Evaluation of an in-shoe pressure measurement system in horses

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Objective—To develop an objective, accurate method for quantifying forelimb ground reaction forces in horses by adapting a human in-shoe pressure measurement system and determine the reliability of the system for shod and unshod horses.

Animals—6 adult Thoroughbreds.

Procedure—Horses were instrumented with a human in-shoe pressure measurement system and evaluated at a trot (3 m/s) on a motorized treadmill. Maximum force, stance time, and peak contact area were evaluated for shod and unshod horses. Three trials were performed for shod and unshod horses, and differences in the measured values were examined with a mixed model ANOVA for repeated measures. Sensor accuracy was evaluated by correlating measured variables to clinically observed lameness and by a variance component analysis.

Results—4 of 6 horses were determined to be lame in a forelimb on the basis of clinical examination and measured values from the system. No significant differences were observed between shod and unshod horses for maximum force and stance time. A significant decrease in peak contact area was observed for shod and unshod horses at each successive trial. Maximum force measurements provided the highest correlation for detecting lameness (r = 0.91, shod horses; r = 1.0, unshod horses). A variance component analysis revealed that 3 trials provided a variance of 35.35 kg for maximum force (± 5.78% accuracy), 0.007 seconds for stance time (± 2.5% accuracy), and 8.58 cm² for peak contact area (± 11.95% accuracy).

Conclusions and Clinical Relevance—The in-shoe pressure measurement system provides an accurate, objective, and effective method to evaluate lameness in horses. (Am J Vet Res 2001;62:23-28)

Lameness is the most common and important performance-limiting problem in horses. Many current concepts in lameness diagnosis depend on subjective evaluation and interpretation of subtle clinical signs. These clinical signs can be elusive and difficult for even the most experienced clinician to identify repeatedly and consistently. In some instances, the anatomic site of lameness cannot be determined. Subtle lameness, lameness only evident at speed, lameness resulting from lesions in multiple locations, or lameness that manifests itself inconsistently are all potential reasons for a veterinarian to be unable to readily determine the cause of a horse’s soundness problem.

Quantitative measurements of locomotion in horses have traditionally relied on kinematics (limb position in time and space) or kinetics (direction and magnitude of forces during weight-bearing). Kinetic gait analysis involves the measurement of forces acting through forelimbs during the weight-bearing stage of motion. This method of analysis has been suggested as a means to detect subtle lameness by providing quantitative data on ground reaction forces. This technique also relies on the fact that most lameness conditions result in a change in distribution, amount, and duration of the ground reaction forces during the weight bearing stage of motion.

Current methods of detecting these changes in kinetics have relied on either force plate evaluation or transducer instrumented shoes. Force plate evaluations are performed by leading a horse over a stationary ground plate at various speeds and interpreting the interaction between the horse’s foot and the plate. Whereas this system provides excellent information when performed properly, it requires isolated repetitive passes over a stationary plate. Slight variations in velocity, location of plate strike, subject cooperation, gait, conformation, and size can substantially alter the data. This system is incapable of measuring forces exerted during successive strides, and cannot accurately provide a temporal relationship between hoof strikes of the same and contralateral forelimb and their relationship to each other.

Instrumented shoes have been used to quantify ground reaction forces in horses. These shoes have been limited in their use by their complexity and weight. However, they have the benefit of providing a vertical ground reaction force and a temporal analysis of hoof strike over successive strides at various gaits. The most current instrumented shoe has 3 transducers embedded in the shoe. The transducers are positioned on the heel and toe of the shoe in a triangular pattern and provide temporal analysis and vertical ground reaction data. The disadvantages of this technique include limited ground reaction data obtained from only 3 sensor locations and the requirement of replacing a horse’s shoe with an instrumented shoe.

In human gait analysis, the advent of modern microcomputer technologic advances, along with the development of an ultra-thin (0.003 cm), flexible, and trimmable in-shoe sensors containing 960 piezoelectric sensors, has revolutionized the diagnosis and treatment of patients with a variety of podiatric and orthopedic problems. This system allows active and accurate measurement of ground reaction forces across the entire
foot, in conjunction with the temporal relationship of foot strike, and its relationship to the other foot. The purpose of the study reported here was to evaluate the accuracy and durability of a human in-shoe pressure measurement system for determining the ground reaction forces, and temporal relationship of hoof strike in the forelimbs of horses.

**Materials and Methods**

**Procedures**—Six adult Thoroughbreds having regular daily treadmill exercise were studied. Each horse was weighed, given a complete physical examination, and evaluated for lameness by trotting in a straight line in hand on asphalt, and then lunged in right and left circles. All lameness evaluations were videotaped for blinded evaluation.

Prior to application, each in-shoe sensor was calibrated with a known force of 50 lb/in² (3.52 kg/cm²), using a sensor calibration system. A calibrated sensor was applied to a prefabricated shoe between two 0.056-cm diameter plastic plates, and secured with porous white tape. A left and right shoe-sensor combination was fabricated for each horse, and each horse was assigned its own sensor pair (Fig 1).

The sensor-shoe combinations were secured to shod horses with adhesive tape, and a converter was secured to the fetlock region with a Velcro wrap and elastic tape. Each in-shoe sensor combination was attached to the converter and connected to a compatible microcomputer via a 30-ft cord and a 16-bit receiver card as per the manufacturer’s instructions (Fig 2 and 3).

Horses were moved to a motorized equine treadmill and exercised at a speed of 3 m/s. The vertical ground force and temporal hoof strike data of both forefeet were acquired simultaneously using a data acquisition software package. The time of acquisition was 8 seconds for a total of 456 frames (57 frames/s). The treadmill was stopped and horses were allowed to rest briefly as the acquired data were translated. A total of 3 pairs of trials were performed per horse in a similar fashion. After acquiring data for shod horses, the front shoes were removed, and the feet were trimmed for balance. Horses were then instrumented with the same shoe-sensor combination and the data was acquired as previously described.

Maximum force (kg), peak area (cm²) of sole contact with the sensor, and stance time (seconds) were examined for each forelimb for 10 successive hoof strikes in shod and unshod horses. All videotaped gait examinations were blindly evaluated for lameness, and any evidence of lameness was graded following the guidelines of the American Association of Equine Practitioners (0 = sound, 1 = lameness inconsistently observable under special circumstances, 2 = lameness consistently observable under special circumstances, 3 =...
lameness consistently observable at a trot in a straight line, \( 4 \) = lameness observable at a walk, \( 5 \) = minimal weight bearing in motion or at rest.\(^1\)

**Statistical analysis**—Data were analyzed for systematic effects attributable to horse, trial, shoe, strike number, and forelimb influences using a mixed model ANOVA for repeated measures. Outlying data points were removed for maximum force (< 408 kg), and were removed for stance time (> 0.36 seconds). Differences were considered significant whenever the \( P \) value was < 0.05.

Differences in mean maximum force, stance time, and peak contact area were compared between forelimbs for shod and unshod trials using a paired 2-tailed Student \( t \)-test. Lameness was considered detectable if there was significant \(( P < 0.05)\) difference between left and right forelimbs. The lame forelimb was determined by which had a lower maximum force, shorter stance time, or reduced peak contact area measurement in reference to the opposite forelimb. A Pearson correlation coefficient was calculated to evaluate the accuracy of the system in reference to the clinical blinded evaluation for lameness and identification of the lame forelimb.\(^2\) A variance component analysis was used to assess the accuracy of the system in shod and unshod horses by determining the variability on the basis of number of trials for maximum force, stance time, and peak contact area.

Figure 4—A force-time curve obtained from a horse without shoes and no lameness that demonstrates the 2-dimensional representation of maximum force measured for the left (playback window 1) and right (playback window 2) forelimbs. The graphic representation of the data facilitates comparison of ground reaction forces between the left (red line) and right (green line) forelimbs.

Figure 5—A force-time curve obtained from a horse with a right forelimb lameness (without shoes). The maximum peak force of the right forelimb (playback window 2) is consistently less than the maximum peak force of the left forelimb (playback window 1) for all gait cycles. The green line represents the right forelimb and the red line represents the left forelimb.
Results

All horses were instrumented and trotted without difficulty on the treadmill according to the protocol. Horses did not resent the equipment and all horses trotted as they had for previous sessions on the treadmill without instrumentation. There was no change in gait detected between instrumented and noninstrumented horses. All the equipment functioned normally for the duration of the study. The software facilitated data evaluation by producing a graphic representation of ground reaction force and time for the left and right forelimbs (Fig 4 and 5).

Four of 6 horses were determined to be lame in a forelimb. Two were grade-3 lame in the left forelimb, 1 was grade-3 lame in the right forelimb, and 1 was grade-4 lame in the right forelimb.

Mean values for maximum force, peak contact area, and stance time were determined for shod and unshod horses (Table 1). When the data were evaluated independently for each forelimb, there were no significant differences identified for maximum force or stance time in shod and unshod horses. However, the peak contact area decreased significantly for each successive trial for shod (P = 0.006) and unshod (P = 0.012) horses.

When each forelimb was evaluated simultaneously for all horses, there were significant differences identified between right and left forelimbs for maximum force (P < 0.001), stance time (P = 0.011), and peak contact area (P < 0.001). When sensor data were compared with the blinded clinical gait evaluations for individual horses, maximum force data were similar for all 6 horses with a correlation coefficient of 0.91 for shod horses and r = 1.0 for unshod horses (Table 2).

Stance time measurements had an r = 0.82 for horses with shoes and r = 0.82 without shoes. Peak contact area had an r = -0.42 for shod and r = 0.13 for unshod horses. Graphic representations of force data for lame horses were created (Fig 5).

A variance component analysis for trial number revealed that 3 trials provided a variance of 35.4 kg for maximum force (± 5.78% accuracy, confidence interval [CI] = 95%), 0.007 seconds for stance time (± 2.5% accuracy, CI = 95%), and 8.6 cm² for peak contact area (± 11.95% accuracy, CI = 95%). The variance for 1 trial was 61.2 kg for maximum force (± 10.02% accuracy, CI = 95%); 0.012 seconds for stance time (± 4.33%, CI = 95%), and 17.1 cm² for peak contact area (± 20.69% accuracy, CI = 95%).

Discussion

In our study the goals were to describe and evaluate the viability and accuracy of a human in-shoe pressure measurement system for use in horses, and to compare the responses of the system in shod and unshod horses. With the identification of lameness in our sample population, the data from this spontaneously occurring problem were included to further evaluate the efficacy of the system.

Application of this system on a motorized treadmill proved to be easy, horses did not resent the equipment, and no changes in gait were detected between instrumented and noninstrumented horses. The equipment withstood repeated trials and had no overt signs of mechanical or physical failure.

The initial evaluation of the pressure measurement system focused on the effects of a horse's normal shoeing on measurements obtained from the system in comparison to the same horse without shoes. There were no significant differences detected for maximum force or stance time between shod and unshod horses. This indicates that horses can be instrumented with this system with or without shoes, thus allowing ground reaction forces and stance time to be evaluated without regard to the horse's shoeing status. Obtaining similar data from shod horses makes the system an attractive technique to supplement lameness diagnosis.

A significant decrease in peak contact area was observed between shod and unshod horses. However, this difference was greater for horses without shoes. Differences between shod and unshod horses may be explained by sensor fatigue. All horses were initially evaluated with shoes on; therefore, the sensors had already undergone 3 trials prior to application to horses without shoes. On the basis of these observations, when evaluating peak contact area data, it is recommended that each sensor pair be used only for a maximum of 3 trials prior to recalibration. In addition, because all trials had sensors initially applied to horses with shoes, future studies will be required to further evaluate peak contact area determination in shod and unshod horses.

The results indicate that the system is viable and useful for evaluating vertical

Table 1—Mean (± SD) values for maximum force stance time and peak contact area recorded from in-shoe pressure sensors attached to the left (L) and right (R) forelimbs of 6 shod and unshod horses exercising at 3 m/s on a motorized treadmill.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Forelimb</th>
<th>Shod</th>
<th>Unshod</th>
</tr>
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<tbody>
<tr>
<td>Max force (kg)</td>
<td>L</td>
<td>594.0 ± 3.0</td>
<td>630.8 ± 104.4</td>
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<tr>
<td></td>
<td>R</td>
<td>627.5 ± 113.3</td>
<td>590.6 ± 73.0</td>
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<tr>
<td>Stance time (s)</td>
<td>L</td>
<td>0.28 ± 0.03</td>
<td>0.27 ± 0.03</td>
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<tr>
<td></td>
<td>R</td>
<td>0.26 ± 0.03</td>
<td>0.27 ± 0.02</td>
</tr>
<tr>
<td>Peak contact area (cm²)</td>
<td>L</td>
<td>53.6 ± 10.2</td>
<td>59.1 ± 8.8</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>57.1 ± 6.2</td>
<td>55.9 ± 5.8</td>
</tr>
</tbody>
</table>

Table 2—Comparison of maximum force data (kg) obtained from the left and right forelimbs of 6 shod and unshod horses.

<table>
<thead>
<tr>
<th>Horse No.</th>
<th>Shod</th>
<th>Unshod</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left</td>
<td>Right</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P</td>
<td></td>
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<tr>
<td>11</td>
<td>594</td>
<td>580</td>
<td>0.328</td>
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<td>2</td>
<td>763</td>
<td>562</td>
<td>0.004</td>
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<td>576</td>
<td>613</td>
<td>0.748</td>
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<tr>
<td>4</td>
<td>572</td>
<td>540</td>
<td>0.171</td>
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<tr>
<td>5</td>
<td>692</td>
<td>500</td>
<td>0.002</td>
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<tr>
<td>6</td>
<td>490</td>
<td>840</td>
<td>0.005</td>
</tr>
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</table>

*A paired t-test was used to detect differences (P < 0.05) in maximum force allowing selection of the lame forelimb (significantly lower maximum force). Maximum force data were then correlated to clinical lameness to assess the systems ability to detect lameness. Horse 1 was found to have a small abscess on his left forefoot after removing his shoes prior to unshod trials. LF = Left forelimb. RF = Right forelimb.
ground reaction forces in horses. The values for maximum force appear to supply the most accurate correlation between observed clinical lameness and measured lameness. This measurement is easily obtained from the software package and is the default measurement determined in graphic representation of force versus time curves generated after each trial. This supplies the veterinarian a graphic representation of which forelimb is lame within seconds after data acquisition.

Maximum force correlated with blinded clinical observations ($r = 0.91$ with shoes and $r = 1.0$ without shoes). In 1 horse with shoes, a sole abscess developed between the time of observation and when tested on the treadmill. If this problem had been identified before the treadmill study, there would have been 100% correlation between the observed and measured values. This, however, supports the sensitivity of the system and its ability to detect lameness or lack of lameness when the problem is resolved.

We recommend evaluating multiple trials from each horse to improve the accuracy of the data obtained from the sensors. This is recommended based on accuracy determination from calculated variance data for multiple trials. By using 3 complete trials, the maximum force and stance time values obtained from sensors will have a greater accuracy (accuracy $\pm 5.78\%$ for maximum force, and $\pm 2.8\%$ for stance time) than if only 1 or 2 trials were performed (one trial variance, $\pm 10.02\%$ for maximum force and $\pm 4.3\%$ for stance time). The more trials performed increases accuracy and subsequently decreases variance of measurements obtained from the system. Obtaining 3 successive trials is easily done once the equipment has been instrumented to the horse and adds only seconds to the examination process while increasing the overall accuracy of the entire system. However, if peak contact area data are to be evaluated, it is recommended to recalibrate the sensors after each successive 3 trial series.

Stance time data have been reported for horses with instrumented shoes. The data from our study indicate that stance time may provide valuable information as to which forelimb is lame, but its correlation with the clinical examinations was lower than that for maximum force for shod and unshod horses. This limitation may be associated with software sensitivity (measuring only to 0.001 seconds), or stance time may not be a reliable indicator for lameness detection on a motorized treadmill. Further studies will be required to determine the usefulness of stance time for lameness detection in horses.

One study, using center of force acquisition software, was able to differentiate between lateral and medial impact forces in a hoof wall balance model. The conclusions corroborated well with a previously described radiographic technique. However, the study did not address or attempt lameness identification, nor did it evaluate the functionality of the system in shod and unshod horses. This report has examined these differences, and in conjunction with the findings of the hoof wall balance study, adds further validation of this system's ability to evaluate forces involved in equine locomotion and to differentiate lameness in horses.

One potential limitation of this system is the requirement to instrument and use the system on a motorized treadmill. Motorized treadmills are expensive and require specialized equipment and personnel to operate properly. Future applications may allow telemetric application in a field setting to eliminate the need for a treadmill. Horses in our study were only taken to a speed of 3 m/s, and application of the system at faster gaits and speeds has not been studied. Further evaluation of the system is needed to validate its use in equine locomotion analysis at different gaits and speeds.

By using maximum force data, this system should provide an accurate simultaneous assessment of the ground reaction forces of the left and right forelimbs of shod and unshod horses running on a motorized treadmill. When force recordings obtained from 3 repetitive trials are compared between left and right forelimbs, this system should provide an objective, accurate modality to identify and diagnose lameness in horses. Future investigation involving application of the system to horses with known lameness problems, and their response to regional anesthesia, should help validate use of the pressure sensing system for lameness diagnosis.

References


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