacturer. An insole pressure measuring device mounted underneath the hooves, as an alternative to the pressure plate, has shown to be questionable for assessment of equine lameness, due to difficulties with sensor wear, calibration and lack of correlation with subjective and force plate evaluation (Perino et al., 2007).

### Calibration

Ideally, calibration is performed using a weight within a range equivalent to that of the subject to be measured. As the present software only allowed calibration to be performed with an object weighing less than 150 kg, calibration using a pony could not be done and was initially undertaken following the manufacturer's instructions with a person of 83 kg. Consecutively, fine-tuning this calibration factor was performed to optimise the settings. Specifically designed software for use in equids would further optimise the calibration procedure. We are aware that vertical force data derived from the activation of a multitude of pressure-sensitive sensors without force plate calibration, should be regarded with caution. The gold standard for force evaluation remains a force plate.

Dynamic calibration with a force plate (Van Heel et al., 2004) was not done as we wished to evaluate the clinical applicability of the pressure plate without a costly and laborious installation of a force plate. Rogers and Back (2003, 2007) mentioned an accuracy error of a similar, earlier version of this pressure plate system of 3.3%, and used it without concurrent dynamic force plate calibration to study the effects of eggbar and wedge shoes in sound horses.

As Barr et al. (1995) mentioned, the use of symmetry indices avoids the need to allow for the variations in the absolute values between recording sessions. Consistent errors in accuracy disappear when considering a symmetry ratio, thus decreasing the importance of highly accurate measurements. As long as the precision (i.e. repeatability) of the data that are averaged in one testing-session is high, symmetry ratios can be compared on different testing occasions. This could enable easy quantitative evaluation of equine locomotor symmetry in a training setting to evaluate handedness or in a clinical setting during lameness examination.

### Conclusions

We observed a high degree of forelimb PVP, PVF and VI symmetry in sound ponies. Moreover, the PVF and VI measurements and their symmetry ratios proved to be highly repeatable. The similarity between pressure plate data in this study and force plate data in the literature, together with the possibility of recording additional information on the loading of the different portions of the foot during a complete stance period, seem to look promising. This pressure plate may therefore have a use in a clinical setting as an alternative to the force plate for the quantification of forelimb PVP, PVF and VI symmetry, at least in ponies. Further research is needed to investigate whether the findings can be extrapolated to horses. A larger pressure-measuring surface and specifically de-

signed software and calibration techniques would improve the development of this human podiatric system for equine clinical use.

### Conflict of interest statement

None of the authors of this paper has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of the paper.

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