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Withers vertical movement asymmetry in dressage horses walking in different head-neck positions with and without riders

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ABSTRACT

The superimposed influences of different head and neck positions (HNPs) and rider effects on symmetry in sound horses have not been studied. Our aim was to investigate the effects of HNPs and rider on the symmetry in minimum height of the withers at the walk. Seven high-level dressage horses were studied with and without rider in six HNPs: HNP1, free position; HNP2, dressage competition position; HNP3, flexed poll position; HNP4, over-flexed position; HNP5, extended raised position; and HNP6, forward downward position. Kinematic and vertical ground reaction force data were recorded during 15 s trials on an instrumented treadmill. In mixed models, difference in the minimal height of the withers in early left vs right forelimb stance was modelled as dependent variable. The more restricted HNP3 (T-values 2.62 to 1.98, 118 DF, $P = 0.001$ to <0.05) and HNP5 ($P = 0.002$ to <0.05) were generally less symmetrical while unridden and more symmetrical while ridden, compared with the free (HNP1) or forward downward (HNP6) positions. Both with and without rider, when the withers dropped lower in early stance of one forelimb, this was associated with shorter protraction at the start of stance in the ipsilateral hind limb, and shorter stance overlaps between this hind limb and the other limbs during diagonal support, 3-limb support with two forelimbs and one hind limb, and ipsilateral support. HNP effects on withers movement asymmetry differed between unridden and ridden conditions. The considerable variation between horses stresses the need for trainers to use individualized training programs to address horse asymmetry.

Introduction

The optimal head and neck position (HNP) of the horse for achieving the best result in dressage training and competition and its consequences for sustainable health of the riding horse have been a subject of debate among riders for centuries (de la Guérinière, 1733; Podhajsky 1967; Nelson, 1992). More recently, Lashley et al. (2014) have shown that horses performing piaffe and passage at Grand Prix competition had the dorsum of the nose further behind the vertical in the 2008 World Cup compared with the 1992 Olympic Games.

Scientific investigations have centered on concerns related to equine welfare, psychological effects, and mechanical stresses associated with various HNPs. Areas addressed during the last two decades include (but are not limited to) comparison of HNPs to the amount of "conflict" behavior (Eisersiö et al., 2010; Christensen et al., 2014; Kienapfel et al., 2014; Smiet et al., 2014), whether horses will voluntarily avoid being ridden in a lower position (von Borstel et al., 2009); effects on heart rate, rein tension, and salivary cortisol in horses ridden (Christensen et al., 2014) or lunged in various HNPs (Becker-Birk et al., 2012; Smiet et al., 2014); and effects on intrathoracic pressure and arterial blood gas values of

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lunging in various HNPs (Sleutjens et al., 2012). Most of the studies have been performed under experimental conditions, but a few were based on data from training/competition (Kienapfel et al., 2014; Lashley et al., 2014). Some of these studies included data on walk in their evaluation (Christensen et al., 2014; Kienapfel et al., 2014; Lashley et al., 2014). The evidence from these studies suggests that using constrained HNPs when training, at the population level, will at times be associated with nonoptimal welfare (Sloet van Oldruitenborgh-Oosterbaan et al., 2006; von Borstel et al., 2009; McGreevy et al., 2010; Wijnberg et al., 2010; Becker-Birck et al., 2012; Sleutjens et al., 2012). However, the effects of HNPs in front of the vertical have received less attention. Furthermore, comparing the same HNP with and without a rider, it was found that the presence of a rider was associated with increased frequencies of conflict behavior and higher maximum rein tension (Piccolo and Kienapfel 2019).

There are differences between gaits in terms of the contribution of neck movements to energy conservation (Gellman and Bertram 2002; Loscher et al., 2016). Elastic strain energy stored in the nuchal ligament contributes 55% of the work of moving the head and neck at the walk and 33% and 31%, respectively, at the trot and canter (Gellman and Bertram 2002). Vertical head motion in the walking horse conserves energy in single forelimb supports and returns energy during dual forelimb support phases (Loscher et al., 2016). Constraining the HNP may alter the magnitude and timing of this energy-conserving strategy. It has been shown that constraining the HNP with side reins decreased stride length in walk but not in trot (Rhodin et al., 2005), and different HNPs each had a significant influence on the movement pattern in walk (Rhodin et al., 2018).

Pain-related lameness is known to cause movement asymmetries in walk (Merkens and Schamhardt, 1988; Buchner et al., 1996), but kinematic asymmetries of the walk have also been described in riding horses that meet the generally-accepted criteria for soundness at trot (Byström et al., 2018). In the latter study, withers drop asymmetry in walk, that is, the difference between withers vertical minima during early stance of the left forelimb versus early stance of the right forelimb, was found to be associated with asymmetry in other biomechanical variables. In walk, the vertical movement of the withers shows two cycles per stride; the minima occur during forelimb stance overlaps, when one forelimb is protracted and the other is retracted. In the horses studied by Byström et al. (2018), the withers consistently dropped lower when either the left (4/7) or right (1/7) forelimb was protracted. A similar proportion of horses (7/9) were shown to exhibit asymmetry in forelimb horizontal moment around a vertical axis through the hoof's center of pressure during walking (Colborne et al., 2009). Asymmetries of this nature may be manifestations of motor laterality originating from the cerebral cortex (c.f. Grzimek 1949; Rogers 1989), although the biomechanical characteristics of laterality in horses have not been conclusively determined (Byström et al., accepted). There are no studies published on the influence of the rider on movement symmetry in walk. In trot, increasing weight load increased vertical movement asymmetry only marginally in sound horses (Matsuura et al., 2013), whereas horses became more asymmetrical with a professional rider versus a novice (Licka et al., 2004). This suggests a greater importance the rider's influence than of mere physical load.

Thus, there are several reasons to define and study the biomechanical effects of different HNPs in riding horses, including possible welfare effects on the horses when subjected to various HNPs. If a constrained HNP increases movement asymmetry, this may be a concern from performance, health, and welfare perspectives alike. While systematic differences are generally the topic of scientific studies, riders and veterinary clinicians need to deal with complex individual locomotor patterns. In the present study, the first aim was to investigate the effects of different HNPs and the presence of a rider on asymmetry of the movement of the withers in walk. A second aim was to study if and how the associations previously found between asymmetry in vertical withers movement and other biomechanical variables in walk (Byström et al., 2018) change when the HNP is manipulated, in the unridden horse by using side reins or by the rider. A third aim was to explore variation of the vertical movement of the withers in individual horses.

Materials and methods

Horses and riders

Seven advanced-level dressage horses that were deemed sound after clinical examination at trot (M.A.W.) were studied unridden and ridden at walk. Horses were of Warmblood breed and of height 1.70 (standard deviation $\pm$0.07) m and equipped with their own bridle with a normal snaffle bit, to which the horses were accustomed. While ridden, horses had their own well-fitted saddle. Adult riders, three males and four females (weight 78 [standard deviation $\pm$17] kg), rode their usual horses that they had trained and competed with at Grand Prix (n = 6) and Intermédiaire (n = 1) level. During their stay at the clinic, horses spent 30-45 mins daily in the horse walker and were always hand-walked 30 min before each measurement session. The Animal Health and Welfare Commission of the canton of Zürich (188/2005) approved the experimental protocol. Informed consent was obtained from the riders regarding participation of themselves and their horses.

Design

The experimental setup has been described previously (Weishaupt et al., 2006; Rhodin et al., 2009). Horses were evaluated in 6 different HNPs (Figure 1) in both ridden and unridden trials.

HNP1 (free position): natural, voluntarily acquired position, unrestrained (reins loose).
HNP2 (competition position): neck raised, poll high, and bridge of nose slightly in front of the vertical.
HNP3 (flexed poll position): neck raised, poll high, and bridge of nose slightly behind the vertical.
HNP4 (overflexed position): neck lowered and flexed, bridge of nose considerably behind the vertical.
HNP5 (extended raised position): neck extremely elevated and bridge of nose considerably in front of the vertical.
HNP6 (forward downward position): neck and head extended forward and downward.

A series of trials were recorded at a range of speeds for the reference HNPs which were HNP1 for unridden trials (4 to 7 trials per horse) and HNP2 for ridden trials (4 to 5 trials per horse). This was done to achieve an overlap with the speed ranges for the other HNPs (Weishaupt et al., 2006). In the other HNPs, one trial per horse and unridden/ridden was recorded at the horse's preferred speed, to optimize the comfort for the horses in the more demanding HNPs. In the ridden trials, HNP4 was achieved with draw reins (reins attached to the girth, running through the bit rings, and to the rider's hands) in some horses where the rider was not accustomed to ride in this HNP. HNPs in the unridden trials were achieved with side reins (reins with elastic inserts, fastened between a lunging girth and the bit) adjusted to an appropriate length and height of attachment to achieve the desired position (for HNP2, HNP3, HNP4, and HNP5).

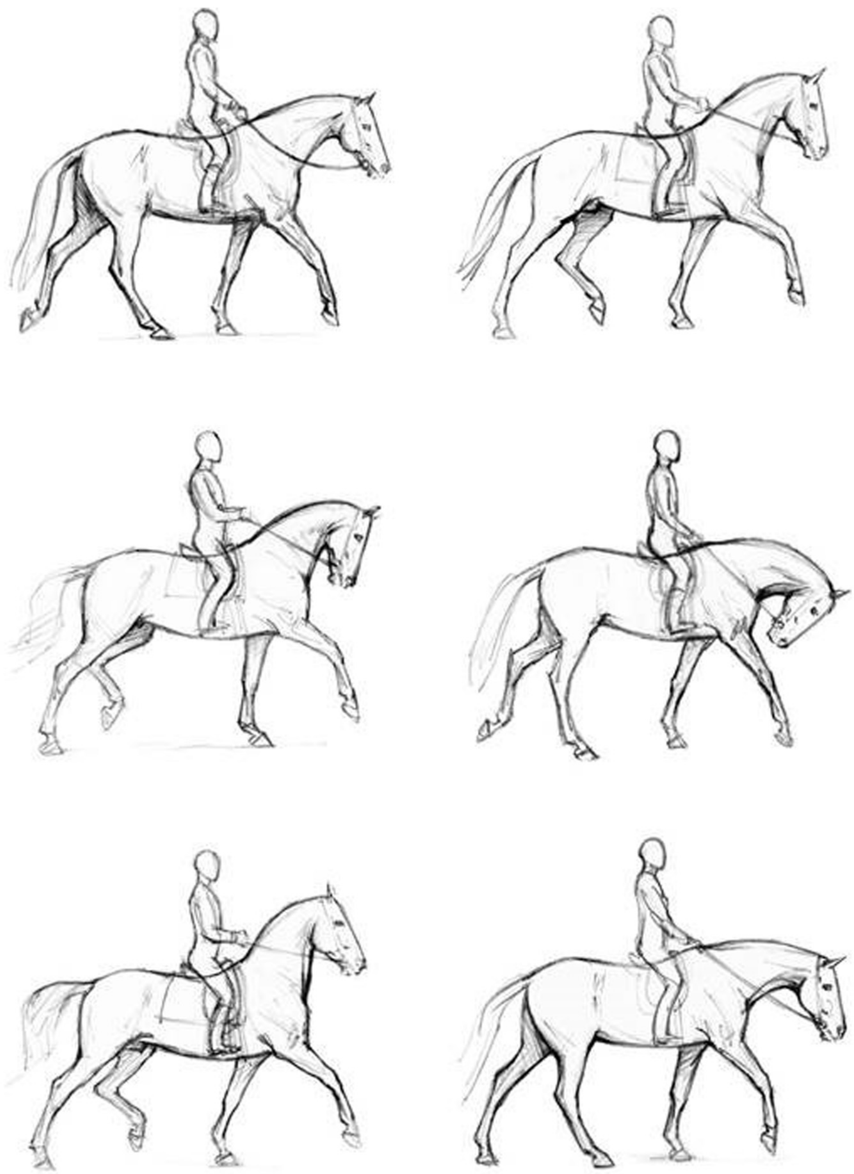

Figure 1. Head and neck positions (HNPs) studied. Illustration: Matthias Haab.

The horses were studied on a treadmill (Karga AG, Fahrwangen, Switzerland) with an integrated force-measuring system (Weishaupt et al., 2002). The treadmill software automatically detected the hoof positions during stance and decomposed the reaction force responses at the multiple bearing points of the treadmill platform into vertical forces acting on each of the four limbs. For each stride and limb, first contact and toe-off were determined from the intersection of the linear approximation of the initial and terminal slope of the force curve with the zero-baseline (Weishaupt et al., 2002).

Horse and rider movements were registered using multiple, 19-mm diameter, spherical reflective markers attached with glue. Marker placement is found in Supplementary Item 1. Marker positions were registered by using 12 infrared optical cameras (ProReflex; Qualisys, Gothenburg, Sweden) with Q-Track software (QTrack; Qualisys, Gothenburg, Sweden) to capture data. Kinematic data were collected at a sampling rate of 240 Hz for 15 s for unridden horses and at 240 Hz for 12 s (3 horses) or 140 Hz for 15 s (4 horses) for ridden horses with the difference being due to technical reasons. Treadmill data were sampled at 420 Hz or 480 Hz as a multiple of the kinematic sampling frequencies. Care was taken to minimize the duration of the more demanding HNPs (HNP3-HNP5). This ensured limited exposure to HNPs that horses were not accustomed to.

Data management

Raw x-, y-, and z-coordinates were exported to, and further analyzed in, MATLAB (version 2016b; The MathWorks Inc., Natick, MA, USA).

Kinetic and spatiotemporal walk variables

The following spatiotemporal variables and vertical ground reaction force (vGRF) variables were extracted from the treadmill force-measuring system:

i) stance duration of the individual limbs;
ii) longitudinal position of each hoof on the treadmill at first contact and toe off. The positive direction was toward the rear not front of the treadmill;
iii) duration of bipedal (diagonal, ipsilateral) and tripedal support phases (2 fore/1 hind, 1 fore/2 hind) measured as a percentage of stride duration (% StrD);
iv) time of first and second vGRF peaks in the forelimbs and hind limbs measured as a percentage of stance duration (% StD);
v) peak vGRF magnitude (normalized to horse body mass) for the first and second force peaks;
vi) transverse distance between placements of the ipsilateral fore and hind hooves, that is, ipsilateral limb tracking. Positive values indicate that the hind hoof is placed to the right of the ipsilateral fore hoof. Negative values indicate that the hind hoof is placed to the left of the ipsilateral fore hoof.

Kinematic variables

The markers used in the current analysis were attached to the skin overlying the spinous processes of the sixth thoracic vertebrae (T6) and, in the data from the unridden trials, also of T10 and T13. Stride split of kinematic data for each limb was performed using first contact and toe-off time information from the treadmill derived data set. Data from each stride sequence were time-normalized to 1-101 data points. The minimal vertical position of the marker on T6 in early left and right forelimb stance was extracted, together with their times of occurrence expressed as percent of stance duration (% StD) for the forelimb that was in early stance.

Definition of left-right differences

Left versus right differences were calculated for all variables by subtracting the value for the right limb from the value for the left limb. Vertical movement of the withers (represented by the marker over the spinous process of T6) follows a sinusoidal path with two peaks and valleys in each stride. The valleys occur during early stance of each forelimb. The values for the minimum height during early stance of the right forelimb were subtracted from the minimum height during early stance of the left forelimb (T6minDiff, withers drop asymmetry). The ipsilateral limb tracking left-right difference (vi) was defined as positive if the hind hoofs tracked predominately to the right of the ipsilateral fore hoof. For longitudinal hoof positions on the treadmill at the start or end of stance, a positive difference indicate that the left limb was further backward not forward than the right limb, that is, the left limb was relatively more protracted at the start of stance, or less retracted at the end of stance, than the right limb at the corresponding stride phase.

Statistics

Descriptive statistics were calculated. Statistical mixed models were used to study associations (PROC MIXED, SAS version 9.4; SAS Institute Inc., Cary, NC). Two model strategies (I, II) used trial means for the difference between T6 minima, T6minDiff, as outcome data with horse modeled as a random effect. In model III, whole stride data for T6 minimum vertical position were used with trial modeled as a random effect (horse-specific models). For models II and III, least square means were derived and compared using the option PDIFF in SAS. The *P* value limit was 0.05 in models I and II as we diminished the power by using trial-mean data. For model III, *P* values < 0.01 were considered significant. Corrections for multiple comparisons were not employed. Data used in the study can be found at https://data.mendeley.com/submissions/evise/edit/8xy2ck2cwv?submission_id=S1558-7878(19)30089-9&token=8f442422-5143-4df2-9d13-3fc5060d779d.

I. Effects of selected biomechanical asymmetry variables on T6minDiff were evaluated separately for ridden and unridden trials. Six models were made that correspond with the variable groups i-vi listed previously. To achieve normally distributed residuals, the outcome variable was transformed. For the ridden trials, the outcome variable was log-transformed, and for the unridden outcome variable, the square root transformation was considered optimal. Linearity of independent fixed effects was checked through plotting and through modeling by adding the square of each variable to univariable fixed-effect models (one fixed-effect variable at a time). Interactions were not tested because of difficulties with interpretation. Reduction was based on significance testing, and the Akaike criterion was also used to guide model selection when appropriate. After using the transformed outcome variables for selecting explanatory variables and determining significances, these models were rerun on the untransformed scale so that the findings were expressed in biological units that are more easily understood. This was considered possible as data were relatively close to normal (both the log and the square-root transformation are adjacent to no/unity transformation on the ladder of powers). Model estimates, standard errors, and Wald *P* values have been used for interpretation. The development and rationale for the modeling procedure have been addressed previously (Byström et al., 2018).
II. To study differences in T6minDiff between HNPs in the unridden/ridden conditions, these data were evaluated by modeling HNP and its 2-way interaction with unridden/ridden as fixed effects. The outcome data were analyzed as absolute values to account for between-horse differences in the direction of the asymmetry pattern. Original (absolute) values and values standardized to the trial-mean stride range of motion (ROM) for the vertical movement of T6 were modeled. Normality of these outcome data was confirmed before modeling (using plotting and scrutinization of descriptive statistics). Results are reported as least square means including pairwise comparisons.
III. Because there was quite a strong within-horse pattern, horse-specific models were constructed to explore the association between HNP and T6 vertical position during the whole stride. Data from time-normalized stride curves (trial mean data series of 101 points, 0-100%) were used as outcome. Fixed effects were stride percentage, HNP, and their 2-way interaction. Least square means and *P* values from this interaction made it possible to evaluate differences between HNPs at the same stride percentage and to evaluate whether the curves differed between the first and second halves of the stride within the same HNP. In the latter case, comparisons were made between least square means for stride percentages 0% and 50% and so on, which represent data for left forelimb stance versus right forelimb stance. Normality of outcome data was confirmed before modeling.

Results

In the unridden walk trials ($n = 74$), speed ranged from 1.23 m/s to 1.86 m/s (median 1.57 m/s), and in the ridden trials ($n = 66$), speed ranged from 1.35 m/s to 1.74 m/s (median 1.57 m/s). Individual trials comprised 9 to 14 strides. Data on neck angles in the various HNPs have been published (Rhodin et al., 2018).

Each panel in Figures 2 and 3 represents one horse while ridden, and each curve represents a different HNP derived from horse-specific mixed models (909 or 1010 observations in each model). At the walk, T6 followed a sinusoidal path with two minima per stride that typically occurred during the period of overlap between the left and right forelimb stance phases (Figures 2 and 3). However, the shape of the curve and the relationship with temporal kinematics were sometimes disrupted, especially when horses were ridden with a high neck position (Figure 4). The curves for horse 2 can be compared to the raw data in the right panel in Figure 4 (data from unridden trials to the left). The bars in Figure 2 indicate when the vertical T6 positions differed significantly between HNPs (pairwise comparisons from mixed models $P < 0.01$). The bars in Figure 3 indicate when the vertical position of T6 differed significantly ($P < 0.01$) between the first and second halves of the stride within the same HNP (e.g., values at 0% are compared with values at 50%). The effects of HNP on the timing of T6 minima are further illustrated in Figure 5.

Figure 6 contains raw data plots of the vertical positions of T6, T10, and T13 from the same horse as in Figure 4 (horse 2). Visually, the three spinal markers follow similar trajectories, and the asymmetrical left-right pattern is evident in all HNPs.

Effect of HNP on T6minDiff (withers drop asymmetry)

Table 1 shows mean, minimum, and maximum for T6minDiff (absolute values) trial means across horses and HNPs. There were several significant differences in T6minDiff between HNPs in unridden and ridden conditions (indicated by numbers, Table 1). The more restricted HNP3 and HNP5 were generally less symmetrical while unridden and more symmetrical while ridden than the free (HNP1) or forward downward position (HNP6).

For unridden trials, the T6minDiff nonnormalized outcome variable showed no significant differences between HNPs. The ROM-normalized outcome for T6minDiff had four significant differences. HNP1 was more symmetrical than HNP3 or HNP5 ($P = 0.01$, $P < 0.05$, respectively). HNP6 was also more symmetrical compared to HNP3 or HNP5 ($P < 0.05$, $P = 0.02$, respectively).

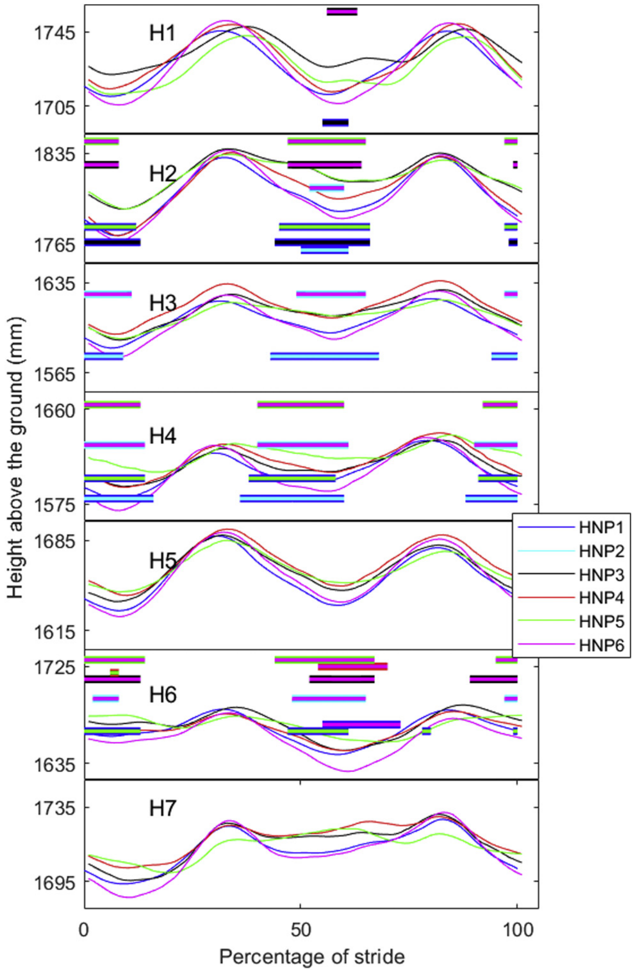

Figure 2. Least square means from horse-specific mixed models (III) on data from ridden trials, using time-normalized stride data where 0 and 100% represent first contact of the left forelimb. Each curve shows the vertical motion of the withers (T6) through the stride for each horse (H1-H7) and head and neck position (HNP1, 2, 3, 4, 5, and 6). The colored bars demonstrate significant differences between HNPs, where the color code shows which HNPs are compared. Significances are shown at $P < 0.01$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

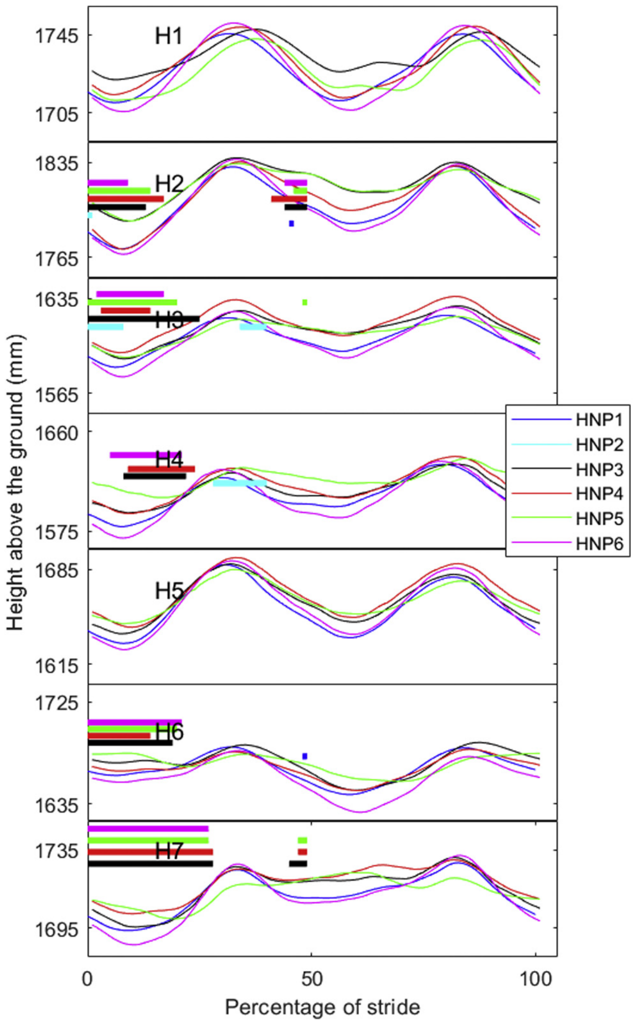

Figure 3. Least square means from horse-specific mixed models on data from ridden trials, using time-normalized stride data where 0 and 100% represent first contact of the left forelimb. Each curve shows the vertical motion of the withers (T6) through the stride for each horse (H1-H7) and head and neck position (HNP1, 2, 3, 4, 5, and 6). Between stride-halves, statistical differences between the first half of the stride (0%-49%) and the second (50%-99%) are shown using bars. Significances are shown at $P < 0.01$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

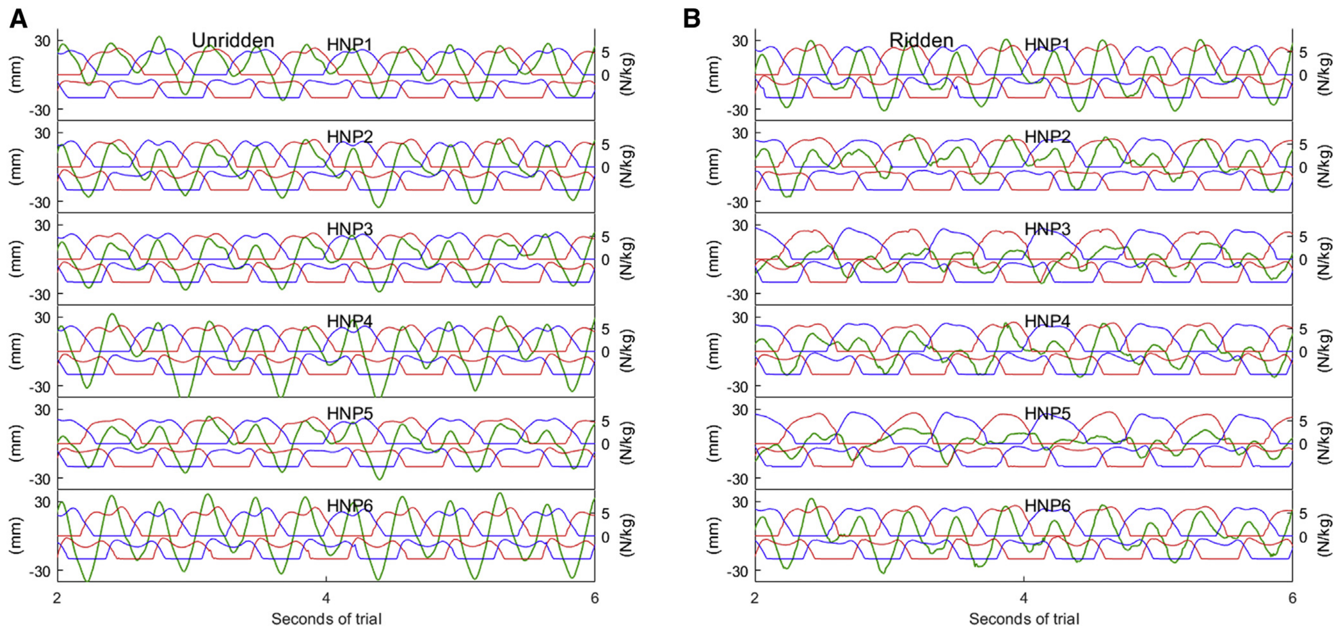

Figure 4. Raw data series (from 2-6 s of the trial) from one horse (horse 2) for withers (T6) vertical position (centered around zero) for unridden (left, A) and ridden trials (right, B) in head and neck position (HNP)1-6, and mass-normalized ground reaction forces (red-left, blue-right, top-forelimbs, and bottom hind limbs). For visibility, hind limb ground reaction force curves are displaced downwards by 5 N/kg. The trials for ridden HNP2 and unridden HNP1 are evacuated at the median speed of the designed speed series. Note that asymmetry of the withers is clearly visible in all trials. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

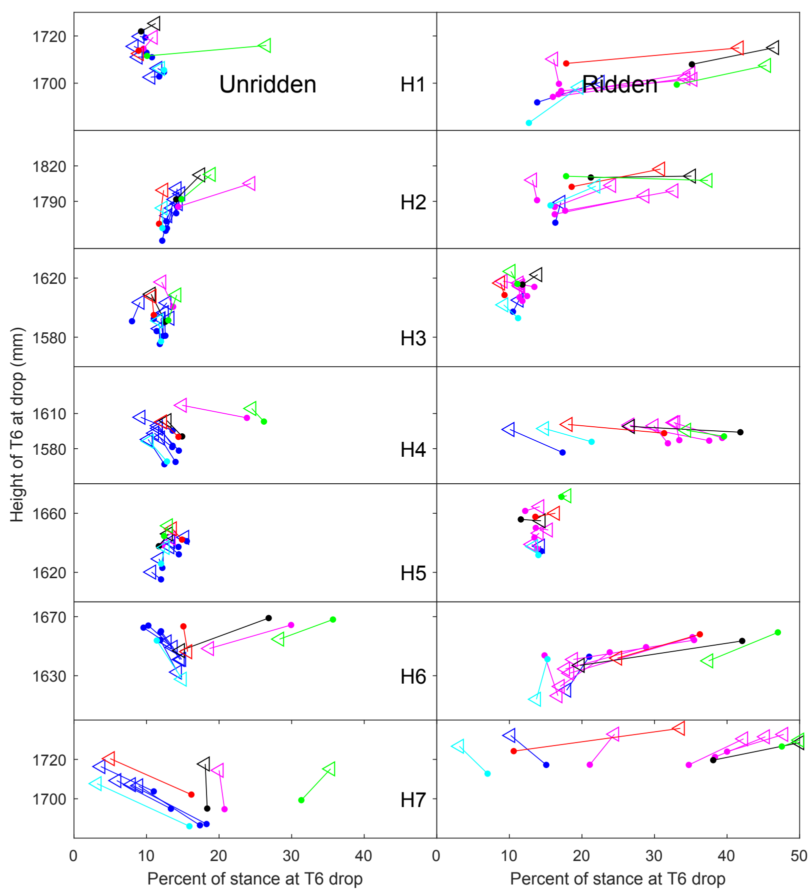

Figure 5. The magnitude of minima of T6 in early stance (y-axis) versus the percent of the stance phase (x-axis) where the minima have been evacuated. Horses are depicted from top to bottom (horse 1-7) and unridden (left/) and ridden (right). Colors correspond to head and neck positions (HNP1-blue [multiple trials unridden], HNP2-magenta [multiple trials ridden], HNP3-black, HNP4-red, HNP5-green, HNP6-cyan). Dots/triangles are for left/right early forelimb stance. (Forty percent stance equals 25% of the stride.). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

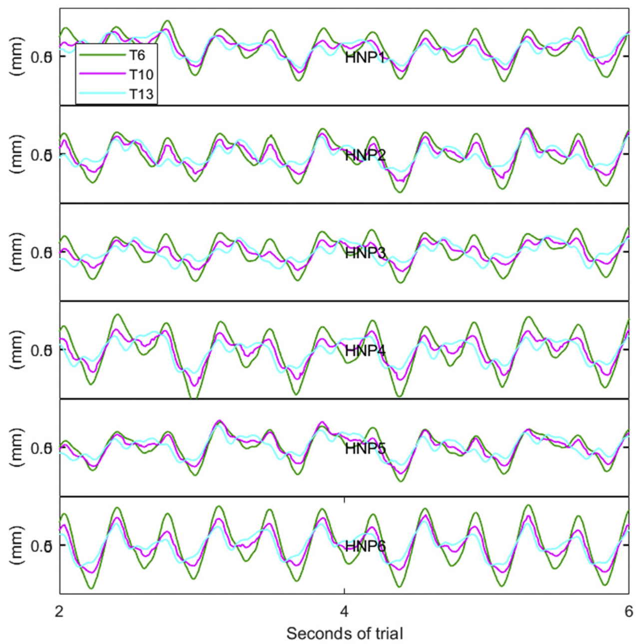

Figure 6. Raw data series (from 2 to 6 seconds of the trial) from one horse (horse 2) for vertical T6, T10, and T13 vertical position (all centered around zero) for unridden trials in HNP1-6. The HNP1 trials are evacuated at the median speed of the designed speed series.

For ridden trials, the T6minDiff nonnormalized outcome variable had six significant differences. HNP1 was less symmetrical than HNP3 or HNP5 ($P = 0.003$, $P = 0.005$, respectively), HNP2 was less symmetrical than HNP3 or HNP5 ($P = 0.004$, $P = 0.008$, respectively), and HNP6 was less symmetrical than HNP3 or HNP5 ($P = 0.001$, $P = 0.002$, respectively). The ROM-normalized outcome had three significant differences: HNP1 was less symmetrical than HNP5 ($P < 0.05$), and HNP2 was less symmetrical than HNP3 or HNP5 ($P = 0.003$, $P = 0.001$, respectively). For the comparisons mentioned, the T-values varied between 3.37 and 1.98 with 118 degrees of freedom.

Effect of rider on T6minDiff (withers drop asymmetry)

Both absolute T6minDiff and ROM-normalized absolute T6minDiff show statistical significances between unridden and ridden conditions for HNP3 ($P < 0.0001$, $P = 0.009$, respectively) and HNP5 ($P = 0.01$, $P = 0.002$, respectively). HNP3 and HNP5 were more symmetrical when ridden than when unridden (indicated by bolded numbers in Table 1). For the comparisons mentioned, the T-values varied between 4.03 and 2.68 with 118 degrees of freedom.

Model results

Asymmetries in a number of spatiotemporal and vGRF variables predicted an increase in the difference between T6 minima in early left versus right forelimb stance (Supplementary Item 2 and 3 show plots of tested independent variables versus dependent data in untransformed formats). A positive estimate means that a relatively higher variable value on the ipsilateral (e.g., left) side predicts a relatively higher (less accentuated) T6 minimum in early ipsilateral (left) forelimb stance, that is, a lower withers drop in contralateral (right) forelimb early stance. For ease of reading, the estimates will be described for the forelimb in early stance when T6 minimum is lowest, and the other limbs will be denoted accordingly (ipsilateral/contralateral).

In the ridden trials (Table 2), increased withers drop in early forelimb stance was associated with relatively shorter protraction (distance) at stance start in the ipsilateral hind limb and relatively shorter stance phase overlaps between this hind limb and the other limbs in the phases of diagonal support, 3-limb support with two forelimbs and one hind limb, and ipsilateral support. The same was true for unridden trials (Supplementary Item 4).

There were also differences between the ridden and unridden conditions. For the ridden trials, greater withers drop in early stance of one forelimb was additionally associated with a relatively higher and earlier first vGRF peak and shorter stance duration in this forelimb, longer ipsilateral hind limb stance duration, and hind quarters tracking toward the contralateral side (to the right if dropping the withers more on the left forelimb) (Table 2). In the unridden condition, greater withers drop in early stance of one forelimb was associated with relatively shorter retraction at stance end in this forelimb, a higher second vGRF peak, and shorter stance duration in the ipsilateral hind limb (Supplementary Item 4). This suggests that the association to hind limb stance duration was opposite between unridden and ridden conditions, possibly related to the fact that forelimb stance duration difference was significant in the ridden condition. For a more extensive description, see Supplementary Item 4.

Individual variation

There were large individual variations (as well as group effects) in response to imposing different HNPs. Individual data from horses 2, 3, 4, and 6 showed many similarities including a substantial withers drop asymmetry in most trials. The between-HNP significances were most prevalent in these more asymmetrical horses and typically occurred around the time of T6 minima. In horses 2, 3, 4, 6, and 7, long durations of statistically significant differences between the first and second halves of the stride are seen, including at the time of T6 minimum. Horse 7 was an exception in having generally large withers drop asymmetry, but no between-HNP significances. This horse also had minima that were shallow (Figures 2 and 3), and the exact timing was therefore difficult to determine, resulting in more variation in timing than in the other horses (Figure 5).

Horses generally showed consistent timing for T6 minima over most of the HNPs when unridden (Figure 5). However, in some horses, trials for HNPs 4 and 5 deviated from this pattern. Horses 1, 2, and 4 showed greater variation in the timing when ridden. Horses 3 and 5 were quite consistent across unridden and ridden trials. Horses 6 and 7 had considerable variation both in magnitude and timing under unridden and ridden conditions. In Figure 7, T6 minimum is plotted against ipsilateral limb tracking, showing whether the hind limb is placed lateral or medial to its ipsilateral forelimb.

Discussion

Associations between withers drop and other variables

The previously described associations between withers drop asymmetry, defined as a systematic and pronounced difference between withers vertical minima coinciding with the protracted position of the left or right forelimb and asymmetry in spatiotemporal variables including limb protraction and retraction (Byström et al., 2018), proved relatively stable when the influence of a rider and/or a restricted HNP was added. Comparing variable estimates and significances between statistical models on data from ridden trials (Table 2), unridden trials (Supplementary Item 4 Table), and unridden trials with the free HNPs (Byström et al., 2018), only two significant variables had opposite signs for the estimates, of the 19

Table 1
Mean, minimum, and maximum values for the absolute difference between minimumT6 vertical positions in left and right early forelimb stance (T6minDiff in mm) by horse and head and neck position (HNP)

Variable	Absolute T6minDiff									
	Category	Unridden				Ridden				
		n	Mean	Min	Max	n	Mean	Min	Max	Diff
Horse	1	10	1.93	0.082	4.821	9	8.658	4.872	15.2	
	2	11	19.87	15.02	28.46	9	13.45	1.721	18.2	
	3	11	13.63	9.336	19.18	9	7.88	4.225	9.64	
	4	11	15.12	10.72	21.16	9	11.66	4.934	19.7	
	5	10	6.06	2.564	11.1	9	2.567	0.738	5.81	
	6	10	17.83	11.05	26.19	10	20.38	13.13	27.3	
	7	9	18.37	12.73	22.63	9	11.16	3.538	15.6	
HNP	HNP1	37	12.45	0.082	22.96	7	13.4	3.01	22.6	3:5
	HNP2	7	13.22	4.608	19.67	29	11.94	1.431	27.3	3:5
	HNP3	**7**	**15.71**	**3.36**	**22.63**	7	**6.65**	**0.928**	**16.5**	1:2:6
	HNP4	7	14.01	1.51	28.46	7	9.711	2.401	16	
	HNP5	**7**	**12.74**	**4.167**	**21.01**	7	**6.998**	**0.738**	**19.3**	1:2:6
	HNP6	7	15.4	0.694	26.19	7	14.11	5.807	27	3:5
Total		72	13.31	0.082	28.46	64	10.97	0.738	27.3	

	Absolute T6minDiff normalized to vertical excursion										
		Unridden					Ridden				
		n	Mean	Min	Max		n	Mean	Min	Max	
Horse	1	10	0.059	0.002	0.14		9	0.337	0.222	0.47	
	2	11	0.351	0.243	0.496		9	0.298	0.065	0.42	
	3	11	0.365	0.225	0.566		9	0.254	0.168	0.35	
	4	11	0.302	0.262	0.354		9	0.413	0.231	0.58	
	5	10	0.111	0.056	0.171		9	0.057	0.026	0.1	
	6	10	0.435	0.368	0.52		10	0.514	0.456	0.65	
	7	9	0.531	0.405	0.643		9	0.4	0.106	0.64	
HNP	HNP1	37	0.267	0.002	0.514	3:5	7	0.339	0.046	0.64	5
	HNP2	7	0.349	0.092	0.566		29	0.375	0.034	0.65	3:5
	HNP3	7	**0.385**	**0.129**	**0.621**	1	**7**	**0.238**	**0.026**	**0.5**	2
	HNP4	7	0.325	0.04	0.622		7	0.315	0.079	0.48	
	HNP5	7	**0.403**	**0.132**	**0.643**	1:6	**7**	**0.227**	**0.039**	**0.48**	1:2
	HNP6	7	0.273	0.015	0.483	5	7	0.321	0.096	0.54	
Total		72	0.306	0.002	0.643		64	0.328	0.026	0.65	

The absolute T6minDiff was also analyzed normalized to the vertical range of the marker within trial.
That the number of trials (n) is larger for HNP1 unridden and HNP2 ridden is due to the speed-match series done in these HNPs.
Bolded numbers indicate significant differences between unridden and ridden within HNP ($P = 0.01$ to <0.0001).
Numbers in last column (Diff) indicate significant differences (pairwise comparisons, Walds $P < 0.05$) between HNPs within column, for the unridden/ridden conditions ($P \leq$ 0.05-0.001).

variables evaluated. However, some variables were not significant in all three data sets (differences between models are further described in Supplementary Item 4).

In the unridden condition, a decrease in hind limb stance duration and an increase in the second hind limb force peak were associated with increased withers drop in early stance of the ipsilateral forelimb, whereas in the ridden condition, there was instead an association to decreased forelimb stance duration and an increase in the first vertical force peak for the forelimb in early stance when the withers dropped lower. This difference may be due to the rider's weight having more influence on the GRFs of the forelimbs than on those of the hind limbs (Schamhardt et al., 1991; Clayton et al., 1999) and the fact that forelimb retraction increases when the horse carries weight (de Cocq et al., 2004). However, both the forelimb and hind limb variables discussed previously relate to the period of ipsilateral bipedal support, which was consistently shorter (estimate with positive coefficient) when including the forelimb that was in early stance when the withers dropped lower for all three data sets (Table 2, Supplementary Item 4 Table, Byström et al., 2018).

Forehand vertical movement energetics in walk

The findings in this and our previous study (Byström et al., 2018) suggest a functional difference between the two forelimbs, with similar conclusions to studies on left-right differences in hoof conformation and limb loading patterns (van Heel et al., 2006, 2010, Wiggers et al., 2015; Colborne et al., 2016). The associations between T6minDiff and other biomechanical variables can be related to the fact that directional changes in the path of the forehand are energetically expensive. During the period of overlapping forelimb stance phases, when the withers reach their lowest height, the trajectory of the forehand is reversed from forwards and downwards to forwards and upwards under the influence of vertical and opposing horizontal forces generated by the two forelimbs. In people, redirection of the center of mass during dual limb support can account for 60%-70% of the overall metabolic energy expended for walking (Donelan et al., 2002).

Several previous studies of the effects of restricting the HNP of walking horses have found an extensive influence on the horse's movement pattern, both with a rider (Biau et al., 2002; Weishaupt et al., 2006; Rhodin et al., 2018) and without a rider (Rhodin et al., 2005; Gomez-Alvarez et al., 2006; Waldern et al., 2009). The walk may be particularly sensitive to changes in HNPs because horses, in common with many ungulate species, show an obvious nodding motion of the head during walking, which plays a role in minimizing energy expenditure while using inverted pendular dynamics (Loscher et al., 2016). It is not known whether restricting the HNP in walk is particularly stressful for the horse as the studies on behavior and stress-related effects of various HNPs that included

Table 2
Mixed model estimates of the models in the study, on the ridden data including data on all head and neck positions

Symmetry variables	Est	SE	95% CI	*P* value	
				Untrans.	Transf.
Intercept i)	−5.39	4.93	−15.1, 4.3	0.32	<0.0001
Forelimb stance duration (ms)	0.12	0.06	0.1, 0.0	0.05	0.03
Hind limb stance duration (ms)	−0.38	0.09	0.1, 0.5	<0.0001	<0.0001
Intercept ii)	−6.74	4.30	−15.1, 1.7	0.17	<0.0001
Hind limb stance protraction (mm)	−0.08	0.03	0.1, 0.1	0.005	0.002
Intercept iii)	−6.50	5.17	−17.1, 3.6	0.26	<0.0001
Duration of 3-limb support with 2 forelimbs (% of StrD)	5.32	0.76	4.1, 6.8	<0.0001	<0.0001
Ipsilateral support duration (% of StrD)	2.68	0.87	1.1, 4.4	0.003	0.004
Diagonal support duration (% of StrD)	−2.02	1.02	−4.1, 0.0	0.05	0.008
Intercept iv)	−5.49	3.84	−13.1, 2.0	0.20	<0.0001
Time of forelimb force peak I (% of StD)	0.17	0.03	0.1, 0.2	<0.0001	<0.0001
Intercept v)	−4.06	3.89	−12.1, 3.6	0.32	<0.0001
Forelimb force peak I (N)	−0.03	0.01	0.1, 0.0	<0.0001	<0.0001
Intercept iv)	3.14	0.13	3.1, 3.4	<0.0001	0.29
Ipsilateral limb tracking (mm)	−0.002	0.0005	0.1, 0.0	0.002	0.001

StrD, stride duration; StD, stance duration.
In general, differences are calculated taking left limb values minus right limb values. A positive estimate means that a relatively higher variable value on the ipsilateral (e.g., left) side predicts a relatively higher (less accentuated) T6 vertical minimum in early ipsilateral (left) forelimb stance, that is, a lower withers drop in contralateral forelimb early stance. In all analyses, there are 7 horses, and each horse contributes data from between 9 and 10 trials (n = 61-64 trials in each analysis). The outcome is the difference between T6 vertical minimum in early left forelimb and right forelimb stance phases. *P* values are obtained from Wald's test. *P*-values from untransformed (Untrans.) or log-transformed data (Transf.).

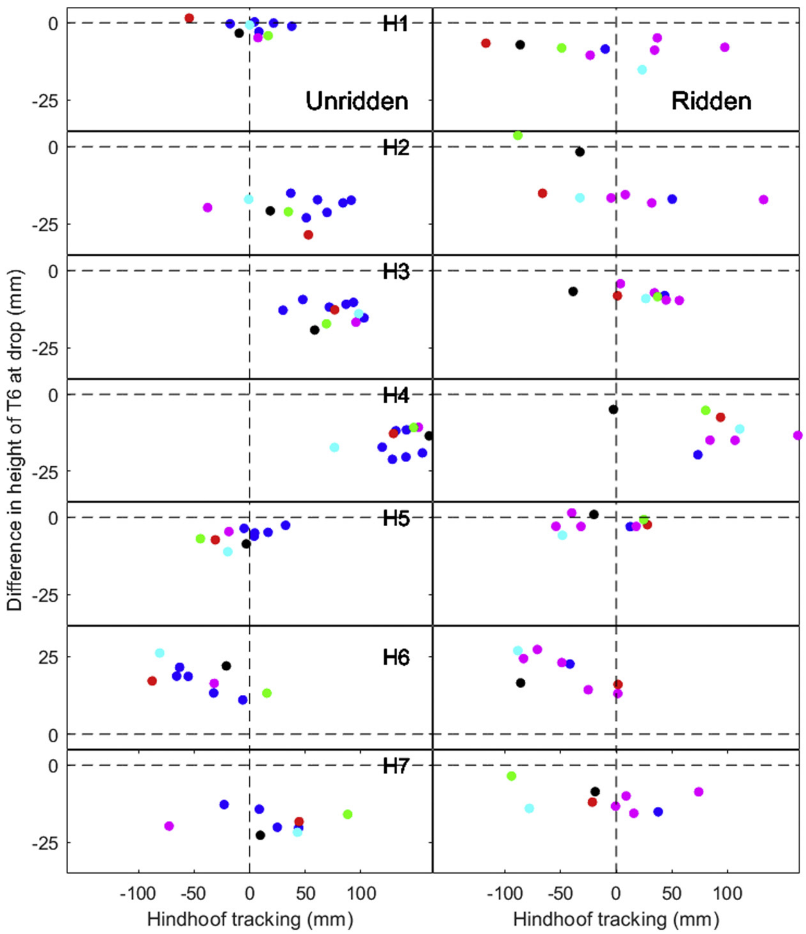

Figure 7. Left-right differences of T6 minima in early stance (y-axis) versus the left/right placement of the hind limbs in relation to the forelimbs (x-axis). Horses are depicted from top to bottom (horse 1-7) and unridden and ridden (left/right). Colors correspond to HNPs (HNP1-blue, HNP2-magenta, HNP3-black, HNP4-red, HNP5-green, HNP6-cyan). Left/right placement is positive if the hind limbs are placed to the right of the respective fore hoof (mean of the two hind limbs). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

data on walk in their evaluation do not address differences between gaits (Christensen et al., 2014; Lashley et al., 2014; Kienapfel et al., 2014). Furthermore, this and other studies have evaluated effects of HNPs when applied only for a short period of time. Long-term effects have not been addressed with regard to either performance or health and welfare.

The influence of the rider on symmetry

In our study, when constraining the HNP without a rider, the difference between T6 minima became more consistent and more accentuated in most horses (Table 1, Figure 4). In the more restrained HNP3 and HNP5, the presence of a rider was associated with a smaller T6minDiff, which was achieved because the lower drop was reduced. This reduced, but did not completely eliminate, the difference in withers minimum height between the left and right forelimb stance phases (Table 1, Figure 4). This may be related to that the forelimbs moved through a smaller range of protraction and retraction, as in collection (Holmström et al., 1995), and therefore supported the forehand in a higher position. Studying systematic findings between HNPs over the stride in ridden horses (Rhodin et al., 2018), it was found that, compared with the competition position (HNP2), withers minimum height was lower in HNP1 and HNP6, both of which have the neck extended more forward and down and have a larger range of vertical movements of the withers. On the other hand, in the more restrained HNP3 and HNP5, the withers minimum height was increased (higher minimum).

However, even if horses were more symmetrical when ridden in constrained HNPs, the timing was less consistent in the ridden trials for most horses and particularly for HNP5 (Figure 3, raw data not shown). The downwards nodding motion of the head and neck is timed to increase loading when a single forelimb is grounded, at which time it is relatively inexpensive to redirect the body motion. It has been demonstrated experimentally that a change in timing of the head movements can increase the metabolic cost estimate of carrying the head and neck by as much as 63% (Loscher et al., 2016). Thus, HNP is likely to affect energetics through its effect on both the position and movements of the head and neck including the timing of withers minimum height.

The study findings indicate that it cannot generally be assumed that the effect of HNP on withers drop asymmetry (T6minDiff) is consistent with and without the rider. HNP3 and HNP5 differed significantly between these two conditions, regardless of normalization to the range of vertical movement of the withers. The rider can influence the symmetry of the horse through the challenge of carrying a load, through asymmetrical rider movements or position, or by the way in which the rider applies the aids. The relative influence of these aspects could not be partitioned out in the present study and thus requires further research.

Individual variation

Within-individual patterns are demonstrated for some variables (Figures 2-5 and 7). By following individual horses between these graphs, it can be seen, for example, that when horse 3 was unridden, the hind limbs tracked to the right of the respective forelimbs and T6 asymmetry was more pronounced than in the ridden situation in which the hind limbs tracked almost straight along the same tracks as the forelimbs (Figure 7). However, the timing of events was consistent between ridden and unridden conditions (Figure 5). In this horse, both within and between HNP differences in T6 vertical position stride curves occurred around the time of withers minimum height (Figures 2-3). The data from this horse demonstrated differences between HNPs when comparing the competition position (HNP2) to the free (HNP1) and the forward downward position (HNP6).

Our results suggest that if a sound warmblood horse drops the withers “unevenly and systematically” in walk, then systematic biomechanical mechanisms are involved, but the degree to which the individual parameters are affected by the rider varies between individual horse-rider combinations. Given that we had a lot of data on each study horse, we have strived to also demonstrate individual patterns within this complex biomechanical phenomenon because training and clinical evaluation usually target the individual. If an asymmetry is perceived, it may be a reason for riders to seek professional advice (veterinarian, physiotherapist, chiropractor, and so forth). Although clinical observations suggest that a pronounced withers drop asymmetry in walk is not always linked to asymmetry in trot (Byström et al., 2018), we suggest that it may be associated with inherent laterality.

The equestrian perspective

Because the movement asymmetries described in this study may reflect equine laterality and because asymmetries were influenced by the rider, it is relevant to review the findings relative to descriptions of horse sidedness in equestrian texts. The suggested proportion of right-versus left-lateralized horses varies somewhat among equestrian authors, from an equal distribution (Karl 2008) to an overrepresentation of right-lateralized horses (Podhajsky 1967). This classification relies on observations within training, such as the ease of bending the horse around the rider’s leg and the direction in which the shoulders tend to drift when turning, but sidedness has not been defined in terms of measurable biomechanical variables. We do not know if riders and trainers commonly see or feel the asymmetry in withers or forehand movements at walk, but the authors are not aware of descriptions of this phenomenon in the equestrian literature. Our experience suggests that riders can detect the asymmetry when viewing horses from the ground or on video recordings (Byström et al., 2018, S1 video). It remains to be investigated whether the forehand asymmetry described here is consistent with the laterality perceived by riders. Asymmetrical hind limb tracking has frequently been cited as an expression of laterality (Steinbrecht 1886; Podhajsky 1967; Rachen-Schöneich and Schöneich 2007; Karl 2008). Our results show that the hind limbs consistently tracked away from the forelimb that was in early stance when the withers dropped lower (Figure 7), although to a lesser degree when ridden, which we interpreted as an improvement in gait symmetry when ridden. However, it cannot be determined whether this effect was due to the rider’s efforts to straighten the horse or simply a side-effect of holding the horse in a firmer frame.

Limitations of the study

Limitations of the study include the fact that treadmill locomotion is known to differ from over-ground locomotion (Buchner et al., 1994), but for studies such as the one reported here, the benefits of being able to collect kinematic and GRF data continuously over a large number of strides seem to outweigh many of these disadvantages. Furthermore, the straightness of the treadmill belt removed the condition of riding on the left or right rein with the inherent lateral bending of the horse. Other limitations include the fact that riders were not asked to subjectively assess laterality of their horses or themselves. Skin displacement is always an issue in studies using skin markers (van Weeren et al., 1990; Bergh et al., 2014). Speed was not included in the models presented here because preliminary mixed models, with speed included, indicated that speed did not affect conclusions (data not shown). In fact, it is well known that speed affects the magnitudes of the variables that were studied, but because speed has a limited effect on asymmetries in trot (Moorman et al., 2017), this is likely also true for walk.

It is unclear if asymmetries are more relevant to quantify as absolute values or as a percentage of the ROM. Because HNPs had a substantial influence on range of vertical motion of the withers, mainly for the ridden condition (Rhodin et al., 2018), withers drop asymmetry (T6minDiff) was analyzed in two ways in the present study, as absolute values and normalized to the range of vertical movement of the withers. Using data from only seven horses studied on a treadmill limits, the scope of the general conclusions and a detailed evaluation of a larger number of horses will be needed to confirm the distribution of the individual strategies and their determinants in a larger and more diverse population of horses moving not only on the straight but also on turns and circles.

Conclusions

The biomechanical chain of events associated with withers drop asymmetry was similar with and without a rider but showed differences between HNPs that were not consistent across unridden and ridden conditions. Therefore, it is not always possible to extrapolate conclusions about HNPs without a rider to the ridden situation or vice versa. The considerable variation between individual horses indicates the necessity for trainers to use individualized training programs to address horse asymmetry.

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Link to mendeley data

https://data.mendeley.com/submissions/evise/edit/8xy2ck2cwv?submission_id=S1558-7878(19)30089-9&token=8f442422-5143-4df2-9d13-3fc5060d779d.

Authorship statement

The idea for the article was conceived by A.E. and A.B. The experiments were designed by L.R., M.R., M.A.W., and R.v.W. The experiments were performed by L.R., M.R., and M.A.W. The data were analyzed by A.E. and A.B. The article was written by A.E., A.B., and H.M.C.

Ethical considerations

Compliance with regulations on the ethical treatment of animals including the identification of the institutional committee that approved the experiments has been reached.

Conflicts of interest

No competing interests have been declared.

Sources of funding

There was no specific funding for this study.

In memoriam

This manuscript is dedicated to Chris Johnston, who was a driving force in conceiving and setting up the original study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jveb.2019.10.010.

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