Compensation for changes in hoof conformation between shoeing sessions through the adaptation of angular kinematics of the distal segments of the limbs of horses

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Objective—To determine the mechanism that enables horses to partially counteract the shift of the center of pressure under the hoof induced by changes in hoof morphology attributable to growth and wear during a shoeing interval.

Animals—18 clinically sound Warmblood horses.

Procedures—Horses were evaluated 2 days and 8 weeks after shoeing during trotting on a track containing pressure-force measuring plates and by use of a synchronous infrared gait analysis system set at a frequency of 240 Hz. All feet were trimmed toward straight alignment of the proximal, middle, and distal phalanges and shod with standard flat shoes.

Results—Temporal characteristics such as stance time and the time between heel lift and toe off (ie, breakover duration) did not change significantly as a result of shoeing interval. Protraction and retraction angles of the limbs did not change. Compensation was achieved through an increase in the dorsal angle of the metacarpophalangeal or metarsophalangeal (fetlock) joint and a concomitant decrease of the dorsal angle of the hoof wall and fetlock. There was an additional compensatory mechanism in the hind limbs during the landing phase.

Conclusions and Clinical Relevance—Horses compensate for changes in hoof morphology that develop during an 8-week shoeing interval such that they are able to maintain their neuromuscular pattern of movement. The compensation consists of slight alterations in the angles between the distal segments of the limb. Insight into natural compensation mechanisms for hoof imbalance will aid in the understanding and treatment of pathologic conditions in horses. (*Am J Vet Res* 2006;67:1199–1203)

Abbreviations

CoP	Center of pressure
FA	Fetlock angle
PHA	Proximal hoof angle

Shoeing was originally intended to protect the feet of horses against excessive wear. However, farriers currently also try to optimize performance by use of shoeing methods and application of specific shoes. In addition, shoeing techniques are often used during the rehabilitation process for lame horses. Farriery is still a craft based primarily on empiric observations, rather than science-based information. This is not because of a lack of interest; however, it has proven extremely difficult to measure effects of shoeing interventions because of the speed with which events happen and the subtlety of the changes induced by typical shoeing practices. Studies on the effects of special shoes, such as rocker[1] and rolled-toed[2] shoes, or specific shoeing techniques, such as natural balance,[3] were unable to provide scientific evidence for the effects these shoes were presumed to have on locomotion of horses. However, to optimize shoeing for modern equine athletes and to improve therapeutic shoeing interventions, it is essential to know how horses compensate for the changes induced with shoeing.

The effects of an 8-week shoeing interval have been studied.[4,5] Changes in hoof morphology attributable to hoof growth and wear during this shoeing interval were a decrease of 3.3° in hoof angle of the forefeet and a decrease of 3.2° in the hoof angle of the hind feet. Length of the dorsal hoof wall increased by 1.4 cm and 1.5 cm, respectively.[4] On mere geometric analysis, these changes in hoof morphology should lead to a shift of the CoP at midstance in a palmar or plantar direction to maintain equilibrium. This indeed was the case but to a smaller extent than calculated, which indicated a compensatory mechanism.[4] In a follow-up study[5] that used a subgroup of the same cohort of horses and focused on changes in joint moments in standing horses, it was reported that horses at the end of the shoeing interval had a more broken or backward alignment of the distal segments of the limbs, especially for the distal interphalangeal joint but not for the proximal interphalangeal joint, which suggested compensation through the adaptation of angles between the distal segments of the limbs.

Relationships between hoof angles and limb angulation have been the subjects of other studies. In standing horses, artificially induced changes achieved by the use of heel and toe wedges resulted in linear relationships between hoof angle changes and alterations in angulation of the distal portions of the limbs.[6–8] Furthermore, a change of 10° in the hoof angle can cause an increase in the time between heel lift and toe off (ie, breakover duration), but other stride characteristics (eg, stance time and step length) remain unal-

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tered.[9,10] However, all of these studies focused on artificially induced changes, achieved primarily by the use of wedges, and investigators often evaluated only acute effects. The reports do not yield information about how horses compensate for typical hoof growth and the ensuing changes in hoof morphology during a typical shoeing interval in which changes are subtle and develop over a prolonged period.

In the study reported here, we tested the hypothesis that horses maintained their specific neuromuscular pattern of movement and therefore compensated for changes induced by typical hoof growth by subtle changes in angular motion patterns, rather than by changes in linear or temporal stride characteristics. To minimize variation, kinematic measurements were obtained from the same population of horses and for identical circumstances as those in the aforementioned studies.[4,5]

Materials and Methods

Animals—Eighteen clinically sound Warmblood horses were used in the study. The horses were owned by 2 owners[a] who approved their use (ie, written informed consent). The horses were brought to the Derona Equine Performance Laboratory in the morning, were measured, and were transported home in the evening. These horses were also part of a larger project intended to quantify effects of typical shoeing procedures and typical hoof growth during shoeing intervals on kinetics and kinematics of the distal segment of the limbs of horses and loading of internal structures.[4,5] All horses were saddled, ridden, and trained daily during the experiment. Mean ± SD age of the horses was 4.9 ± 2.3 years, and mean weight was 569.4 ± 40.7 kg.

Procedure—Two experienced farriers were each assigned a group of horses (9 horses/group). Hooves of each horse were trimmed toward a static hoof balance, which refers to a geometric equilibrium of the limb and hoof in a square standing position, with straight alignment of the proximal, middle, and distal phalanges. Afterward, the horses were shod with standard flat iron shoes.[b] Feet of the forelimbs were shod with 1 toe clip, whereas feet of the hind limbs were shod with 2 side clips. Kinematic and kinetic measurements were obtained 2 days and 8 weeks after shoeing. Data from kinetic measurements in the same study population have been published elsewhere.[11] The study reported here focused on possible changes in limb kinematics during a typical interval between shoeing episodes.

Data acquisition—Two days and 8 weeks after shoeing, each horse was led at a trot over and along a combination of synchronized measuring systems (ie, a pressure-force measuring system and a 3-dimensional kinematic system). The pressure-force measuring device consisted of a pressure plate[c] and a force plate.[d] The pressure plate was dynamically calibrated by use of the force plate.[11]

Three-dimensional kinematic data were collected from the right side of each horse by use of 6 infrared cameras[e] positioned in a semicircle with a radius of 3 m. Reflective markers were glued to the skin at anatomic landmarks[12] of the right forelimbs and hind limbs (**Figure 1**). To standardize this procedure, all markers were positioned by the same investigator. This technique for marker placement in foals on 2 days has good reproducibility.[13] The proximal marker on the hoof wall was positioned on the most lateral aspect of the coronary band. The position of the distal marker on the hoof wall was determined by starting at the proximal marker and proceeding in a distal direction along the horn tubules.

Figure 1—Photograph indicating the position of reflective markers on the right forelimb and hind limb of a representative horse. Proximal markers on the radius or tibia and the most distal markers on the hoof wall were used to calculate protraction and retraction angles. The FA (indicated on the hind limb; curved arrow) is the craniodorsal angle between the distal marker on the carpus or tarsus and a line extending between the marker on the metacarpus or metatarsus and the proximal hoof marker. The PHA (indicated on the forelimb; curved arrow) is the craniodorsal angle between the distal hoof marker and a line extending between the marker on the metacarpophalangeal or metatarsophalangeal (fetlock) joint and the proximal hoof marker. All angles were determined at 4 moments of interest (initial contact, midstance, heel lift, and toe off) during the stance phase.

All measurement systems were synchronized at a frequency of 240 Hz and were initiated by an infrared gate that also started the time measurements. Five measurements were collected from all limbs of each horse. A measurement was considered valid when a horse trotted in a straight line at a constant velocity (determined for each horse) and enabled measurement of the right forelimb and ipsilateral hind limb. Velocity varied among horses (from 3.3 to 3.7 m/s), and the maximum intrahorse variation was 0.08 m/s.

Variables—Four moments of interest (initial contact, midstance, heel lift, and toe off) were defined within the stance phase and used for further data analysis. For initial contact, the first contact was detected by use of the pressure plate. Landing was subsequently classified as lateral asymmetric (lateral heel or lateral toe), symmetric (flat footed, heels, or toe), or medial asymmetric (medial heel or medial toe).[11] Duration of landing was defined as the time lapse between initial contact and the point at which > 50% of the hoof made contact with the pressure plate. Midstance was defined as the measurement frame at which the vertical component of the ground reaction force measured by the force plate reached a maximum value. Heel lift was defined as the first frame at which both heels of the right forelimb and hind limb had left the pressure plate. Toe off was defined as the final frame in which the hoof made contact with the pressure plate. The interval between initial contact and toe off was defined as total stance time. The interval between heel lift and toe off was defined as breakover duration.

Protraction and retraction angles at the 4 moments of interest were determined by use of angles between the marker attached to the cubital (elbow) joint, the distal hoof marker, and the ground surface for the forelimbs. A similar procedure was used for the hind limbs, except the marker at the stifle joint was used as the most proximal marker. For the analysis of joint angles in the distal segments of the limbs, the FA was calculated as the craniodorsal angle between the distal marker on the carpus or tarsus and a line extending between the marker on the metacarpophalangeal or metarsophalangeal (fetlock) joint and the proximal hoof marker. The PHA was calculated as the craniodorsal angle between the distal hoof marker and a line extending between the marker on the fetlock and the proximal hoof marker (Figure 1).

Statistical analysis—Landing characteristics of all limbs were analyzed by use of a relative frequency analysis. Mean values of all other variables were analyzed by use of a repeated-measures test because data were collected from the same horses twice and data were obtained for the right forelimb and hind limb of each horse. Shoe (2 days or 8 weeks) and limb (forelimb or hind limb) were within-horse factors. Also, joints (FA or PHA) were tested as a within-horse factor with 2 levels. In the case of interactions between shoe and limb, paired *t* tests were used to further analyze data. All analyses were performed by use of commercially available statistical software.[f] The null hypothesis tested was that there would be no differences as a result of the defined within-horse factors. The null hypothesis was rejected at values of $P \leq 0.05$.

Results

Landing characteristics and temporal variables—Classification for the landing remained similar throughout the course of the shoeing interval. Lateral landing was the most frequently detected hoof placement in both the forelimbs and hind limbs. In

Table 1—Mean ± SEM values for timing characteristics of forelimbs and hind limbs of 18 horses during the stance phase 2 days and 8 weeks after shoeing.

	Forelimb		Hind limb	
Variable	**2 days**	**8 weeks**	**2 days**	**8 weeks**
Stance time (ms)	305.4 ± 3.5[a]	311.8 ± 4.5[a]	294.4 ± 4.9[b]	297.1 ± 5.6[b]
Breakover duration *(ms)	58.7 ± 2.1	61.1 ± 1.5	59.7 ± 2.6	60.3 ± 2.0
Relative breakover (%)	19.2 ± 0.6	19.6 ± 0.4	20.3 ± 0.8	20.3 ± 0.5

*The interval between heel lift and toe off was defined as breakover duration. [a,b]Within a row, values with differing superscript letters differ significantly ($P < 0.05$).

Table 2—Mean ± SEM protraction or retraction angles for limb placement at 4 moments of interest during the stance phase in the right forelimb and hind limb of 18 horses 2 days and 8 weeks after shoeing.

	Forelimb		Hind limb	
Variable	**2 days**	**8 weeks**	**2 days**	**8 weeks**
Protraction (°)				
Initial contact	117.6 ± 0.30[a]	117.7 ± 0.27[a]	110.2 ± 0.66[b]	109.6 ± 0.39[b]
Midstance	103.1 ± 0.32[a]	103.4 ± 0.36[a]	95.2 ± 0.70[b]	94.4 ± 0.45[b]
Retraction (°)				
Heel lift	82.7 ± 0.60[a]	82.5 ± 0.49[a]	77.5 ± 0.63[b]	77.6 ± 0.48[b]
Toe off	69.5 ± 0.40	69.0 ± 0.54	68.5 ± 0.49	63.9 ± 0.44

Initial contact = First contact between hoof and the pressure plate. Midstance = Measurement frame at which the vertical component of the ground reaction force measured by the force plate reached a maximum value. Heel lift = First frame at which both heels of the right forelimb and hind limb had left the pressure plate. Toe off = Final frame in which the hoof made contact with the pressure plate.

See Table 1 for remainder of key.

Table 3—Mean ± SEM values for FA and PHA at 4 moments of interest during the stance phase in 18 horses 2 days and 8 weeks after shoeing.

	FA		PHA	
Variable	**2 days**	**8 weeks**	**2 days**	**8 weeks**
Initial contact (°)				
Forelimb	155.5 ± 1.4[a]	157.2 ± 1.0[a]	184.0 ± 1.3[b]	181.1 ± 1.3[b]
Hind limb	162.2 ± 1.3[a]	166.1 ± 1.4[b]	178.7 ± 2.4[c]	184.0 ± 1.3[d]
Midstance (°)				
Forelimb	117.8 ± 1.4[a]	119.2 ± 1.0[a]	207.7 ± 1.4[b]	202.2 ± 1.4[c]
Hind limb	124.1 ± 1.2[a]	125.7 ± 1.4[a]	206.6 ± 2.7[b]	207.7 ± 1.4[b]
Heel lift (°)				
Forelimb	136.5 ± 1.7[a]	140.7 ± 1.2[b]	168.0 ± 2.2[c]	160.3 ± 2.0[d]
Hind limb	140.3 ± 1.8[a]	145.0 ± 2.1[a]	169.1 ± 3.1[b]	168.0 ± 2.2[b]
Toe off (°)				
Forelimb	156.6 ± 1.6	158.3 ± 1.1	162.9 ± 2.3	158.8 ± 1.5
Hind limb	165.2 ± 1.4[a]	168.4 ± 1.5[b]	170.3 ± 2.2[c]	161.8 ± 1.7[d]

FA = Craniodorsal angle between the distal marker on the carpus or tarsus and a line extending between the marker on the metacarpus or metatarsus and the proximal hoof marker. PHA = Craniodorsal angle between the distal hoof marker and a line extending between the marker on the metatarsophalangeal or metacarpophalangeal (fetlock) joint and the proximal hoof marker.

[a–d]Within a row, values with differing superscript letters differ significantly ($P < 0.05$).

See Table 2 for remainder of key.

the forelimbs, 125 of 180 (69.4%) landings were lateral asymmetric 2 days after shoeing, whereas 108 of 180 (60.0%) landings were lateral asymmetric 8 weeks after shoeing. In the hind limbs, lateral asymmetric landings at 2 days and 8 weeks after shoeing represented 178 of 180 (98.9%) and 176 of 180 (97.8%) landings, respectively.

Duration of landing decreased significantly in the hind limbs of the horses during the shoeing interval (**Table 1**). Mean ± SEM duration of landing 2 days after shoeing was 18.9 ± 2.0 milliseconds, whereas the mean duration 8 weeks after shoeing was 12.7 ± 1.5 milliseconds. We did not detect a similar change in landing duration for the forelimbs. Mean landing duration for the forelimbs during the shoeing interval was 7.9 ± 0.8 milliseconds. There was no significant absolute or relative change in breakover duration during the shoeing interval.

Angular limb kinematics—We did not detect significant differences in the protraction and retraction angles of the forelimbs and hind limbs at the 4 defined moments of interest as a result of the shoeing interval (**Table 2**). An interaction was detected; therefore, joint angles were tested separately for the forelimbs and hind limbs. In the forelimbs, the FA increased, which led to less overextension of the metacarpophalangeal joint at all 4 moments of interest. However, only heel lift had a significant increase. The PHA decreased at all moments throughout the stance phase, but only heel lift and toe off had significant decreases (**Table 3**).

Similar to results for the forelimbs, the FA of the hind limbs had an increase in angle, but it was only a significant increase for the initial contact and toe off (Table 3). Also similar to results for the forelimbs, the PHA of the hind limbs decreased at heel lift and toe off; however, only toe off had a significant decrease. In contrast to results for the forelimbs, the PHA remained approximately equal at midstance but increased significantly at initial contact.

Discussion

We did not detect significant differences in temporal variables as a result of the 8-week shoeing interval. Therefore, it appears that horses are able to maintain their neuromuscular pattern of movement when changes in hoof morphology develop gradually. In other studies,[9,10] investigators could not detect effects on stance duration or stride length in horses in which a gradual change of 10° in hoof angle was induced; however, they did find an increase in breakover duration. Apparently, changes much larger than those that develop during a shoeing interval result in only minor changes in the timing of movement.

Landing characteristics of the feet were also not affected by the 8-week shoeing interval. Shoeing may influence gait quality of horses, but this is through changes in the swing phase of the stride.[14,15] In a similar manner, the hoof angle can influence the flight arc of the swing phase.[9] Therefore, the 2 moments of interest in our study that were related to the swing phase (initial contact and toe off) may have been influenced by changes in shoeing or hoof angle, but it is conceivable that the changes during our study were much too subtle to induce such an effect.

No significant changes in protraction or retraction angles could be detected, but there were significant changes in the joint angles of the distal segments of the limbs during the stance phase. In the forelimbs, PHA decreased and FA increased at all 4 moments of interest, which indicated less overextension of the fetlock and a more upright position of the proximal and middle phalanges. On the basis of analysis of data from this study, we cannot state whether the change in PHA was primarily attributable to a change in position of the distal interphalangeal joint or the proximal interphalangeal joint. However, it is more likely to be attributable to changes in the distal interphalangeal joint on the basis of results for standing horses in another study.[5]

The decrease in hoof angle is approximately 3.3° in the feet of the forelimbs and hind limbs.[4] Thus, a decrease in PHA was expected. However, the changes in hoof angle in that study[4] were measured in accordance with a standardized protocol in standing horses. In the study reported here, horses were measured during trotting, and the extent to which the hoof mechanism would affect changes in the hoof angle during movement is unknown. Therefore, the statically measured changes in hoof angle cannot be used to explain the results for this kinematic data set.

Similar results for FA have also been reported in other studies that investigated acute effects of changes in hoof angle in standing horses. In an in vitro study[6] of a single limb, investigators determined that when elevation of the heel is decreased, the dorsal angle of the fetlock is increased. A detailed radiographic in vivo study[8] on the effects of changes in hoof angle on joint angles, including those of the proximal and distal interphalangeal joints, in standing horses revealed a clear linear relationship of hoof angle with all 3 joint angles of the distal segments of the limbs. In contrast, the study reported here revealed a slowly decreasing hoof angle, rather than an acute change. In trotting horses, this gradual change shifts the CoP in the palmar direction, but the change is less than calculated from hoof morphology, which indicates some compensatory mechanism.[4] In the study reported here, we determined that this compensatory mechanism consists of changes in both the metacarpophalangeal or metatarsophalangeal joint angles and the angle between the dorsal hoof wall and fetlock. Less extension in the fetlock will shift the location of the CoP in the palmar direction but to a lesser amount; thus, it acts as a compensation for the palmar shift induced by the change in hoof angle. The observed change in FA is consistent at all examined moments and in the forelimbs and hind limbs. Changes were significant in approximately half of the moments of interest, but given the general pattern, it is possible that significant differences may have been detected at other moments as well had a larger number of horses been used or SE values been smaller.

The PHA decreased throughout the stance phase for the forelimbs. Therefore, the same logic applies for the PHA as for the FA (ie, a more upright position of the proximal and middle phalanges will counteract the shift of the CoP in the palmar direction, which is induced by the change in hoof shape). In the hind limbs, the situation differs. At initial contact, there is a significant increase in PHA, rather than the decrease in PHA detected in the forelimbs. In a study[10] in which the changes in hoof angle were approximately 3 times the changes in the study reported here, investigators determined that overreach distance (ie, the distance between placement of a hoof of the forelimb and the succeeding placement of the hoof of the ipsilateral hind limb) of the limbs was dependent on hoof angle, with a decrease in hoof angle resulting in a significant increase in overreach distance. Although overreach distance in that study was measured on the ground and not from angular limb kinematics, this could only have resulted from an increase in the protraction angle. Such a change in limb protraction could explain the increase of the PHA and the decrease of almost one third for landing duration of the hind limbs but not the forelimbs in the study reported here. We did not detect a significant increase in protraction angle in our study, but this may have been attributable to the fact that the differences in hoof angle were much smaller than in the aforementioned study[10] and that we used the marker affixed to the proximal portion of the tibia to calculate protraction. This site is heavily affected by artifacts attributable to skin displacement.[16] Compensation during movement can also be achieved by changing the angle in more proximally located joints, but the same skin displacement artifact makes it impossible to reliably measure the expected small differences, and angular kinematics of the proximal segments of the limbs were therefore not analyzed in the study reported here.

On the basis of the study reported here, it is concluded that horses maintain their neuromuscular pattern of movement and partially compensate for changes in hoof morphology attributable to hoof growth during a regular shoeing interval through changes in the angles of the distal segments of the limbs, rather than through changes in timing or placement of the limbs. The mechanism is similar in forelimbs and hind limbs, except for the landing phase in which the hind limb appears to have an additional compensatory mechanism, possibly in the form of an increase in protraction angle. Knowledge of this type of natural compensation mechanism for hoof imbalance may enhance our understanding of the ability of horses to respond to pathologic conditions and thus aid in the development of treatments.

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a. Horses for the study were provided by Dr. Leendert-Jan Hofland and Jan Van Kooten.
b. Mustad shoe, 22/8 lb, Mustad Hoofcare SA, Bulle, Switzerland.
c. RsFootscan scientific version, RSscan International, Olen, Belgiun.
c. Kistler force plate type Z4852/c, 600 × 900 mm, Kistler Corp, Winterthur, Switzerland.
e. Proreflex, Qualisys AB, Sävedalen, Sweden.
f. SPSS, version 10.0, SPSS Inc, Chicago, Ill.

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