

Effect of trotting speed and circle radius on movement symmetry in horses during lunging on a soft surface

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Objective—To determine whether body lean angle could be predicted from circle radius and speed in horses during lunging and whether an increase in that angle would decrease the degree of movement symmetry (MS).

Animals—11 medium- to high-level dressage horses in competition training.

Procedures—Body lean angle, head MS, and trunk MS were quantified during trotting while horses were instrumented with a 5-sensor global positioning system–enhanced inertial sensor system and lunged on a soft surface. Speed and circle radius were varied and used to calculate predicted body lean angle. Agreement between observed and predicted values was assessed, and the association between lean angle and MS was determined via least squares linear regression.

Results—162 trials totaling 3,368 strides (mean, 21 strides/trial) representing trotting speeds of 1.5 to 4.7 m/s and circle radii of 1.8 to 11.2 m were conducted in both lunging directions. Differences between observed and predicted lean angles were small (mean \pm SD difference, $-1.2 \pm 2.4^\circ$) but significantly greater for circling to the right versus left. Movement symmetry values had a larger spread for the head than for the pelvis, and values of all but 1 MS variable changed with body lean angle.

Conclusions and Clinical Relevance—Body lean angle agreed well with predictions from gravitational and centripetal forces, but differences observed between lunging directions emphasize the need to investigate other factors that might influence this variable. For a fair comparison of MS between directions, body lean angle needs to be controlled for or corrected with the regression equations. Whether the regression equations need to be adapted for lame horses requires additional investigation. (*Am J Vet Res* 2012;73:1890–1899)

Movement of terrestrial animals in a natural environment often deviates from the steady-state, straight-line, hard-surface condition that can most easily be assessed in a gait evaluation laboratory, with or without a treadmill. For example, to navigate obstacles or avoid being caught by a predator, animals often change movement direction, which requires increasing mediolateral forces for turning.^a During locomotion on a circular path, the centripetal force is directed toward the center of the circle, and horses lean inward.^{1,2} If an animal's posture were to remain the same during lung-

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ABBREVIATIONS

CI	Confidence interval
$\Delta_{\text{obs,pred}}$	Difference between the absolute values of the observed and predicted body lean angles
GPS	Global positioning system
HipHikeDiff	Difference in vertical upward movement between left and right tuber coxae
IMU	Inertial measurement unit
LTC	Left tuber coxae
MaxDiff	Difference between first and second maximum values in vertical displacement
MinDiff	Difference between first and second minimum values in vertical displacement
RTC	Right tuber coxae

ing as during straight-line movement, an increase in ground reaction force moment arms would be observed with respect to the limb joints. Thus, it is not surprising that heavy animals, like horses, adapt their posture to

achieve a better alignment between the ground reaction force vector and the limbs.

When an animal is leaning into a circle, the need to produce centripetal force to change movement direction must increase as a function of decreasing circle radius and increasing speed. Even when an animal is leaning into the circle, the total resultant force is then no longer aligned with gravity.

During an equine clinical lameness examination, the increase in overall force magnitude and, possibly even more, the increase in vertical force in the outside versus inside limb^a are used to exacerbate mild movement asymmetries that might be difficult to detect during straight-line locomotion or to investigate bilateral lameness.³ A threshold of approximately 25% movement asymmetry has been suggested for detecting movement asymmetry.⁴ Inside and outside limbs also generate substantial centripetal (mediolateral) force,^a possibly contributing to the potential of lunging to help discriminate among certain orthopedic conditions.³

In previous research, we showed that head and trunk movement undergoes systematic kinematic changes when horses trot in a circle⁵ and that commonly used symmetry measurements change in different ways when straight-line and circular movement data are compared.⁶ However, many horses have non-systematic differences between directions.⁵ Vertical displacement of anatomic landmarks (eg, head, highest point of the shoulders [ie, withers], and sacrum) in the sagittal plane is asymmetric during trotting in a circle. Most prominently, the head and withers drop to a lower minimum position during the stance phase of the outside versus inside forelimb, and the sacrum drops to a lower minimum position during stance phase of the outside versus inside hind limb.⁵ This observation is in agreement with the observed higher peak forces during stance phase of outside forelimb^a because an increase in downward movement of the head (and neck) will increase the downward movement of the center of mass during stance phase of the sound limb.⁷ The degree to which (if at all) these adaptations change when speed and circle radius are varied is unknown.

The purpose of the study reported here was to quantify basic kinematic changes in 5 upper body landmarks in nonlame horses when trotted on a circle during lunging on a soft surface with variations in speed and circle radius. Of particular interest were the effects of speed and circle radius on body lean angle as a value quantifying the severity of the circular motion and on movement symmetry. The expectation was that the amount of symmetric movement would decrease with increasing severity of the lunging condition. Specifically, we hypothesized that horses would lean toward the inside of the circle and that the body lean angle could be determined from the angle between vertical (gravitational) and mediolateral (centripetal) forces. We also hypothesized that an increase in body lean angle would lead to a decrease in movement symmetry.

Materials and Methods

Animals—Eighteen horses that were actively training for or competing in dressage competitions (medium to advanced or Prix St. George level) were enrolled in

the study. Horse owners were informed about the study aims and signed a consent form. All procedures were approved by the Michigan State University Institutional Animal Care and Use Committee.

Procedures—Each horse was instrumented with miniature IMUs, including 4 lightweight devices^b for determining 3-D orientation and calculating 3-D displacement ($18 \times g$; $1,200^\circ/s$) and 1 modified GPS-aided IMU^c for determining speed and heading ($18 \times g$; $1,200^\circ/s$). The IMUs were attached to the highest point of the horse's head (poll) via a head piece to which a custom-made fabric hook-and-loop fastener was applied and to the skin over the withers and LTC and RTC via custom-made pouches that were applied to the skin with a cross-elastic cohesive foam fixative.^d The GPS-enhanced IMU,^c which also contains a pressure sensor, was attached over the sacrum with a custom-made pouch with cross-elastic cohesive foam fixative. The external GPS antenna was attached with cross-elastic cohesive foam fixative approximately 0.15 m caudal to the GPS-enhanced IMU. An elasticated surcingule was used to affix the wireless transmitter unit^e to the horse's body. Sensors were attached in 2 strings (1 to the head and withers and 2 to the LTC, sacrum, and RTC) to the wireless transmitter unit,^c which transmitted IMU data at a sampling rate of 100 Hz/individual sensor channel.

Horses were first led by hand in a straight line along a 40- to 50-m path with a firm surface (compacted sand or gravel or compacted hardcore) to subjectively assess whether any lameness was apparent and to objectively collect movement symmetry data. Two walk trials were recorded, followed by 4 trot trials at the horse's preferred speed and then 2 trials each of slow and fast trots. When a horse deviated from the required movement condition (eg, broke into different gait), data collection was repeated. Each horse was lunged in both directions with a consistent lunging technique (lunge line threaded through the inside bit ring over the bridle and attached to the outside bit ring).

The handlers (selected by their familiarity with the horses) were asked to vary speed and circle radius, choosing 1 of 3 speeds (working trot, medium trot, and slow trot) and adapting the circle radius in 3 steps between the smallest circle that could be achieved at a given speed and a circle with a radius of approximately 10 m. Orders of speed and circle radius varied among horses, and for each condition, IMU and GPS data were collected for a period of at least 20 seconds. Notes and video recordings were made during data collection to document deviations from the expected movement condition (eg, changes in gait, speed, or gait quality).

Data processing—Vertical displacements of the head, withers, sacrum, LTC, and RTC were measured. The IMU data were processed in accordance with published methods⁸ with custom-written computer software.^f In brief, sensor orientation and calibrated acceleration (3 axes) were used to rotate sensor-based 3-D acceleration data into a right-handed, horse-based Cartesian coordinate system (x-axis, positive forward; y-axis, positive left; z-axis, positive upward). High-pass filtering (cutoff, 1 Hz) and numeric integration were repeated twice to integrate to horse-based 3-D velocity

and 3-D displacement. For the IMU positioned over the sacrum, orientation was calculated by amalgamating GPS and IMU data with the manufacturer's software⁸ and data on 3-D sensor velocity were exported in addition to data on orientation and acceleration; this amalgamation combines the GPS data (4 Hz) with the IMU data (100 Hz) to create a velocity output sampled at 100 Hz synchronously with the calibrated sensor data.

For each movement condition (trial), a period of steady-state movement was selected by inspection of raw 3-D acceleration data in consultation with the videos and notes for the trials. Within each trial, integrated IMU data were separated into strides on the basis of minima in vertical velocity of the sacral sensor guided by the direction of sacral roll to distinguish between left and right stance phases. With this technique, stride start time coincides approximately with left hind foot contact. Exact timing varies among conditions and horses, but of critical importance for the calculation of asymmetry values for lameness evaluation, the beginning of the stride is always identified between the vertical displacement maximum preceding left hind foot contact and the minimum reached during midstance of the left hind limb.⁹

Body lean angle—The observed body lean angle was defined as the amount of rotation of the entire trunk determined from the GPS-enhanced IMU positioned over the sacrum. Sensor orientation is reportedly accurate to 1° or 2.6°⁹⁸ with respect to the true value. To account for body lean angle deviating from zero during straight-line trotting (caused by imperfect sensor attachment or asymmetries of the musculoskeletal structures in the sacral region), the mean value of sensor roll observed during straight-line trotting was subtracted from the values observed during lunging. When the right-handed Cartesian coordinate system of the IMU and the definition of Euler angles^b are applied, body lean angle is positive when a horse leans to the left and negative when it leans to the right.

The predicted body lean angle (α) was calculated with the following equation:

$$\alpha = \text{atan} (F_{\text{centripetal}}/F_{\text{gravitational}}) = \text{atan} ([m \times v^2] / r / [m \times g]) = \text{atan} (v^2 / r \times g)$$

in which $F_{\text{centripetal}}$ represents the centripetal force, $F_{\text{gravitational}}$ represents the gravitational force, m represents body mass, v represents velocity, r represents the circle radius, and g represents gravitational acceleration (9.81 m/s²).

The $\Delta_{\text{obs,pred}}$ was calculated by subtracting the predicted value from the observed value. Positive differences hence represent the horse leaning more into the circle than predicted, and negative values indicate that the inward lean was less than predicted.

Speed and circle radius—Speed and circle radius were calculated from the Kalman-filtered output of the modified GPS-enhanced IMU.^c Speed was calculated as the vector sum of the 2 horizontal velocity components. A mean speed value was calculated for each trial.

Circle radius was calculated from latitudinal and longitudinal GPS data converted into a local Cartesian coordinate system with positive axes pointing east,

north, and up and with the centroid of the latitude and longitude data chosen as the origin of the coordinate system.¹⁰ The resulting position data (in meters) were then used to perform Gauss-Newton least squares regression with circle center and circle radius as output parameters in the customized analysis program.^{11,f}

Kinematic symmetry measures—The kinematic symmetry measurements were based on vertical displacement of the upper body landmarks. Symmetry index of upward movement amplitude (SI_{up}) was calculated as follows¹²:

$$SI_{\text{up}} = (A_{1,\text{up}} - A_{2,\text{up}}) / \max(A_{1,\text{up}}, A_{2,\text{up}}) + 1$$

in which $A_{1,\text{up}}$ is the amount of upward movement during the first half of the stride (from the minimum reached during the right forelimb or left hind limb in midstance to the maximum height reached during the following aerial phase) and $A_{2,\text{up}}$ is the amount of upward movement during the second half of the stride (from the minimum observed from the left forelimb or right hind limb in midstance to the maximum height reached during the following aerial phase). A horse moving perfectly symmetrically will have a symmetry index value of 1; horses with a larger upward movement amplitude during the first half of the stride will have values > 1, and horses with a smaller upward movement amplitude during the first half of the stride will have values < 1.

MinDiff and MaxDiff—The MinDiff was calculated as follows:

$$\text{MinDiff} = \min_1 - \min_2$$

in which \min_1 is the first minimum reached during right forelimb or left hind limb stance phase and \min_2 is the second minimum measured during right forelimb or left hind limb stance phase.¹³ The MaxDiff was calculated as follows¹³:

$$\text{MaxDiff} = \max_1 - \max_2$$

in which \max_1 is the first maximum value after the right forelimb or left hind limb stance phase and \max_2 is the second maximum value after the left forelimb or right hind limb stance phase of the head and sacrum.¹³ Horses with lower downward movement during the first (right forelimb or left hind limb) versus second (left forelimb or right hind limb) stance phase will have positive MinDiff values (expressed in millimeters), and horses with a lower downward movement during the second versus first stance phase will have negative MinDiff values. Horses with higher upward movement during and after the first versus second stance phase will have positive MaxDiff values, and horses with higher upward movement during and after the second versus first stance phase will have negative MaxDiff values.

The HipHikeDiff was calculated as follows⁵:

$$\text{HipHikeDiff} = (\max_{2,\text{LTC}} - \min_{2,\text{LTC}}) - (\max_{1,\text{RTC}} - \min_{1,\text{RTC}})$$

This variable reflects observations from the subjective lameness examination of a horse with hind limb lameness and quantifies the difference between the

upward movement of the LTC that occurs just before ground contact of the left hind hoof and the upward movement of the RTC that occurs just before ground contact of the right hind hoof.¹⁴ Positive HipHikeDiff values indicate a higher movement amplitude of the LTC versus RTC, and negative values indicate a higher movement amplitude of the RTC versus LTC.

Statistical analysis—Statistical analysis was performed with the aid of custom-made computer software.⁶ To investigate the relationship between trotting speed, circle radius, and body lean angle, values for $\Delta_{\text{obs,pred}}$ were assessed for normal data distribution via the Lilliefors test, then a Wilcoxon signed rank test was used to investigate whether the difference was zero (agreement between measurement and theory). Data were evaluated on horses lunging in left and right circles as well as in individual directions. Mean and SD values of $\Delta_{\text{obs,pred}}$ were calculated to quantify the amount of agreement.¹⁵

The relationship between body lean angle and changes in kinematic symmetry values was illustrated with scatterplots with data from all trials (x-axis, body

lean angle; y-axis, median symmetry value). Individual plots were produced for each symmetry variable. Linear least squares regression was performed, and goodness of fit was evaluated via the square root of the mean of the squared residuals, which reflected the mean distance between the regression line and the data. In addition, 95% CIs were calculated for the slope of each regression line to assess whether the slope differed significantly (CI does not include 1) from zero.

Results

Animals—Eleven of the 18 dressage horses yielded consistent IMU and GPS data from straight-line trials while walked by hand and from left and right circles during lunging. One hundred sixty-two trials (83 left circle and 79 right circle) totaling 3,368 strides (mean, 21 strides/trial) were conducted, covering a range of trotting speeds (mean \pm SD for 11 horses, 3.0 ± 0.6 m/s) and circle radii (4.6 ± 1.4 m).

General measurements—The mean body lean angle of 11 horses for right and left sides combined was

Table 1—Values for trotting speed, circle radius, and body lean angle in 11 dressage horses.

Value type	Trotting speed (m/s)	Circle radius (m)	Observed angle (°)	Predicted angle (°)	$\Delta_{\text{obs,pred}}$ (°)
Mean \pm SD	3.0 ± 0.6	4.6 ± 1.4	0.0 ± 11	-1.3 ± 12.2	-1.2 ± 2.4
Range	1.5 to 4.7	1.8 to 11.2	-20.1 to 16.3	-22.7 to 19.7	-8.1 to 3.8
Mean absolute value \pm SD	—	—	10.5 ± 3.3	11.7 ± 3.6	2.1 ± 1.7

— = Not applicable.
 Values for $\Delta_{\text{obs,pred}}$ differed significantly ($P < 0.001$) with direction of lunging (left vs right circle).

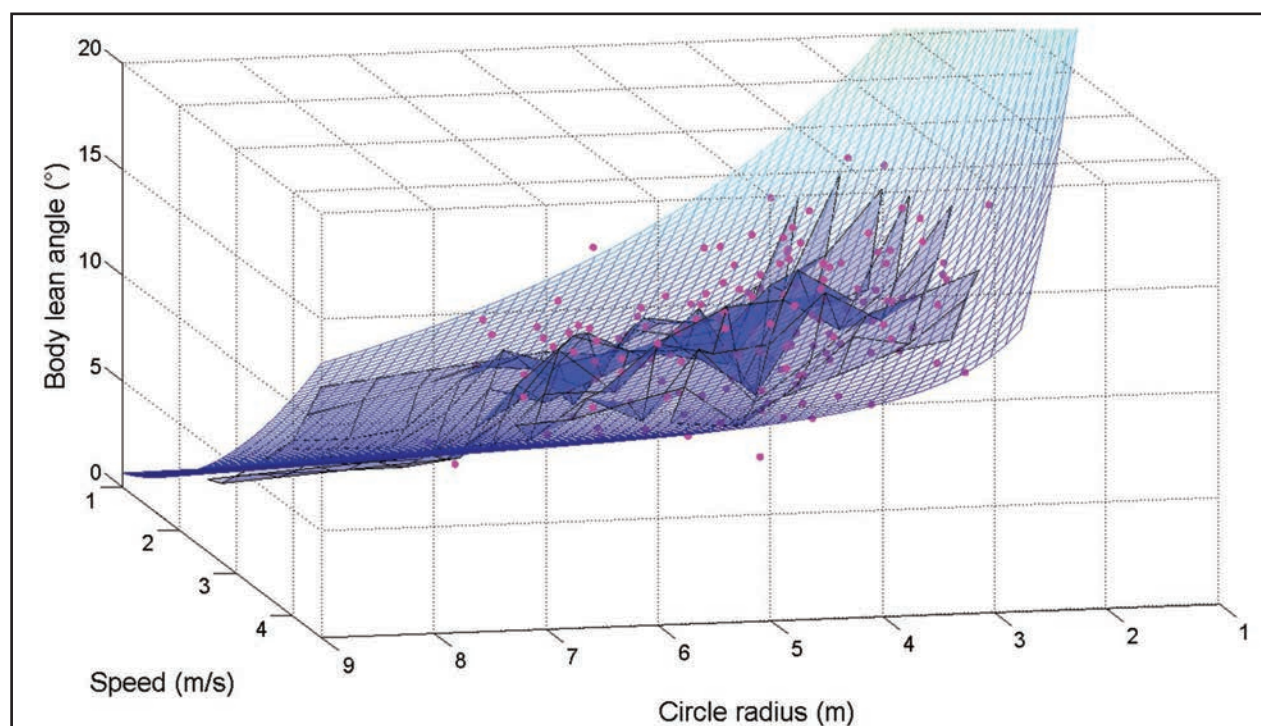


Figure 1—Body lean angle as a function of speed and circle radius in dressage horses ($n = 11$) trotting in a circle. Plotted are all 162 individual trials (magenta circles) as well as a surface showing the best fit to the data (coarse blue surface mesh) and the predicted lean angle from gravitational and centripetal force (fine blue-cyan grid). Individual trial data points as well as the surface mesh fitted to the data points show a good match with the predicted shape: increasing body lean angle with decreasing circle radius and with increasing speed.

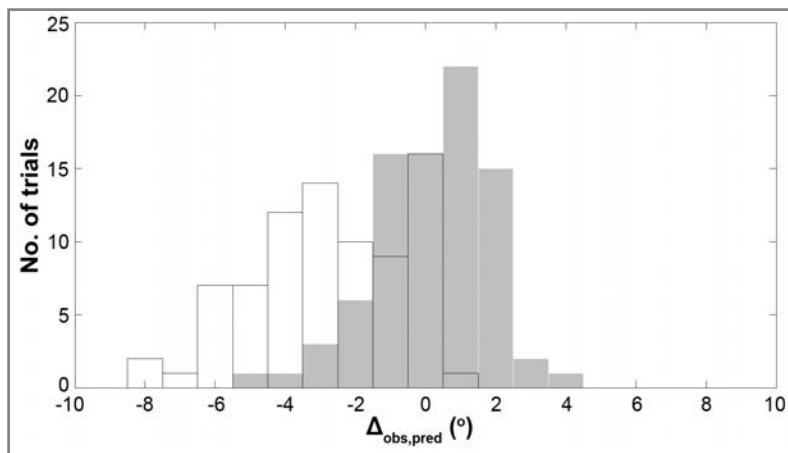


Figure 2—Histogram showing $\Delta_{\text{obs,pred}}$ for 11 dressage horses lunged in a circle to the left (gray bars) and right (white bars).

$0.0 \pm 11.0^\circ$ (range, -20.1° to 16.3°), and the $\Delta_{\text{obs,pred}}$ was $-1.2 \pm 2.4^\circ$ (range, -8.1° to 3.8°). Predicted absolute body lean angles ranged between 3.7° and 22.7° (mean, 11.7°).

Directional means of the measured symmetry variables, which take into account any direction in observed movement symmetry, suggested a high degree of symmetry for straight-line trials for the poll of 11 horses (symmetry index, 0.88; MinDiff, 1 mm; MaxDiff, -5 mm) and sacrum (symmetry index, 0.95; MinDiff, 2 mm; MaxDiff, -1 mm; HipHikeDiff, 4 mm). The mean of absolute values is a nondirectional statistic that avoids having the left- and right-sided asymmetries cancel each other out. Means of absolute values were as follows for the poll: symmetry index, 0.83; MinDiff, 5 mm; MaxDiff, 5 mm. For the sacrum, they were as follows: symmetry index, 0.95; MinDiff, 3 mm; MaxDiff, 3 mm; HipHikeDiff, 5 mm.

Relationships among body lean angle, angle between gravitational and centripetal acceleration, speed, and circle radius—Values for body lean angle, speed, and circle radius were summarized (Table 1). The surface mesh graphically fitted to the triplets of speed, circle radius, and observed absolute body lean angle closely followed the predicted relationship with gravitational and centripetal force (Figure 1). When the data were grouped by direction of the lunge, for the left circle, the $\Delta_{\text{obs,pred}}$ was always within 3° higher or lower than the prediction (Figure 2). For the right circle, 6 of 11 horses had differences outside 3° . Results of the Lilliefors test confirmed that data for $\Delta_{\text{obs,pred}}$ were normally distributed for left circle observations ($P = 0.237$) but not for right circle values ($P = 0.007$). A Wilcoxon rank sum test revealed that the absolute data for left and right circles did not have identical median values ($P < 0.001$), and 8 of 11 horses had bigger differences between observed and predicted values when turning to the right.

Relationship between body lean angle and movement asymmetry—Changes in movement symmetry as a function of body lean angle were graphically displayed for head movement (Figure 3) and pelvic movement (Figure 4). Scatterplots for head movement sym-

metry showed a greater spread of the data and wider 95% CIs for the fitted regression lines, compared with the corresponding plots for pelvic movement (Table 2). For both pairs of limbs, the movement symmetry variable that took into account the minima (MinDiff) had steeper slopes than measurements relating to the maxima (MaxDiff). This effect was more pronounced for the sacrum. All but one of the slope values were significantly different from zero, as indicated by the 95% CIs of the slope values excluding zero. The only symmetry variable that remained unaffected by body lean angle was symmetry index for head movement. Intercept values (predicted symmetry values observed at a body lean angle of zero) were close to perfect movement symmetry, with small deviations of ≤ 6 mm (MaxDiff at the poll) or $< 7\%$ (SI at the poll, 0.93).

Discussion

The present study yielded objective evidence for kinematic changes related to 5 upper body landmarks in trotting horses as they were lunged on a soft surface. Small, lightweight IMUs with 6 degrees of freedom^{8,16} allowed us to collect data during movements that are difficult, although not impossible, to assess with traditional kinetic or kinematic techniques when in a straight line.^{1,2} The sensors provide validated⁸ 3-D orientation and 3-D translation and, theoretically, kinematic data of the assessed landmarks in any 3-D coordinate system. A right-handed Cartesian coordinate system aligned with the direction of gravity (vertical) and with the horses' forward (craniocaudal) motion was used.

Uniaxial accelerometers need to be carefully aligned with the desired coordinate system. Because horses lean to the inside of the circle by a considerable amount (in the present study, up to 20°), a uniaxial system will then report movement along a horse's dorsoventral axis. When horses lean by different amounts on left and right circles, uniaxial measurements of movement symmetry are based on different reference systems, possibly adding to the reported difference between directions.^h To date, it is not clear which approach (vertical or dorsoventral) is clinically more relevant during lunging.

Wireless data transmission to a portable laptop computer within 50 m of the horse allowed seamless changes of trotting speed and circle radius without interrupting the horse's exercise pattern and allowed gathering of data on > 20 strides/movement condition, close to a previously suggested minimum of 27 strides.¹⁷ Data collection was limited to 5 upper body landmarks and did not provide detailed quantification of spatio-temporal limb movement parameters or limb angles, which have been reported.^{1,2} More detailed studies with simultaneous measurement of limb forces would complement the understanding of circular movement mechanics beyond mere observation and quantification of the kinematic effects.

Kinematic symmetry values were used to quantify lameness during straight-line locomotion in accordance

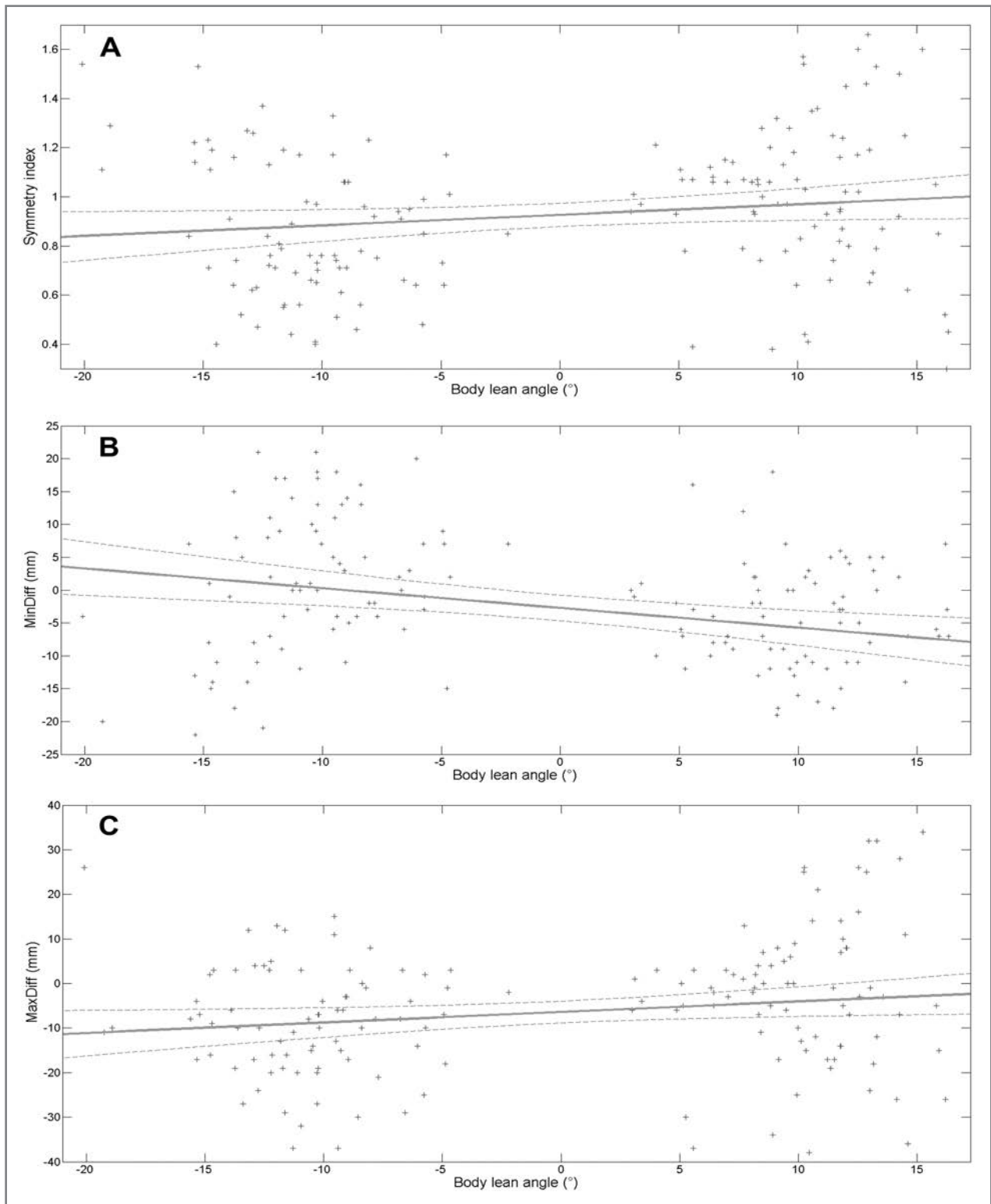


Figure 3—Change in movement symmetry of the poll as a function of body lean angle in the horses in Figure 1. Although symmetry index values (A) remain unaffected, MinDiff values decrease (B) and MaxDiff values increase (C) with increasing body lean angle. The 95% CIs for regression line slopes exclude zero for MinDiff and MaxDiff but include zero for symmetry index (indicating a lack of significance).

with previous studies^{13,17–19} on objective quantification of lameness. We also measured HipHikeDiff,⁵ which we believed was particularly important in relation to subjective assessment of hind limb lameness quantifying the difference in upward movement amplitude of the

LTC and RTC.¹⁴ Again, this raises the question as to the proper reference frame (vertical or dorsoventral) for such quantification. Objectively determined movement symmetry differs between movement in a straight line and in a circle,⁶ and head and trunk movement adapta-

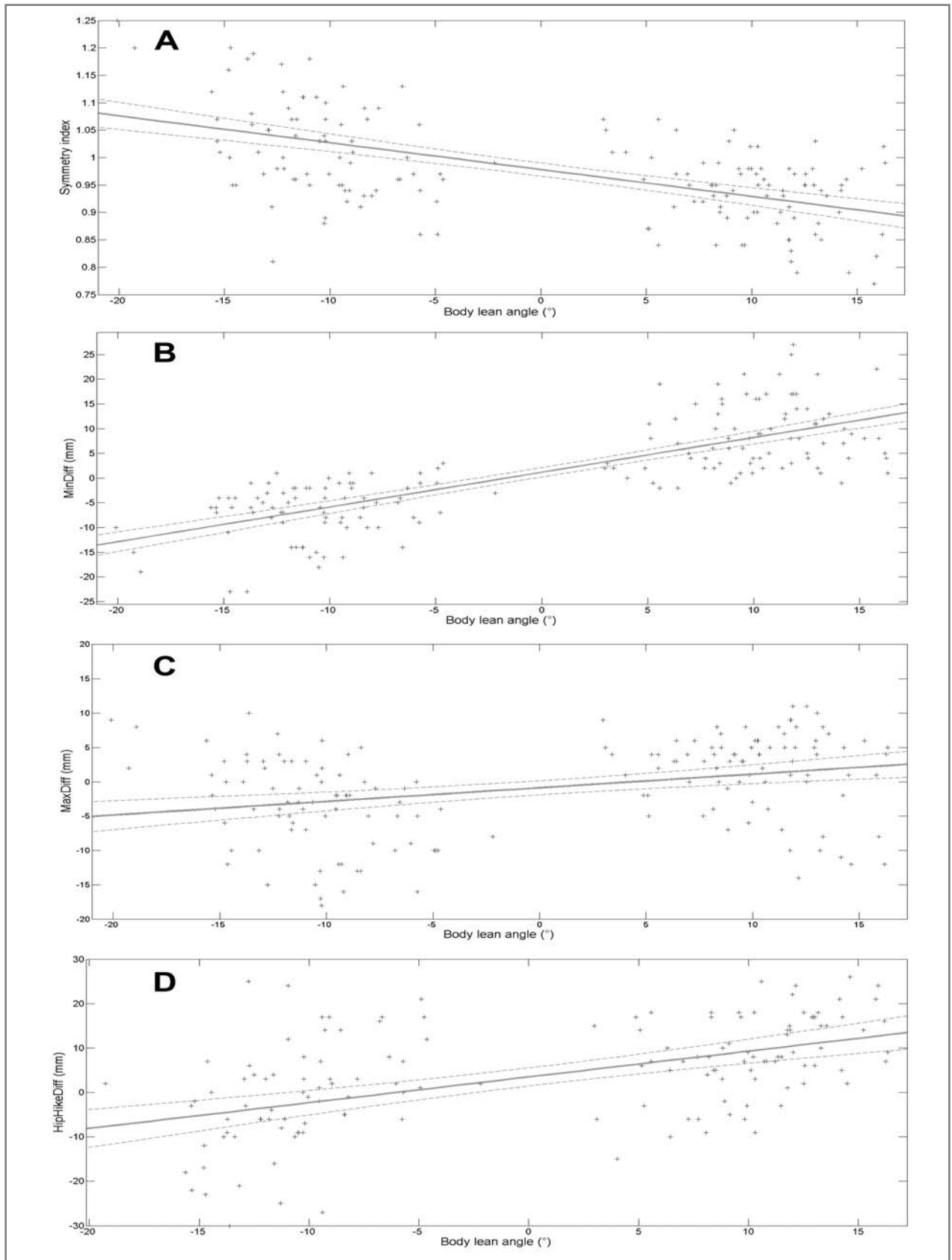


Figure 4—Change in movement symmetry of the sacrum in the horses in Figure 1 as a function of symmetry index (A). MinDiff (B), MaxDiff (C), and HipHikeDiff (D) increase with increasing body lean angle, while symmetry index decreases in value. Confidence intervals of the slope of the regression lines exclude zero.

Table 2—Slope and intercept (95% CI) of linear regression lines fitted to symmetry values as a function of body lean angle in 11 dressage horses.

Variable	Slope	Intercept	Square root of the sum of the residuals
Sacrum			
Symmetry index	-0.005 (-0.006 to -0.004)*	0.98 (0.96 to 0.99)	0.08
MinDiff (mm)	0.70 (0.62 to 0.79)	1.2 (0.21 to 2.1)	6.1
MaxDiff (mm)	0.20 (0.10 to 0.29)	-0.88 (-1.9 to 0.14)	6.5
HipHikeDiff (mm)	0.58 (0.40 to 0.76)	3.5 (1.5 to 5.5)	12.5
Poll			
Symmetry index	0.004 (-0.001 to 0.009)*	0.93 (0.88 to 0.97)	0.31
MinDiff (mm)	-0.30 (-0.48 to -0.12)	-2.7 (-4.7 to -0.76)	12.6
MaxDiff (mm)	0.24 (0.012 to 0.46)	-6.4 (-8.8 to -3.9)	15.7

*All CIs of slope values, with the exception of that for poll symmetry index, did not include zero, indicating a significant ($P < 0.05$) lean angle dependency of symmetry measurements.

tions have been quantified in horses during lunging^{5,h}: the head and pelvis drop to a lower minimum position during the stance phase of the outside limb of each girdle, and movement of the inside tuber coxae increases, mimicking inside hind limb lameness.⁵ This increased movement of the inside tuber coxae might be necessary to achieve ground clearance during the swing phase of the inside limb while the horse leans inward by folding the limb more, lifting it higher, or a combination of both.

Threshold values for objectively assessed movement symmetry values are important in clinical lameness examinations, in particular for the expected difference between directions, to which the movement symmetry values of an individual lame horse can be compared. In a research situation, it may be possible to vary speed and circle radius until matching conditions are achieved; however, this variation cannot be expected in the clinical situation, where the orthopedic deficit might restrict speed or radius in 1 or both directions. In this situation, it is necessary to correct for these differences to achieve a fair comparison between directions.

We hypothesized that body lean angle changes with speed and circle radius according to the direction of the resultant force calculated from gravitational and centripetal components. The sensor system could not directly quantify spatiotemporal limb parameters; hence, sensor roll of the sacrum-mounted GPS-enhanced sensor was used as an indicator of whole body lean angle. Limb angles might differ somewhat, particularly between inside and outside limbs.² We predicted a whole body lean angle of 15.6° for a horse trotting at 3.7 m/s on a circle with radius of 5 m, for which other investigators² measured limb angles of 14° to 20°. However, an exact comparison of the present findings to published data is not possible because individual limb angles cannot be provided.

The mean $\Delta_{\text{obs,pred}}$ across horses and movement conditions was small in the study horses. Consequently, body lean angle was chosen to represent the severity of each lunging exercise and to produce scatterplots with 1 rather than 2 independent variables. Interestingly, there was better agreement with the prediction when horses were lunged to the left. We did not randomize the order in which horses were exercised in the 2 directions and, because it is commonly recommended to handle a horse from the left side,²⁰ all horses were first lunged to the

left. Possibly as a result of this lack of randomization, all 11 horses had higher mean trotting speeds at similar (sometimes even at smaller) mean circle radii, resulting in a typical increase in severity (predicted value of body lean angle from mean values of speed and circle radius) of the lunging condition for all 11 horses when circled to the right. This lack of randomization and the higher observed trotting speed to the right versus left contributed to the difference between directions.

Differences in movement symmetry for horses turning left and right are known to exist.^{5,h} In equestrian terminology, straightness describes a horse's ability to use the left and right sides of its body symmetrically. Horses have been described as having a natural sidedness pattern, with approximately 70% of horses said to be right sided, as defined by perceived preference to loading of the right forelimb.²¹ Right-sided horses are described as falling in with the shoulders or leaning in when circling to the right and falling out on the shoulder when circling left. In the present study, the opposite pattern was found, with most horses leaning more inward to the left, although with decreased lunging severity compared to the right, where horses on average had higher trotting speeds and smaller circle radii. Additional research is needed to understand the effects of a horse's sidedness on turning kinematics and kinetics.

Other factors worth consideration are training and lateralization.²² Pure motor lateralization²³ must be distinguished from other factors such as visual²⁴ and auditory effects²⁵ that influence a horse's reactions and behaviors. Horses prefer the dominant left eye (independent of whether being trained traditionally from the left side or bilaterally) for assessment and evaluation.²² When a horse is circled to the left, the dominant eye is on the inside of the circle facing the handler and horses may be naturally more comfortable and hence more willing to lean into the circle. Randomized order of the turning direction would be ideal for evaluating traditionally and bilaterally trained horses to exclude a bias in the results due to training effects.

Lameness may affect body lean angles of horses with affected limbs on the inside versus the outside of the circle. Therefore, body lean angle could potentially be used as an indicator of orthopedic problems.

All but one of the symmetry variables evaluated changed as a function of body lean angle. The increase in asymmetry appeared more pronounced and more

consistent for the pelvic parameters, compared with the head movement parameters, which is not surprising, given that the head moves independently of the trunk to stabilize the proprioceptive receptors.²⁶ However, compensatory head movement patterns during straight-line trotting in lame horses¹⁷ directly affect the center of mass movement.⁷ Movements of the head are possibly transmitted to the trunk via the neck acting as a lever arm, influencing passive dynamic energy exchange during locomotion.²⁷ This mechanism would also affect force distribution between inside and outside limbs during lunging. Measurement of an increase in downward movement during outside forelimb stance⁵ and asymmetric force measurements confirm this supposition.^a In the study horses, the spread of asymmetry values for the head increased as a function of lean angle, possibly indicating that individual horses had developed slightly different mechanisms to deal with the asymmetric forces during lunging, but this variability could also have been attributable to the different handlers.

The steepest slope and the narrowest CI were evident for the pelvis MinDiff. The pelvis drops to a lower minimum position during the outside hind limb stance phase, and this effect is exacerbated with increasing body lean angle, which might mean that higher vertical forces are present when the outside hind limb is in stance. The reported linear relationship between limb force and metacarpophalangeal (fetlock) joint angle,²⁸ and hence the increasing drop of the trunk with increasing force, might make this premise appear logical. However, the relationship is more complicated during turning when the trunk leans inward and a drop in pelvic position reflects a combination of limb (fetlock joint) compression and whole-body tilt, which differs for inside and outside stance phases. Therefore, direct relation of the vertical position of the pelvis to limb force is not possible. The inverse relationship between duty factor and peak force^{29,30} also fails because this would require detailed knowledge of the weight distribution between inside and outside limbs. Use of fetlock joint angle as a measure of force might be more promising; however, peak force in the hind limbs does not appear to increase with speed as duty factor decreases.³¹

Clinical lameness examination is a complex procedure that involves a logical sequence of diagnostic analgesia of anatomic structures that may result in subtle changes in locomotion. Various sources of information must factor into the decision-making process, and it has been argued that clinical expertise is more than pure intuition.³² Use of video recordings to subjectively compare the movement of a horse before and after a diagnostic test is considered good practice. However, even this cannot completely eliminate the influence of clinical bias in assignment of subjective lameness grades.³³

Clinical decision making requires incorporation of objective measurements³² that might also eliminate the limitations of the human visual system.⁴ However, when horses are assessed during lunging, the amount of body lean, and hence the speed and circle radius, significantly influences all but one of the objectively measured symmetry parameters. Therefore, it is impor-

tant to standardize speed and circle radius or, if this is not possible because of the nature of the lameness, to quantify these parameters.

Body lean angle can be easily measured with an IMU that has a full 6 degrees of freedom or with 3-D motion capture technology and might be used alone to represent the severity of the lunging exercise with simple linear regression equations to correct symmetry values between directions. Should future studies show that body lean angle changes as a function of lameness grade or site, then a correction on the basis of speed and circle radius could be achieved with an additional GPS sensor.

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