

# Use of gyroscopic sensors for objective evaluation of trimming and shoeing to alter time between heel and toe lift-off at end of the stance phase in horses walking and trotting on a treadmill

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**Objective**—To determine whether a shoe with an axial-contoured lateral branch would induce greater lateral roll of the forelimb hoof during the time between heel and toe lift-off at end of the stance phase (breakover).

**Animals**—10 adult horses.

**Procedure**—A gyroscopic transducer was placed on the hoof of the right forelimb and connected to a transmitter. Data on hoof angular velocity were collected as each horse walked and trotted on a treadmill before (treatment 1, no trim–no shoe) and after 2 treatments by a farrier (treatment 2, trim–standard shoe; and treatment 3, trim–contoured shoe). Data were converted to hoof angles by mathematical integration. Breakover duration was divided into 4 segments, and hoof angles in 3 planes (pitch, roll, and yaw) were calculated at the end of each segment. Multivariable ANOVA was performed to detect differences among treatments and gaits.

**Results**—Trimming and shoeing with a shoe with contoured lateral branches induced greater mean lateral roll to the hoof of 3.2° and 2.5° during the first half of breakover when trotting, compared with values for no trim–no shoe and trim–standard shoe, respectively. This effect dissipated during the second half of breakover. When horses walked, lateral roll during breakover was not significantly enhanced by use of this shoe.

**Conclusions and Clinical Relevance**—A shoe with an axial-contoured lateral branch induced greater lateral roll during breakover in trotting horses, but change in orientation of the hoof was small and limited to the first half of breakover. (*Am J Vet Res* 2005;66:2046–2054)

**I**n horses, the period between the point at which the heel leaves the ground and the toe leaves the ground

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at the end of the stance phase of the stride is referred to as breakover, and the last point at which a hoof makes contact before it leaves the ground is the point of breakover. Ideally, the point of breakover is at the apex of the hoof at the most dorsal aspect of the center line bisecting the bottom of the foot. Asymmetric weight bearing during off-center breakover concentrates forces on the internal structures of the foot on the side opposite the point of breakover.<sup>1,4</sup> Off-center breakover is also believed to cause swing abnormalities of the foot, which predispose it to interference with the opposite limb.<sup>5</sup>

Because of the suspected potential problems secondary to off-center breakover, veterinarians and farriers use shoeing techniques to induce a more optimal breakover point.<sup>5,6</sup> Rasping the weight-bearing aspect of the hoof wall or applying shoes that have been rolled or contoured axially on 1 side of the hoof are common techniques used to try to induce breakover toward that side of the hoof.<sup>5,7</sup> However, the ability of these techniques to alter breakover has not been objectively evaluated. The purpose of the study reported here was to determine whether application of shoes with an axial-contoured lateral branch could successfully induce more lateral hoof breakover in horses when walking and trotting.

## Materials and Methods

**Animals**—Ten adult horses were used in the study. All horses were breeding stock or blood donors and were part of a university teaching herd. Each horse was maintained on a preventative medicine program that included regular hoof trimming by an experienced farrier at intervals of 8 to 12 weeks; the hooves of each horse had been trimmed 4 to 8 weeks before the study. All horses were considered sound after a routine subjective, overground lameness evaluation and, in general, had typical hoof conformation. The experimental protocol was reviewed and approved by the University of Missouri Animal Care and Use Committee.

**Procedure**—Each horse was trained to walk and trot on a treadmill during at least 3 sessions conducted during a period of 3 days.<sup>8</sup> Speeds during training at which a horse walked and trotted on the treadmill without excessive prodding or restraint by a handler were determined. These self-selected walking and trotting speeds were recorded and used for all evaluations of each horse.

Hoof orientation during breakover was evaluated for each horse when walking and trotting before and after 2 treatments. The first evaluation was performed before any trimming or shoeing of a horse (treatment 1, no trim–no

shoe). At one of the subsequent evaluations, the forelimb hooves were trimmed and the horse shod by application of a standard steel shoe to both forelimb feet (treatment 2, trim-standard shoe), whereas at the other subsequent evaluation, the hooves were trimmed and the horse shod by application of a steel shoe that had an axially contoured lateral branch to the foot of the right forelimb and a standard steel shoe to the foot of the left forelimb (treatment 3, trim-contoured shoe; Figure 1). Order of treatments 2 and 3 was randomized for each horse. Trimming and shoeing were performed by an experienced farrier (JMC). All evaluations were performed during a period of 3 days; trimming and shoeing for treatments 2 and 3 were performed approximately 8 hours before evaluation.

The second and third evaluations were performed after trimming to balance the forelimb feet of each horse. A foot was considered balanced when the angle of the dorsal hoof wall was equivalent to the angle of the heel and the midsagittal axis of the second phalanx (pastern axis) when the horse was bearing full weight and when the heights of the medial and lateral aspects of the heel were equivalent.

**Instruments**—Hoof orientation during breakover was evaluated by attaching a custom-designed 3-directional gyroscopic transducer to the dorsal hoof wall of the foot of the right forelimb; the gyroscopic transducer was affixed by use of sticky cloth tape (Figure 2). The gyroscopic transducer, which measures angular velocity of the hoof around 3 orthogonal axes, consisted of 3 piezoelectric vibrating gyroscopic sensors<sup>a</sup> and a microcomputer<sup>b</sup> in a noninverting, low-pass filter, integrated-circuit design (resolution, 0.67 mV/degree/s; gain, 2X; cutoff frequency, 53 Hz; accuracy, 0.1 degree/s). A 6-channel, 8-bit, analogue-to-digital converter and low-power transmitter<sup>c</sup> (transmission frequency, 1.9 GHz) powered by 3 AA-size batteries was attached to the dorsum of the horse at the thoracolumbar junction by use of a hook-and-loop patch glued to the skin or to a girth strap worn by the horse. A cable running from the gyroscopic transducer was taped to the limb

and attached to the mane before connecting to the transmitter on the dorsum of the horse. The gyroscopic transducer (27 × 27 × 12 mm) weighed 33 g, and the transmitter (30 × 40 × 146 mm) weighed 231.5 g. Only 3 of the 6 channels of the converter were used in the study. The digital signal was transmitted at a frequency of 200 Hz to a receiver<sup>c</sup> attached through a universal serial bus port to a laptop computer. Data collection was performed by use of a custom-written graphic user interface.<sup>d</sup>

**Data collection**—Data were collected from each horse as it walked (1.8 to 2.2 m/s) and trotted (3.6 to 4.8 m/s) on a treadmill for 3 trials (2 min/trial). This duration of collection resulted in data from > 100 complete strides during walking and > 200 strides during trotting for each trial. Thus, a total of > 300 strides for walking and > 600 strides for trotting were collected. Output of the transducer was rotational angular velocity around the dorsopalmar axis (x-axis; hoof roll), lateromedial axis (y-axis; hoof pitch), and vertical axis (z-axis; hoof yaw; Figure 3).

**Data analysis**—Signals of rotational angular velocity for pitch, roll, and yaw of the hoof were converted to rotational angular position of pitch, roll, and yaw by integration or summing every preceding number in that channel. Mathematically, this can be stated as the following matrix:

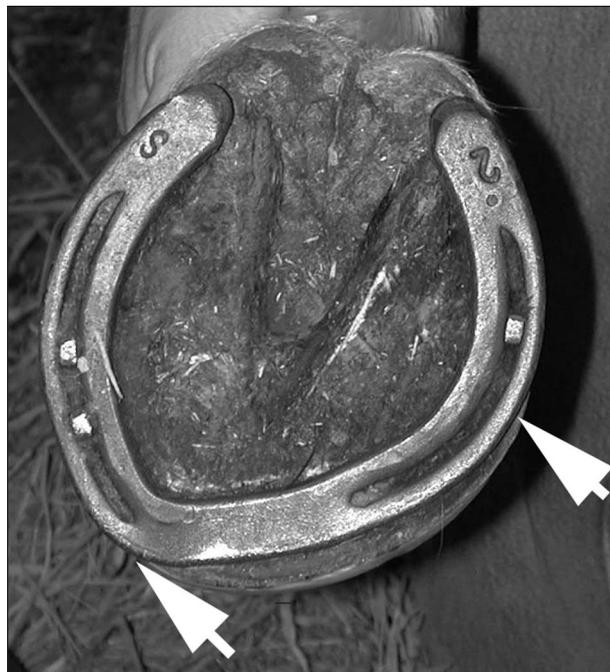


Figure 1—Photograph of the foot of a representative horse for treatment 3 (trim-contour shoe). Notice the lateral branch of the shoe is contoured (area between arrows) toward the midline of the hoof.



Figure 2—Photograph of a horse with a 3-axis gyroscopic transducer attached to the foot of the right forelimb by use of sticky cloth tape (arrow). Notice the transmitter (arrowhead) is located on the dorsum of the horse and is attached to a girth strap. Inset = View of the position of the gyroscopic transducer on the dorsal wall of the hoof.

$$\begin{bmatrix} \alpha(t) \\ \beta(t) \\ \gamma(t) \end{bmatrix} = \begin{bmatrix} \sum_{t=1}^N v_{\alpha}(t) \\ \sum_{t=1}^N v_{\beta}(t) \\ \sum_{t=1}^N v_{\gamma}(t) \end{bmatrix}$$

where  $\alpha(t)$  is the rotational angle of the dorsal wall of the hoof in the sagittal plane (x-z plane; pitch angle),  $\beta(t)$  is the rotational angle of the dorsal wall of the hoof in the frontal plane (y-z plane; roll angle),  $\lambda(t)$  is the rotational angle of the dorsal wall of the hoof in the horizontal plane (x-y plane; yaw angle), N is the number of data points,  $v_{\alpha}$  is the angular velocity of the hoof rotational pitch,  $v_{\beta}$  is the angular velocity of the hoof rotational roll,  $v_{\lambda}$  is the angular velocity of the hoof rotational yaw, and t is time.

Rotational angle of the hoof was calibrated to zero by subtracting the most frequent number within the signal (ie, statistical mode) from the raw signal values. Rotation of the hoof in 1 direction was considered a positive deflection, whereas rotation in the opposite direction was a negative deflection (Figure 4). Because of errors in summation and analogue-to-digital conversion, there was a steady baseline shift of the rotational angular position signals. Rotational angular position was recalibrated to zero after each breakover during the swing phase of the stride to correct for the baseline shift, which forced each breakover at the end of each stride to start at rotational roll, pitch, and yaw angles equal to 0°.

Start and end of breakover for each stride were defined from the rotational pitch channel. Breakover began at the first negative deflection of hoof pitch in the dorsal direction, which indicated the heel had left the ground or negative rotation of the hoof in the sagittal plane. Breakover ended when hoof pitch reached a minimum negative position, which indicated the start of rotation of the hoof in the opposite direction at the beginning of the swing phase of the stride. Beginning and end of breakover were determined for each stride during the 2-minute period of each trial. During breakover, a positive deflection in the hoof roll channel indicated lateral rolling or breakover and a positive deflection in the hoof yaw channel indicated clockwise or external rotation of the foot of the right forelimb.

Total breakover duration was then divided into 4 equal segments (Figure 5). Output was roll and yaw angles of the dorsal hoof wall at the end of each segment of breakover for each stride. Mean  $\pm$  SEM values for roll and yaw angle of the dorsal hoof wall for all strides in all 3 trials were computed for each segment of breakover, gait (walking and trotting), and treatment.

A general linear model, repeated-measures, multivariable ANOVA was performed to evaluate differences among the 3 treatments and 2 gaits. Because each horse served as its own control animal, between-subject factors were not tested. Within-subject factors included segment of breakover (1 to 4), treatment (1, 2, and 3), and gait (walking and trotting). Experiment-wise significance was set at  $\alpha = 0.05$ . Post hoc comparisons were made by use of least squared differences. The Mauchly test of sphericity was used to test for equality of variance in the dependant variable among the factors tested (segment, treatment, and gait), which is an assumption of the multivariate technique. When the sphericity assumption was violated, adjustments were made to the degrees of freedom for the numerator and

denominator, and significance of the F statistic was evaluated with the new degrees of freedom. Adjusting the degrees of freedom for a sphericity violation results in a more conservative F statistic, which makes it more difficult to conclude a difference between treatments.

## Results

Data for 1 horse for treatment 1 when walking and trotting and for 1 horse for treatment 2 when walking were not available for analysis. Data for these 2 horses for the other treatments and gaits were used for further analysis.

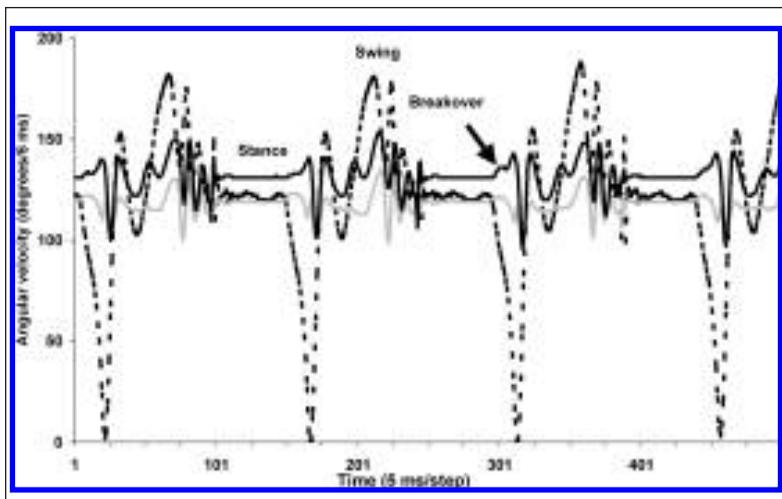


Figure 3—Raw gyrosopic data collected from a representative horse trotting on a treadmill. Data were collected for a period of 2.5 seconds for all 3 channels (ie, pitch [dotted line], roll [gray line], and yaw [black line]) for the foot of the right forelimb. Breakover = Period between the point at which the heel leaves the ground and the toe leaves the ground at the end of the stance phase of the stride.

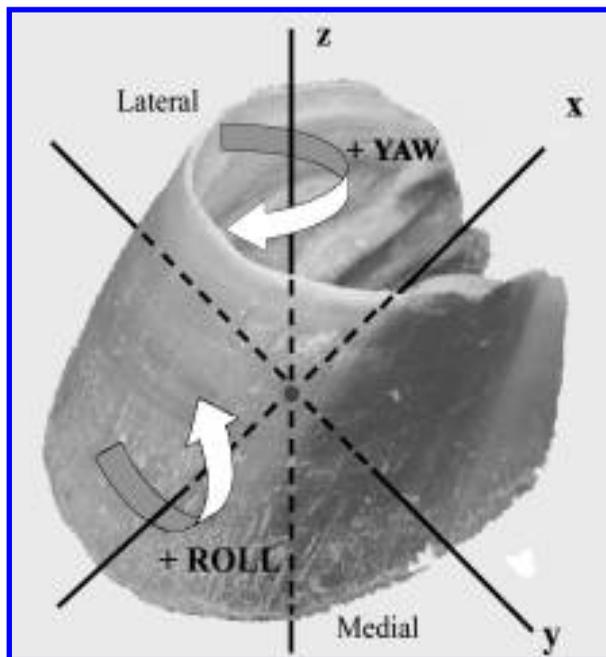


Figure 4—A 3-dimensional representation of a horse's right hoof indicating the axes (x-axis [dorsopalmar axis], hoof roll; y-axis [lateromedial axis], hoof pitch; and z-axis [vertical axis], hoof yaw). Notice the rotation in a positive (+) direction for hoof roll (breakover in a lateral direction) and hoof yaw (external rotation).

Hoof roll and hoof yaw angles differed significantly among the repeated measures, with a significant segment  $\times$  gait  $\times$  treatment interaction (Table 1). Mean, SEM, 95% confidence intervals, and results of statistical analysis for the main treatment effects and interactions for all segments were calculated (Table 2). Variation of hoof roll and hoof yaw angles for all horses for all treatments at all gaits steadily increased from segment 1 to segment 4 of breakover (Figure 6).

Mean hoof roll angle was significantly more positive (which indicated more lateral rolling of the hoof) after trimming and application of contoured shoes for segments 1 and 2 (first half of breakover) during trotting, compared with results for no trimming and no shoeing and trimming and application of a standard shoe (Figure 7). There were no significant differences in hoof roll angle among the 3 treatment conditions for segments 3 and 4 (second half of breakover) during trotting. There were no significant differences in hoof roll angle among the 3 treatment conditions for any segment of breakover during walking.

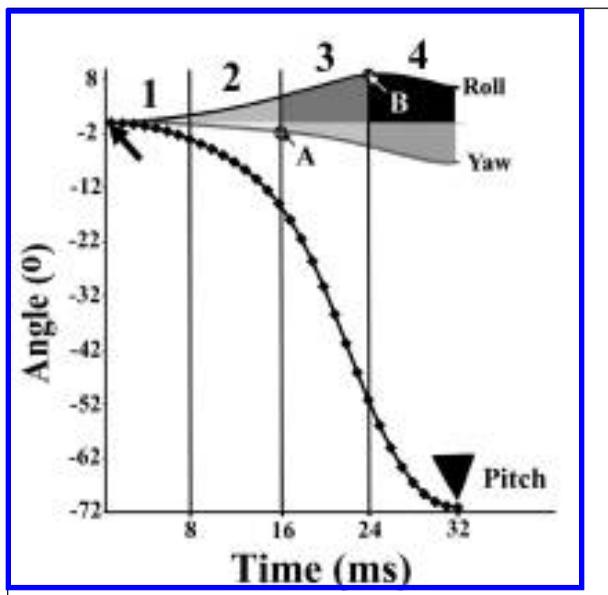


Figure 5—Schematic depicting breakover duration divided into 4 equal segments and evaluation of roll, pitch, and yaw for a hoof. Beginning (arrow) and end (arrowhead) of breakover were determined from data collected for hoof pitch. A = Hoof yaw angle at the end of segment 2. B = Hoof roll angle at the end of segment 3.

Before trimming and shoeing (treatment 1), 2 of 9 horses (data were not available for 1 horse) had negative values for hoof roll within the first half of breakover, which indicated breakover in a medial direction. The other 7 horses had breakover in a lateral direction as indicated by positive values for hoof roll during the first half of breakover. For treatment 2 (trim–standard shoe), 2 horses had negative values for hoof roll (ie, breakover in a medial direction) during the first half of breakover, 6 had positive values for hoof roll (ie, breakover in a lateral direction), and 1 was exactly on the dorsal midline (hoof roll angle, 0°). Horses with breakover in a medial direction before trimming and shoeing were not the same horses with breakover in a medial direction after trimming and application of a standard shoe. All horses had breakover in a lateral direction for treatment 3 (trim–contoured shoe).

Hoof yaw angle was significantly more positive (which indicated clockwise rotation of the foot of the right forelimb) after trimming and application of shoes, compared with values for no trim–no shoe, but only during trotting and only for segments 1 and 2 for the standard shoe and segment 1 for the contoured shoe (Figure 8). There were no significant differences in hoof yaw angle among the 3 treatment conditions for segments 3 and 4 during trotting. Hoof yaw angle did not differ significantly among the 3 treatment conditions for any segment of breakover during walking.

## Discussion

Results of the study reported here support the contention that shoeing can induce a change in hoof orientation during breakover. However, the effect of the shoe alone on breakover seems to dissipate during the second half of breakover. During trotting in our study, a shoe with a fairly dramatic axial contour to the lateral branch induced a mean increase in lateral roll of 0.8° by the end of the first segment of breakover and a mean increase in lateral roll of 2.9° by the end of the second segment of breakover, compared with overall mean values for no trim–no shoe combined with trim–standard shoe. Intrahorse variation increased from segment 1 to segment 4, such that halfway through breakover, the effect of shoeing was overwhelmed. We believe that during the last half of breakover, orientation of the hoof becomes more dependent on overall limb and foot conformation of the horse than on the artificially altered shape of the bottom of the hoof.

Table 1—Results of statistical analysis for the main effect of treatment and the treatment  $\times$  gait interaction for each segment of the period between the point at which the heel leaves the ground and the toe leaves the ground at the end of the stance phase of the stride (breakover).

Hoof angle measure	Breakover segment	Family-wise <i>P</i> value for treatment effect	Family-wise <i>P</i> value for treatment $\times$ gait interaction
Roll	1	0.077	0.003*
	2	0.041*	0.016*
	3	0.168	0.623
	4	0.466	0.434
Yaw	1	0.006*	0.086
	2	0.242	0.008*
	3	0.253	0.068
	4	0.243	0.806

\*Values were considered significant at  $P < 0.05$ .

Table 2—Group mean, SEM, and 95% confidence interval (CI) of hoof roll and hoof yaw angles for all horses for segments 1 and 2 during breakover for both gaits and all 3 treatments.

Hoof angle measure	Breakover segment	Gait	Treatment*	Group mean	SEM	95% CI	P value†
Roll‡	1	Walk	1	0.10	0.13	-0.17 to 0.37	NA
			2	0.07	0.13	-0.21 to 0.34	0.863
			3	0.36	0.12	0.10 to 0.61	0.170
		Trot	1	0.35	0.26	-0.19 to 0.90	NA
			2	0.42	0.25	-0.09 to 0.93	0.857
			3	1.19	0.25	0.68 to 1.71	0.030
	2	Walk	1	0.40	0.55	-0.73 to 1.54	NA
			2	0.74	0.55	-0.39 to 1.88	0.894
			3	1.98	0.52	0.91 to 3.05	0.117
Trot		1	1.17	1.12	-1.14 to 3.47	NA	
		2	1.70	1.05	-0.47 to 3.88	0.729	
		3	4.36	1.05	2.18 to 6.53	0.049	
Yaw§	1	Walk	1	-0.04	0.05	-0.15 to 0.08	NA
			2	-0.04	0.02	-0.10 to 0.02	0.935
			3	0.00	0.09	-0.22 to 0.22	0.734
		Trot	1	-0.04	0.06	-0.18 to 0.10	NA
			2	0.33	0.12	0.04 to 0.62	0.020
			3	0.21	0.08	0.02 to 0.40	0.019
	2	Walk	1	-0.10	0.30	-0.82 to 0.62	NA
			2	-0.02	0.11	-0.28 to 0.23	0.800
			3	-0.28	0.33	-1.09 to 0.53	0.675
		Trot	1	-0.04	0.30	-0.76 to 0.67	NA
			2	1.30	0.49	0.13 to 2.46	0.039
			3	0.58	0.39	-0.24 to 1.27	0.107

Values reported are degrees; a value of 0.0° indicates breakover at the apex of the toe without roll or yaw.  
 \*Treatments are as follows: treatment 1, no trim—no shoe; treatment 2, trim—standard shoe; and treatment 3, trim—contoured shoe. †Results are for multiple post hoc comparisons of treatments 2 and 3 with treatment 1 at each segment and gait; values were considered to differ significantly at  $P < 0.05$ . ‡Negative values for roll indicate rolling in a medial direction at breakover. §Negative values for yaw indicate counterclockwise rotation of the hoof of the right forelimb at breakover.  
 NA = Not applicable.

A more severe but often recommended technique farriers use to alter breakover is to reshape the hoof wall by rasping it to conform to the shape of a contoured shoe.<sup>7</sup> This was not done in our study because doing so would have precluded randomization of the order of the shoeing treatments. Rasping the shape of the foot to conform to the contour of the shoe may have affected hoof orientation during the second half of breakover.

Analysis of results of the study reported here also suggested that application of steel shoes on a horse's hooves increases yaw or twisting of the hoof wall in a lateral direction during breakover when the horse is walking or trotting on a treadmill. This is probably attributable to a decrease in friction between the shoe and treadmill surface. For trotting horses, we found that trimming and application of standard steel shoes resulted in an increase in yaw of 0.4° in the lateral direction after the first segment of breakover and an increase in yaw of 1.4° in the lateral direction after the second segment of breakover, compared with values for no trim—no shoe. This same effect was seen with trimming and application of shoes with an axially contoured lateral branch but to a lesser extent (increase of 0.2° and 0.6° in the lateral direction after segments 1 and 2 of breakover, respectively). The treadmill belt

used in this study had a semihard rubber consistency with a roughened surface. This provided a flat surface for a level stance, which is best for evaluating hoof orientation during breakover, but the jagged edges of the untrimmed hoof wall provided good traction on the rough treadmill belt. Trimming and shoeing smoothed the weight-bearing surface of the hoof, possibly decreasing traction on the treadmill and increasing the amplitude of twisting during the first half of breakover. The effect of trimming and shoeing on hoof roll and hoof yaw during breakover when horses walk or trot on other surfaces should be investigated.

We were unable to measure a change in hoof roll and hoof yaw in horses during walking after trimming and application of shoes. During walking after trimming and application of a specially designed contoured shoe, hoof roll angle at the end of segment 1 (0.4°) and segment 2 (2.0°) of breakover was more positive but did not differ significantly ( $P = 0.170$  and  $0.117$ , respectively), compared with hoof roll angle before trimming and application of a shoe. More dramatic shoes, rasping the hoof wall to conform to the shape of the shoe, or evaluation on a harder surface may have resulted in greater change in the hoof roll angle during walking. Breakover is longer in duration during walking, compared with duration during trotting. Increased

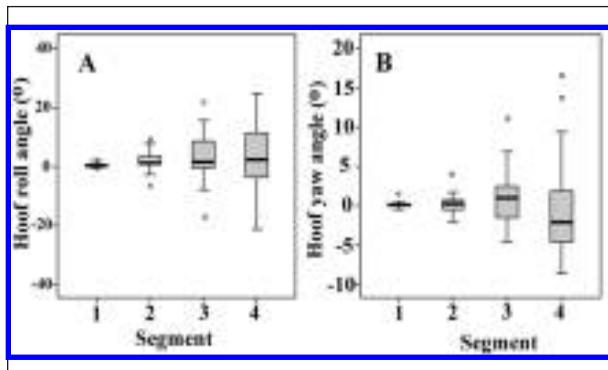


Figure 6—Box-and-whisker plots of the angles for hoof roll (A) and hoof yaw (B) for each of the 4 segments of breakover for all horses and treatments during walking and trotting. Each box represents the interquartile range (25th to 75th percentiles). The black horizontal bar within each box is the median, and extreme values are indicated as the whiskers (T-bars). Outliers (> 2 SD from the mean) are indicated (circles). Notice that the scale on the y-axis differs for each portion of the figure.

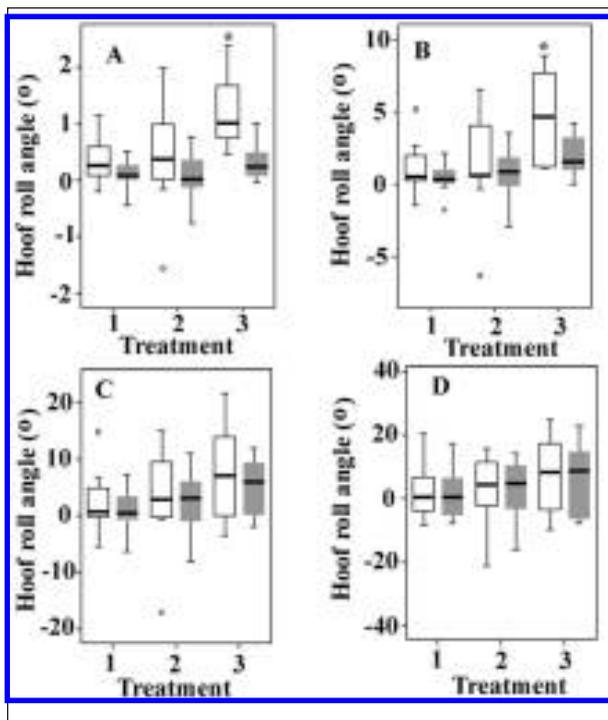


Figure 7—Box-and-whisker plots of hoof roll angle for all horses for segments 1 (A), 2 (B), 3 (C), and 4 (D) of breakover during walking (gray boxes) and trotting (white boxes) for each treatment (treatment 1, no trim–no shoe; treatment 2, trim–standard shoe; and treatment 3, trim–contoured shoe). \*Within a gait, median value differs significantly ( $P < 0.05$ ) from median value for treatment 1. Notice that the scale on the y-axis differs for each portion of the figure. See Figure 6 for remainder of key.

duration of breakover may create opportunities for proprioception-induced, compensatory, weight-shifting mechanisms within a limb to counteract the mechanical effect of the change in the weight-bearing surface of the foot.

In the study reported here, duration of the first half of breakover ranged from approximately 40 to 50 milliseconds during trotting to approximately 50 to 100 milliseconds during walking. The active neuro-

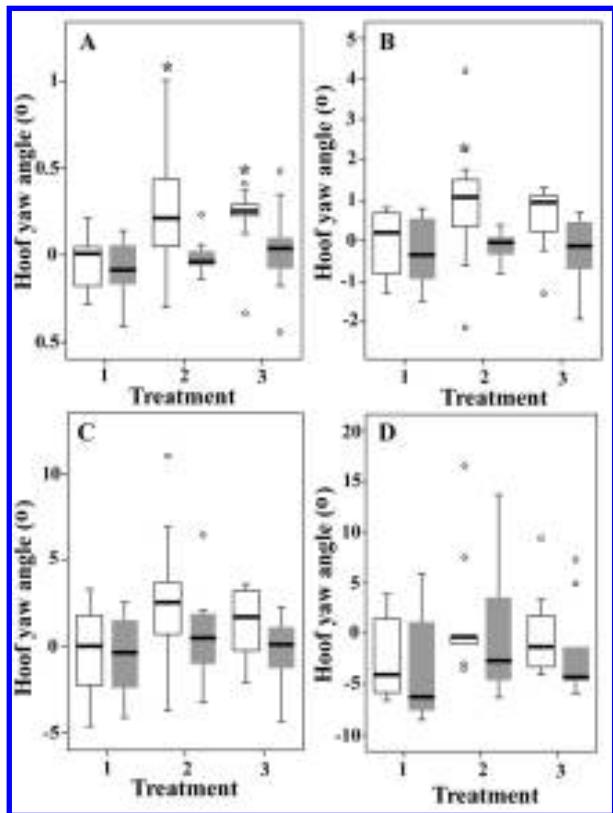


Figure 8—Box-and-whisker plots of hoof yaw angle for all horses for segments 1 (A), 2 (B), 3 (C), and 4 (D) of breakover during walking (gray boxes) and trotting (white boxes) for each treatment. Notice that the scales on the y-axis differ for each portion of the figure. See Figures 6 and 7 for remainder of key.

logic response time required for muscles to respond to a stimulus is approximately 30 to 50 milliseconds.<sup>9,10</sup> The first half of breakover during walking may be of such a long duration that activity of limb muscles compensates for the altered forces acting on the bottom of the foot with the contoured shoe. Also, the torque force creating hoof yaw is expectedly less during walking than during trotting and, as suggested by analysis of the results of this study, less than that required for overcoming frictional resistance of the treadmill surface.

Before trimming and application of a shoe, group mean hoof roll angles after the first 2 segments of breakover were positive during walking and trotting. Thus, breakover in a lateral direction was the most common condition in our group of horses. This agrees with results of another study<sup>11</sup> in which investigators evaluated the point of force application by use of a force plate in 8 horses throughout the stance phase. However, in the study reported here, 2 horses before trimming and application of a shoe and 2 other horses after trimming and application of a standard steel shoe had breakover in a medial direction. All horses had breakover in a lateral direction after trimming and application of the axially contoured shoe. Thus, in the horses with preexisting breakover in the medial direction, breakover direction was redirected after trimming and application of the contoured shoe, whereas in other horses with preexisting breakover in the lateral

direction, breakover was magnified. This could have been the result of breakover in a more lateral direction or of breakover at the same location but to a greater magnitude within the time frame of the first half of breakover.

Conversely, before trimming and application of a shoe, mean hoof yaw angles at the end of the first 2 segments were negative during walking and trotting. Thus, a slight counterclockwise yaw (medial twisting of the foot of the right forelimb) was the most common condition in our group of horses. This was reversed during trotting after horses were trimmed and shod, such that a slight clockwise yaw (lateral twisting of the foot of the right forelimb) was predominant.

The effects of trimming and shoeing on breakover duration have been described. By use of a combination of analysis of force plate data and videotape, investigators in 1 study<sup>12</sup> evaluated breakover duration and joint moment arms of the distal interphalangeal joint for 3 shoe types; however, they did not measure the direction of breakover. In that study, shoes designed to induce earlier breakover and thus ease the biomechanical effects of breakover decreased the moment arm of the distal interphalangeal joint but did not significantly change the duration of breakover. By use of a force-measuring shoe in 2 horses<sup>13</sup> and cinematography,<sup>14</sup> other investigators found that breakover duration was increased by raising the toe or causing an acute angulation of the hoof wall and decreased by raising the heel or creating a more typical angulation of the hoof wall; however, similar to other aforementioned studies, those investigators did not measure hoof orientation during breakover.

Investigators in 1 study<sup>11</sup> used a force plate to evaluate direction of breakover by following the point of force application throughout the complete stance in 8 horses before and after shoeing with wedge pads (5° medial followed by 5° lateral wedge pads). Contrary to common belief, elevating the lateral portion of the hoof wall caused the toe to leave the ground farther laterally at the end of breakover and elevating the medial portion of the hoof wall caused the toe to leave the ground farther medially. In another study,<sup>15</sup> investigators used computerized gait analysis and stationary force plates to perform inverse dynamic analysis in the comparison of typical shoes with rocker-toe shoes. They concluded that rocker-toe shoes did change the proximity of breakover from the center of the toe. We are unaware of any other studies in which investigators specifically evaluated direction of breakover in an objective manner.

Asymmetric hoof landing is often believed to contribute to the development of lameness, but hoof imbalance can also affect the biomechanics of internal foot structures at the start of breakover.<sup>11</sup> Important biomechanical events involving limb structures happen during breakover. During breakover, the vertical ground reaction force against the bottom of the foot is decreasing and is less than that at midstance.<sup>16</sup> However, the point of application of the mean vertical ground reaction force against the bottom of the foot during breakover is moving dorsally toward the toe.<sup>17</sup> This increases the length of the moment arm between the mean point of application of the vertical ground

reaction force and the center of rotation of the distal interphalangeal joint. Therefore, the distal interphalangeal joint is maximally extended at the beginning of breakover, and strain in the deep digital flexor tendon is high.<sup>18,19</sup> During the same time frame, the inferior accessory (check) ligament<sup>20,21</sup> and distal impar ligament of the navicular bone are maximally stressed<sup>22</sup> and there is increased stress in the dorsal wall of the hoof.<sup>23-25</sup> Asymmetric foot orientation throughout the stance phase is believed to induce rotation in joints in the distal aspect of the limb, which places excessive strain on collateral and annular ligaments and causes abnormal transfer of forces across joint surfaces.<sup>1,2,3,7</sup> Changing the direction of breakover improves alignment between the second and third phalanx.<sup>26</sup> This information about the forces acting within the foot suggests that biomechanical stresses are altered during off-center breakover.

The roll and yaw changes induced by application of a shoe within the first 2 segments of breakover during the study reported here were small (< 3.0° for roll and 1.5° for yaw). There is a paucity of other reports from which to extrapolate information that would be of aid in determining whether such small changes, although statistically significant, are clinically relevant. Elevation of the heel by use of a 2° wedge pad decreases the force exerted by the deep digital flexor tendon on the navicular bone by 24%.<sup>27</sup> Medial or lateral wedges as small as 2° placed between the bottom of the hoof and a shoe will cause asymmetry of the same magnitude within the proximal and distal interphalangeal joints.<sup>1,2</sup> Asymmetry of 5° in the interphalangeal joints induced by trimming the medial wall of the hoof shorter than the lateral wall results in a shift in the center of force on the bottom of the foot to a point approximately midway between the center of the foot and the lateral wall of the hoof.<sup>3</sup> A 5° lateral wedge placed on the hooves of the hind limbs of Shetland ponies induced significant changes in the transverse plane angles of all joints in the hind limbs.<sup>28</sup>

Interpretation of the results of these studies suggests that asymmetry of 2° to 5° is clinically important. The small changes in angle found in our study (approx 1.5° to 3°) are at the lower range of angles tested in other studies. However, it must also be kept in mind that the first half of breakover in a horse trotting at moderate speed (approx 4 m/s) is of short duration (40 to 50 milliseconds). Rapid changes, even of small magnitude, may be more clinically important. It should also be mentioned that we did not limit variability for treatment 1 by adjusting the no trim–no shoe condition of each horse. Although the horses were on a regularly scheduled program for hoof trimming, they were used as is when retrieved from the pasture. Hooves of each horse were then trimmed in the same manner. Had we instead evaluated treatment 1 as a trimmed but unshod condition, perhaps greater differences between the unshod and shod conditions would have been detected.

In contrast, at equivalent speeds in the same horses, duration of the stance phase is slightly longer and the forelimbs generally move more caudally on the treadmill than for overground locomotion on a hard

surface (eg, asphalt).<sup>29</sup> Breakover with a longer duration at equivalent speeds on the treadmill probably facilitated an increased likelihood that we would detect an effect of shoeing, compared with results for overground locomotion on a hard surface in which breakover is of shorter duration. Also, we evaluated our horses only 8 hours after trimming and shoeing. The small effects that we saw may diminish with additional time as a horse becomes more adapted to the shoeing changes. Lastly, the shoeing technique we used in this study was fairly dramatic and designed to induce a significant effect on breakover. Shoeing techniques commonly used in clinical practice to alter breakover in horses are generally less dramatic. These would be expected to result in smaller changes than those seen in the study reported here. We believe that it is unlikely that even smaller changes in hoof orientation during breakover would be clinically important.

In the study reported here, treatment 1 was always administered before treatments 2 and 3; only the order of treatments 2 and 3 was randomized. Also, both forelimb feet were manipulated between treatment 1 and the succeeding treatment (2 or 3), even though data were collected only for the foot of the right forelimb. Differences between treatments 2 and 3 consisted of changes to the right foot only. Therefore, the cause of changes between the no trim–no shoe and trim–shoe treatments cannot be separated from treatment order or effects on the opposite limb.

Tilt or incline can be measured most directly by sensors that measure inertial forces, rather than through calculation by use of gyroscopes (angular velocity sensor). Tilt meters or inclinometers that measure inertial forces are extremely sensitive and have been evaluated for use in the control of neural prosthetics after electrical stimulation.<sup>30</sup> Segment tilt can be accurately measured by use of a tilt meter during the stance phase of the stride because the inertial force is primarily attributable to gravity and angular acceleration is zero. However, as soon as a hoof rotates during breakover, angular acceleration affects the measurement and tilt cannot be accurately determined. Sensors that directly measure static and dynamic angles do not exist. We calculated hoof angles indirectly from data on hoof angular velocity. The conversion to hoof angle by use of integration introduces errors that accumulate with time. We had to recalibrate (to zero) hoof angle before the beginning of breakover, which precluded accurate determination of hoof orientation during impact. Therefore, this system was limited to determining hoof orientation during breakover. Additional signal processing or use of more accurate (12-bit) digital conversion could lessen this problem and render this system suitable for accurate measurements of hoof angle throughout the stance and swing phases of the stride.

In the study reported here, we only used 3 channels of data collection (1 for each rotational direction for 1 foot); however, the transmission hardware was designed for 6 channels. Therefore, pitch, roll, and yaw data can be collected simultaneously from both feet of the forelimbs or hind limbs. The reported transmission frequency of 200 samples/s (ie, 1 sample/5 ms) would

not be sacrificed by use of 2 transducers. This rate, based on the Nyquist<sup>31</sup> sampling theorem, which states that signal reproduction requires sampling the highest important signal frequency at least twice per cycle, is greater than that required to accurately capture each segment of breakover (20 to 25 milliseconds).

Point of breakover can be objectively determined by use of stationary force plates by monitoring the mean point of application of vertical ground reaction force through the period of breakover. This technique has been used in a few studies in clinically normal horses before and after elevating segments of the weight-bearing surface of a foot. The primary disadvantage of the use of stationary force plates to determine hoof orientation during breakover is that only 1 stride can be measured per trial. Variation in hoof orientation during breakover within each horse requires collection of multiple strides. An advantage to the gyroscopic transducer system for the measurement of hoof orientation during breakover in horses is that data can be collected on several contiguous strides.

We evaluated the horses of this study during walking and trotting on a treadmill. However, reliable transmission range for the equipment was > 100 m. The equipment can be quickly and easily attached to a horse, is inexpensive, and enables unrestricted movement of horses. Thus, the equipment can be used in a field-type setting with the horse traveling overground.

Analysis of results of the study reported here indicated that breakover can be influenced by trimming and application of a shoe with axially contoured branches. The described gyroscopic transducer system offers a straightforward objective method for use in evaluating hoof orientation during breakover and can be used to improve our understanding of breakover and to assess the effects of treatment techniques. A method of objectively determining hoof orientation during breakover for multiple contiguous strides would be helpful for equine veterinarians and farriers assessing corrective trimming and shoeing techniques designed to affect breakover.

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- a. Gyrostar ENC gyroscopic sensor, Murata Manufacturing Co, Kyoto, Japan.
  - b. PIC 18F4520 microcomputer, Microchip, Chandler, Ariz.
  - c. Personal Handyphone System, Adapter mode TPA1005, Toshiba Corp, Tokyo, Japan.
  - d. Visual Basic, Microsoft Corp, Redmond, Wash.
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