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GENERAL ARTICLE

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Asymmetries of horses walking and trotting on treadmill with and without rider

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Abstract

Background: Left-right movement symmetry is a highly desirable characteristic in sport horses.

Objectives: This study compared movement symmetry in well-trained dressage horses in unridden and unrestrained position and ridden in a dressage frame, and investigated possible associations between gaits.

Study design: Experimental study.

Methods: Seven sound, high-level dressage horses were measured at walk and sitting trot on a treadmill at several speeds under two conditions: with and without rider. Left-right differences in stance duration, stance protraction and retraction based on longitudinal hoof positions, ipsilateral limb tracking, minimum and maximum vertical positions of the dorsal spinous processes of the sixth thoracic (T6), third sacral vertebrae (S3) and wing of atlas, and vertical ground reaction forces were calculated and analysed in mixed models.

Results: At walk, five body variables indicated increased asymmetry in the ridden condition compared with unridden condition: forelimb stance duration (unridden/ridden left-right differences 9 vs 13 ms; $P = .008$), forelimb stance protraction ($P = .004$), stance retraction ($P = .001$) and first force peak ($P = .003$), and hindlimb stance retraction ($P = .01$). At trot, six body variables were more asymmetrical in the ridden condition: forelimb stance duration (2.5 vs 3.8 ms, $P = .004$); hindlimb stance protraction ($P < .0001$) and retraction ($P = .01$), T6 minimum (4 vs 6 mm, $P = .001$), T6 maximum (9 vs 11 mm, $P = .01$) and S3 maximum (6 vs 12 mm, $P < .001$). Five variables had significant associations between asymmetries at walk and trot, but only three demonstrated a positive slope.

Main limitations: A limited number of horses and riders were studied. Measurements were performed on a treadmill.

Conclusions: High-level horses moved slightly more asymmetrically when ridden in a dressage frame than in the unridden condition.

KEYWORDS
horse, gait asymmetry, kinematics, kinetics, sidedness, lameness

1 | INTRODUCTION

In symmetrical gaits, such as walk and trot, kinematic and spatiotemporal variables should be similar on the left and right sides when the horse travels on a straight line and should be mirror images on left and right circles. Movement symmetry is a highly desirable characteristic in sport horses,1 in which the quality described as "straightness" implies left-right symmetry of limb movements, muscular strength and rein contact. The importance of managing left-right (a)symmetry of the horse's posture and movements is reflected by the fact that straightness is listed as the fifth step in the six-step dressage training scale.1 Dressage test scores, studbook performance testing, pre-purchase examinations. etc., more or less implicitly will value straightness and favour symmetry of appearance and performance.

Considerable attention has been given to quantify asymmetries in kinematics2,3 and vertical ground reaction forces (vGRFs)4,5 in lame horses. However, some level of kinematic and kinetic asymmetries is often found in sound, well-performing horses in both walk6,7 and trot8-11 with considerable overlap being reported between low-grade lameness and normal horses.12 Laterality, defined as a systematic preference to use one side of the body as a consequence of cerebral lateralisation,13 is discussed as one possible cause for locomotor asymmetries in healthy horses, but other possible factors are conformation,14 trimming and shoeing,15 training16 and pathological or age-related changes. Vertical movement asymmetry increased only marginally in sound trotting horses after the addition of lead weights to the saddle and the rider,17 whereas horses became more asymmetrical with a professional rider vs a novice rider of similar bodyweight.18 This suggests the effect of an active rider goes beyond that of the mere physical load. To the authors' best knowledge, no studies have been published yet on influence of the rider on horse symmetry at walk.

The present exploratory analysis investigated asymmetries in trunk vertical movement, vGRF and spatiotemporal variables in horses assessed clinically as being sound at trot. The aim was to compare movement symmetry of high-level dressage horses at walk and trot in an unridden and unrestrained condition vs ridden between the aids in a dressage frame condition, and to seek associations between corresponding asymmetries in the two gaits. The hypotheses were that asymmetries will increase with a rider and that asymmetries will be related between gaits.

2 | MATERIALS AND METHODS

2.1 | Horses

The subjects were seven high-level dressage horses (1 stallion and 6 geldings; mean ± SD age: 14 ± 4.3 years; height: 1.7 ± 0.07 m; body mass: 609 ± 62 kg) that were judged by an experienced veterinarian (M.A.W.) to be free from lameness, pain or dysfunction of the limbs and back. The horses were habituated over a period of at least 3 days to treadmill locomotion at walk and trot, with and without a rider. During their stay at the clinic, horses spent 30-45 minutes daily in a horse walker and were always hand-walked 30 minutes before each measurement session. For unridden trials, the horses wore their own snaffle bridle and were guided by a handler at the front of the treadmill. For ridden trials, horses wore the same snaffle bridle and their customary saddle. They were each ridden by their regular riders (seven riders: body mass: 78 ± 17 kg) who had trained and competed with the horses up to the Grand Prix (n = 6) or Intermédiaire (n = 1) level. The study protocol was approved by the Animal Health and Welfare Commission of the canton of Zürich (188/2005).

2.2 | Experimental study set-up

Data were collected at walk and trot (each trial lasted 10-15 s of steady-state gait) without (day 1) and with a rider (day 2) at a range of incremental speeds representative of typical dressage schooling paces within each gait on a high-speed treadmill (Mustang 2200, Graber AG). Unridden horses moved without restraint, guided by a handler at the front of the treadmill. Horses were ridden at walk and sitting trot in a dressage frame, that is in a posture that is typical in dressage with the neck raised, the poll as the highest point and the dorsum of the nose on or slightly in front of the vertical, achieved by coordinated aids from the rider's seat, legs and hands.1 A trial was defined as successful when both a dressage judge overseeing the experiment and the rider agreed that the horse performed a correct and steady gait in good posture, and data were recorded successfully.

The treadmill-integrated force measuring system19 provided vGRF, hoof placement locations and timing for all four limbs. Unridden force data were sampled at 480 Hz and ridden data at 480 Hz in four horses and 420 Hz in three horses (due to technical difficulties with the kinematic registrations).

Spherical, infrared-light reflective markers (19 mm Ø, Qualisys) were glued to the horses' skin overlying the dorsal spinous processes of the sixth thoracic (T6) and third sacral (S3) vertebrae, and to the left wing of the atlas. Markers were tracked by 12 infrared cameras (ProReflex, Qualisys). Unridden kinematic data were sampled at 240 Hz and ridden data at 240 Hz in four horses and 140 Hz in three horses (due to technical difficulties). The coordinate data were captured using proprietary software (QTrack, Qualisys) and exported for further processing to Matlab (Matlab version 2016b, The MathWorks® Inc.). Kinematic data were stride-split using the synchronised treadmill data. For each stride and limb, first contact and toe-off were determined by the intersection of the linear

approximation of the initial and terminal slope of the force curve with the zero-baseline.19

2.3 | Kinetic, spatiotemporal and kinematic variables

The following variables were extracted from the treadmill proprietary software output and were analysed:

- Stance duration (time in seconds of hoof contact with the treadmill belt) for each limb;
- Longitudinal position (distance in mm) of each hoof on the treadmill at first contact and toe-off (positive towards the rear of the treadmill);
- Ipsilateral limb tracking (transverse distance (mm) between placements of ipsilateral fore and hind hooves, value positive when hind hoof placed to the right of the ipsilateral fore hoof);
- Peak vGRF magnitude in all limbs (normalised to body mass) for both peaks at walk and the single peak at trot.

In addition, the minimum and maximum vertical positions (mm) of T6, S3 and the left wing of the atlas during left and right steps of the forelimbs and hindlimbs were calculated from the kinematic data. Data quality for these markers was checked by plotting each trial.

2.4 | Calculation of asymmetry variables

Left-right asymmetries were quantified by subtracting right-side/step values from left-side/step values. Stance protraction and retraction differences were calculated by subtracting longitudinal hoof positions at first contact and toe-off respectively.

2.5 | Data analysis

Trial means were calculated for all variables. Descriptive statistics were displayed as plots, including boxplots. Mixed models (PROC MIXED, SAS, Matlab version 2016b, The MathWorks® Inc., SAS version 9.4, SAS Institute Inc.) were used to study associations. In all models, the random effect was horse. The covariance structure was set to variance components. Speed (m/s) was tested in all models as a continuous linear effect and removed if nonsignificant. Associations were considered significant if $P < .05$. PROC PLM (Matlab version 2016b, The MathWorks® Inc.) was used to construct slopes for estimates involving interactions and associated P values. In order to achieve normally distributed residuals, Box-Cox evaluation (PROC TRANSREG, Matlab version 2016b, The MathWorks® Inc.), plotting and scrutinisation of means, standard deviations, medians, skewness and kurtosis were applied to outcome data. Residuals were plotted. Data can be found at 10.6084/m9.figshare.11432943. The following two model types were constructed:

Model I: to assess the difference in asymmetry between unridden and ridden conditions.

Absolute values for the asymmetry variables were used as dependent variables and unridden/ridden condition was used as fixed effect. Square root transformation of the absolute differences yielded good or adequate normality for all analyses. Models were done separately for walk and trot.

Model II: to evaluate association between walk and trot asymmetry.

Walk and trot data were matched on horse, speed and unridden/ridden condition. Trials with the lowest and highest speed, and the two trials closest to median speed, were selected and paired between walk and trot for each horse. Atlas, T6 and S3 variables were excluded in model II because of differences in gait mechanics at walk and trot. For the remaining asymmetry variables, two models were made, with either walk or trot as the dependent variable. Fixed effects in the model were the corresponding trot or walk asymmetry variable, unridden/ridden condition and their interaction. In the models with walk as independent variables, walk speed was tested, and in the model with trot as independent variables, trot speed was tested. Both first and second force peaks at walk were analysed vs peak force at trot. Variables were most normal in the untransformed format.

3 | RESULTS

3.1 | Descriptive statistics

Table 1 shows data on number of trials per horse, strides per trial and speed. Figure 1 shows direction of left-right differences, with

TABLE 1 Descriptive information for the trials from seven horses

		Total trials	No. of trials per horse			Strides per trial		Speed (m/s)		
Gait	Category	n	Min	Median	Max	Min	Max	Min	Median	Max
Walk	Unridden	39	4	6	7	13	17	1.23	1.57	1.86
	Ridden	29	4	4	5	14	18	1.35	1.58	1.74
Trot	Unridden	32	4	4	6	15	19	2.68	3.10	3.69
	Ridden	29	3	4	5	14	18	2.74	3.03	3.42

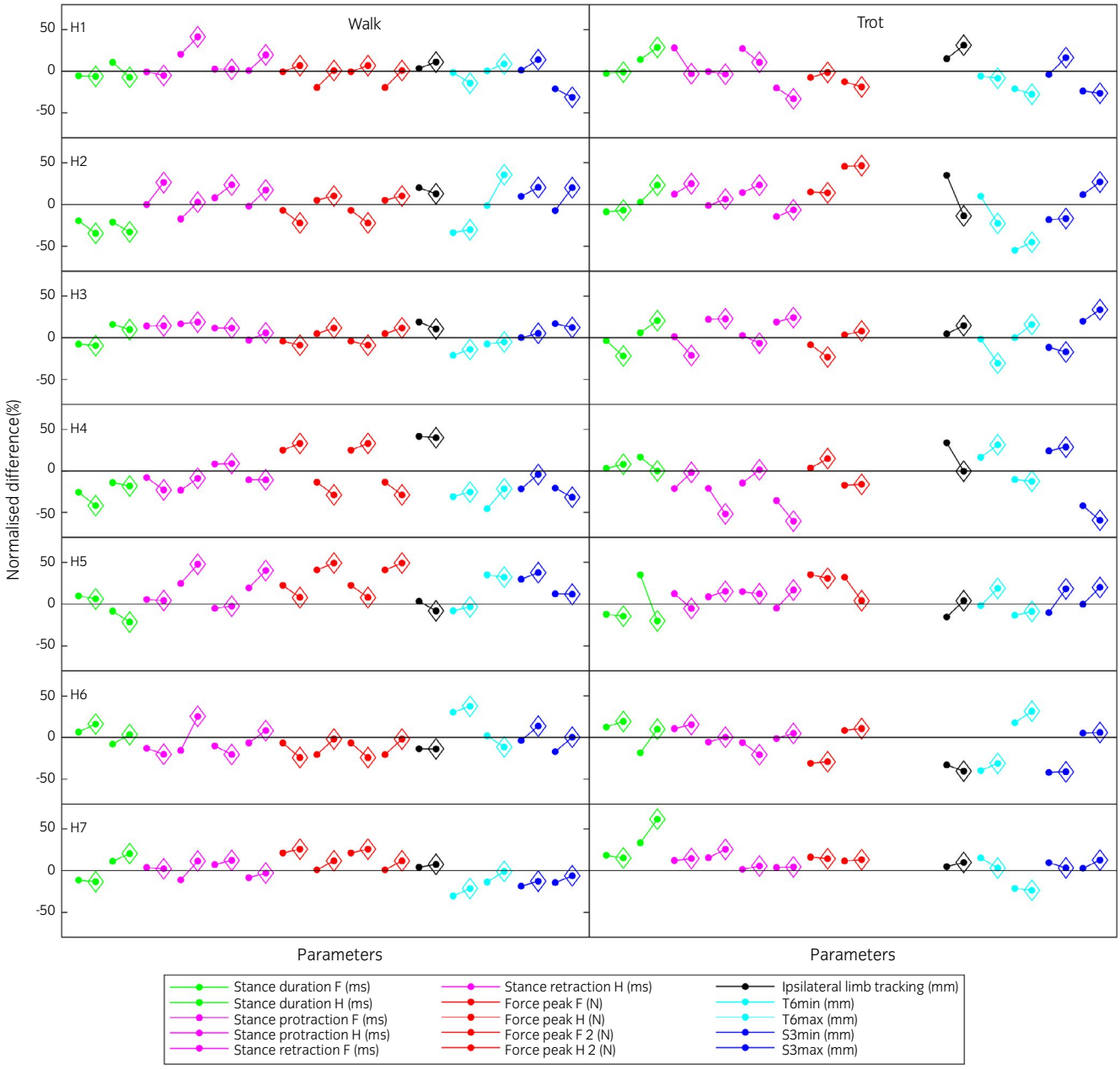

FIGURE 1 Direction and magnitude of left-right differences. Individual data points are mean values for difference parameters displayed by horse, by condition (unridden/ridden represented by the dots/dots within diamonds in each dumbbell), and by gait (left panel walk, right panel trot). Each point is a mean of 3-7 trial means. Positive values indicate a higher value on the left side. The values are normalised to the range of each difference in the data. For ipsilateral limb tracking, a positive difference indicated that the haunches tracked to the right of the shoulders

positive values indicating a higher value on the left (scales adjusted to allow visualisation in the same graph). Boxplots showing the mean differences by trial for the modelled variables are found in Figure S1.

There are similarities within horses across unridden/ridden conditions and also between gaits (Figure 1; Figures S2-S5). Taking Horse 1 as an example, hindlimb stance duration at walk is the only left-right difference that clearly changes sign between conditions, from being higher on the left when unridden to being higher on the right when ridden. At trot, there are no changes in direction of any of the differences in this horse. Comparing walk and trot in Horse 1, the left-right difference values for forelimb stance duration, ipsilateral limb tracking and T6 min appear similar between the two gaits. For the left wing of the atlas, 12 walk and 11 trot trials had insufficient data, either due to data loss (the atlas marker was obscured), or because of noncyclic neck movements, which usually involved trials at a slow walk. Atlas data distributions are found in Table S1 and Data S1.

3.2 | Model I

Absolute value asymmetry variables were analysed to study whether horses were more asymmetric in unridden or ridden conditions (Table 2, including back-transformed least square means; the

TABLE 2 Least square estimates and standard error of the mean (SE) from models of absolute asymmetry variables (left-right differences) analysed using square-root transformation and with unridden/ridden condition as a classification effect and speed as a continuous variable

	Unridden			Ridden			
	LSmean	SE	BT mean	LS mean	SE	BT mean	*P*-value
Walk							
Stance duration F (ms)	**3.01**	**0.43**	**9.04**	**3.65**	**0.44**	**13.29**	**.01**
Stance duration H (ms)	2.61	0.24	6.79	2.82	0.25	7.93	.31
Stance protraction F (mm)	**3.33**	**0.45**	**11.12**	**4.27**	**0.47**	**18.21**	**.01**
Stance protraction H (mm)	4.18	0.35	17.48	4.54	0.38	20.64	.28
Stance retraction F (mm)	**4.85**	**0.58**	**23.56**	**5.89**	**0.59**	**34.73**	**.01**
Stance retraction H (mm)	**3.21**	**0.51**	**10.29**	**4.20**	**0.53**	**17.65**	**.01**
Force peak 1 F (N/kg)	**0.41**	**0.05**	**0.17**	**0.49**	**0.05**	**0.24**	**.01**
Force peak 1 H (N/kg)	0.43	0.06	0.19	0.46	0.06	0.21	.27
Force peak 2 F[a] (N/kg)	0.36	0.04	0.13	0.39	0.04	0.15	.29
Force peak 2 H[a] (N/kg)	0.37	0.03	0.14	0.35	0.03	0.13	.67
Ipsilateral limb tracking (mm)	9.00	0.98	80.94	9.47	1.01	89.72	.48
T6 minimum (mm)	3.27	0.42	10.72	3.27	0.42	10.71	>.9
T6 maximum (mm)	1.75	0.31	3.08	1.85	0.32	3.42	.58
S3 minimum (mm)	2.40	0.32	5.75	2.55	0.33	6.50	.47
S3 maximum (mm)	1.87	0.16	3.51	1.86	0.16	3.47	>.9
Trot							
Stance duration F (ms)	**1.58**	**0.19**	**2.49**	**1.96**	**0.19**	**3.83**	**.01**
Stance duration H (ms)	1.76	0.24	3.11	1.81	0.25	3.29	.79
Stance protraction F (mm)	3.74	0.21	13.98	3.66	0.22	13.39	.79
Stance protraction H (mm)	**4.10**	**0.80**	**16.80**	**5.28**	**0.80**	**27.92**	**<.001**
Stance retraction F (mm)	4.07	0.51	16.56	4.22	0.52	17.83	.66
Stance retraction H (mm)	**4.49**	**0.84**	**20.16**	**5.24**	**0.84**	**27.47**	**.01**
Force peak 1 F (N/kg)	0.53	0.07	0.28	0.57	0.07	0.32	.24
Force peak 1 H (N/kg)	0.45	0.05	0.20	0.43	0.05	0.19	.59
Ipsilateral limb tracking (mm)	7.55	0.89	57.05	7.31	0.89	53.38	.66
T6 minimum (mm)	**1.94**	**0.27**	**3.76**	**2.53**	**0.27**	**6.38**	**.01**
T6 maximum (mm)	**3.01**	**0.39**	**9.04**	**3.34**	**0.39**	**11.15**	**.01**
S3 minimum (mm)	1.97	0.27	3.87	2.22	0.27	4.93	.08
S3 maximum (mm)	**2.49**	**0.47**	**6.21**	**3.42**	**0.48**	**11.68**	**<.001**

Note: Back-transformed least square means (BT mean) are the least square means back transformed to the original scale. In each model, there are data from seven horses, totalling 68 observations at walk and 61 observations at trot (data distributions found in Table S1). Significant differences in unridden/ridden conditions are shown in bold (Walds *P* value).

Abbreviations: F, forelimb; H, hindlimb.

[a]Trot variables are peak force and walk variables are second peaks respectively

distribution of analysed data is found in Table S1, including number of observations in each analysis). Speed (m/s) was significant with positive coefficients in three walk models: hindlimb force peak I (estimate 0.3 [SE 0.1] on the transformed scale, $P = .002$), T6min (estimate 1.7 (SE 0.5); $P = .001$) and S3max (estimate 1.1 [SE 0.5]; $P = .04$). Residual plots were considered adequate to good. At walk, there were five significant differences (15 evaluated), all pointing towards increased asymmetry while ridden. At trot, there were six significant differences (13 evaluated) all indicating greater asymmetry while ridden. In addition, the atlas data available for analysis indicated that at trot the minimum was more asymmetric in unridden condition, 15 mm than in ridden condition, 8 mm ($P = .01$, Data S1).

3.3 | Model II

To investigate whether asymmetries were correlated between gaits, associations were sought between values for the same left-right

TABLE 3 Estimates and standard error of the mean (SE) obtained by modelling the same left-right difference variables at walk (left side of table) and trot (right side of table) as untransformed-dependent variables

		Dependent variable					
		Walk			Trot		
	Ridden	Estimate	SE	*P*-value	Estimate	SE	*P*-value
Stance duration F (ms)	No	0.190	0.613	.76	0.070	0.054	.21
	Yes	0.621	0.485	.21	0.040	0.041	.34
Stance duration H (ms)	No	0.101	0.369	.79	−0.013	0.087	.88
	Yes	0.250	0.277	.37	**0.224**	**0.090**	**.02**
Stance protraction F (mm)	No	**−0.438**	**0.217**	**.05**	0.348	0.196	.08
	Yes	0.394	0.204	.06	−0.032	0.111	.77
Stance protraction H (mm)	No	0.268	0.200	.19	−0.241	0.197	.23
	Yes	0.062	0.115	.59	0.066	0.171	.70
Stance retraction F (mm)	No	−0.064	0.202	.75	−0.258	0.161	.12
	Yes	**0.737**	**0.202**	**.01**	0.113	0.088	.21
Stance retraction H (mm)	No	0.192	0.176	.28	−0.465	0.244	.06
	Yes	0.171	0.107	.12	0.254	0.152	.10
Force peak 1 F (N/kg)	No	0.179	0.125	.16	−0.006	0.231	>.9
	Yes	0.215	0.126	.10	0.177	0.161	.28
Force peak 1 H (N/kg)	No	−0.276	0.161	.09	0.010	0.124	>.9
	Yes	−0.143	0.187	.45	**−0.323**	**0.113**	**.01**
Force peak 1 F (N/kg)[a]	No	0.117	0.091	.21	0.060	0.224	.79
	Yes	−0.005	0.090	>.9	−0.101	0.209	.63
Force peak 1 H (N/kg)[a]	No	0.073	0.125	.56	0.122	0.171	.48
	Yes	0.150	0.146	.31	0.014	0.191	>.9
Ipsilateral limb tracking (mm)	No	0.042	0.124	.74	**0.642**	**0.223**	**.01**
	Yes	0.158	0.123	.21	0.038	0.189	.84

Note: Each model has data from seven horses, totalling 55 observations (data distributions found in Table S1). There are four (in one case three) observations from each horse and condition. Data were speed-paired: trials with the lowest and highest speeds at walk and trot were paired, as well as the two speeds closest to the median. Grey shading implies that the respective interactions with unridden/ridden conditions were significant and significant slopes are bolded (both Walds *P* value).

Abbreviations: F, forelimb; H, hindlimb.

[a]Trot variables are peak force and walk variables are second peaks.

asymmetry at walk and trot. The full dataset contained 55 observations (for one horse in one condition, there were only three trials, Table S1 includes information on missing values). The interaction between the asymmetry variable and unridden/ridden condition was significant in two trot and six walk models (shaded grey in Table 3). A significant association between gaits was found for five variables (bolded in Table 3). In three of these five variables, the estimates were positive, suggesting that the respective asymmetries increased or decreased together. For example, in ridden condition, the larger the left-right difference in hindlimb stance duration at walk, the larger the same difference at trot [1 ms difference at walk predicts 0.22 ms difference at trot]. Reversing the direction of prediction, a 1 ms difference at trot predicts a 0.25 ms difference at walk, but this association was clearly nonsignificant. Speed was nonsignificant in all models and is therefore not included. Residual plots were considered adequate to good.

4 | DISCUSSION

4.1 | Influence of a rider on equine movement symmetry

The current design compares conditions representing two everyday practical situations: the horse moving freely (in the field or in hand) vs when ridden between the aids in a dressage frame, that

is under the rider's active influence. Confirming our hypothesis, the horses moved more asymmetrically when ridden, although increases were small. Changes associated with removal of the handler and addition of the rider, that could influence movement symmetry, included the saddle, the rider's weight, the rider's postural asymmetries, the rider's aids, the horse-rider relationship, and a specific head and neck position of the horse. The interplay between these factors could not be addressed in this study. Previous studies have looked at the effect on horse symmetry of some of these factors in isolation. At trot, but not at walk, loading the horse with ≥25% of bodyweight led to increased gait asymmetry in ponies.17 Symmetry was measured at the sternum, and the results of that study are therefore in agreement with the increased T6 asymmetry we found (Table 2). In another study, a skilled rider but not a novice rider made the vertical movement (acceleration) of the horse's sacrum at trot more asymmetric compared with unridden condition.18 Similarly, in the present study using highly experienced riders, the vertical movement of the horse's sacrum (S3) became clearly more asymmetric with a rider at trot (Table 2). Asymmetry in the interface between horse and rider has also been measured but has been shown to be influenced by both parties.20,21

Without addressing the effect on symmetry, studies have found that the kinetics and kinematics of horses are influenced by weight load,22-25 the rider's skill level,18,26 tack27-29 and the horse's head and neck position.30,31 At walk and trot, GRFs increased if the horse was loaded with dead weight or a rider.22,23 Both studies suggest that the rider effect was not equivalent to that of added weight. At trot, a prolongation of stance duration allowed a longer time to generate the vertical impulse required to support the additional weight.24 De Cocq and co-authors27 found greater extension of the horse's back with a lead-loaded saddle, compared with no saddle or an unloaded saddle. Compared with an unrestrained position, a more restricted head and neck position was associated with a shortened stride length at walk but not at trot in both unridden and ridden horses.30-32 Schöllhorn and co-authors26 found rider-specific patterns for head angles when two riders rode 14 horses—the rider's aids being a probable reason for the patterns. These diverse effects of the rider's weight and aids on the horse's movement pattern makes it likely that the rider will also influence horse symmetry at least to some extent, as was found in the current study.

4.2 | Magnitudes of rider-related asymmetries vs lameness

The asymmetry magnitudes in Table 2 can be compared with published studies of lameness. For example, hindlimb retraction differences at trot increased from 20 mm (unridden) to 27 mm (ridden). Weishaupt and co-authors33 found similar differences of 6-53 mm in horses with mild to more severe hindlimb lameness. Differences in minimum and maximum vertical height between left and right steps for the head and croup (and sometimes also the withers) are frequently used to quantify lameness at trot,34 but only limited data are available for these parameters at walk.2 At trot, asymmetries were 6 mm (unridden) vs 12 mm (ridden) for sacrum vertical maximum, 4 mm (unridden) vs 6 mm (ridden) for withers minimum and 9 mm (unridden) vs 11 mm (ridden) for withers maximum. In a study on induced lameness, similar values were found in the horses not only before induction, but also for the increases in asymmetries when lameness was induced.35 In our study, the rider's weight increased peak vertical force asymmetry only at walk (Table 2). The left-right differences in first forelimb force peak correspond to 3% and 4% of peak force values (which are approximately 6.5 N/kg at walk) respectively in the unridden and ridden conditions. For comparison, reported forelimb force peak differences at trot were 4% and 9% for mild and moderate lameness.36 To summarise, the increases in asymmetry observed with the riders in the current study were small. We believe differences between unridden and ridden conditions to be below the general detection limit of humans.37 However, the increase in asymmetry with a rider may, in some cases, make an asymmetry just large enough to be perceived by skilled clinicians. Changes between unridden and ridden conditions were analysed using absolute values, but few horses/variables changed in asymmetry direction between ridden and unridden conditions (Figure 1; Figures S1-S4), indicating consistent sidedness patterns on an individual level.

4.3 | If not lameness, why more asymmetry with a rider?

The horses in this study were deemed clinically sound, were in active dressage training and were performing to their riders' satisfaction. Together this suggests that the measured asymmetries in these horses were not pain-related, even if a connection to past or present injuries cannot be fully excluded. Low-grade asymmetries are common in sport horses,9 and laterality has been discussed as one of several possible causes.38 Equine motor laterality has been reported in foals and unhandled youngsters14 and seems to increase with age.39 Motor laterality in horses has been associated with preferences for canter strike-off40 and derailment, which is the tendency to cut across a circle rather than following the circumference.39 However, a connection to kinematic left-right step asymmetry has not been investigated.

It is possible that the rider influences the horse in an asymmetric way, since even skilled riders display postural and kinematic asymmetries,41,42 and riders tend to distribute their weight asymmetrically over the left and right tuber ischia.39 Furthermore, riders apparently have difficulty detecting horse asymmetry while riding44 and that the horse becomes more asymmetric with a rider may be a potential health concern, regardless of whether the asymmetry is caused by the rider's weight or the rider's aids. Carefully designed longitudinal studies with enough subjects are needed to evaluate whether this is a health concern. This study suggests variables that could be used to evaluate a horse's symmetry and straightness of movement both ridden and unridden, but further studies are required to confirm any relationship to laterality.

4.4 | Walk vs trot

It has previously been shown that walk kinematics predict trot kinematics. For example, stride duration at walk predicted stride duration at trot.45 This study evaluated whether asymmetries in either walk or trot would predict the presence and direction of asymmetry in the same parameter in the other gait. In most cases, the association between gaits was similar between unridden and ridden conditions. Only 8 of 22 comparisons showed a significant interaction between unridden/ridden conditions (grey in Table 3). There were five significant associations between gaits, but never for the same variable with both walk and trot as dependent variable. Two of the significant slopes were found for the unridden condition. In two cases, the estimates were negative, suggesting reverse associations for forelimb stance protraction (walk as dependent variable) and the first force peak in the hindlimb (trot as dependent variable). For example, in the unridden condition, the model suggests that increased forelimb stance protraction on the *left* side at trot will be associated with increased forelimb stance protraction on the *right* side at walk. In summary, we did not find strong positive associations between walk and trot asymmetries, perhaps because of the different mechanics involved: inverted pendulum mechanics during walking and spring mass mechanics during trotting. This is in contrast to what has previously been found for lameness in which a limited number of strategies are available for unloading the painful limb.2

Asymmetry related to lameness is (usually) a clinical sign of pain avoidance, which can make asymmetries more consistent between gaits. Due to the higher speed and forces involved at trot, a small asymmetry at walk will generally correlate with a higher degree of asymmetry at trot in a lame horse.2 In contrast, laterality-related asymmetries are likely to have been perpetuated through habitual use, perhaps with resultant weakness and/or stiffness in various musculoskeletal structures.38 This makes it less predictable how gaits with different movement patterns or ranges of motion will be affected, and typical biomechanical patterns related to laterality have not been described in the scientific literature.38 However, all significant changes with a rider point towards increased asymmetry, even though increases were generally small. The analysis was made over all three variable categories (kinetic, spatiotemporal and kinematic), and in both gaits. This, in accordance with a previous study,18 suggests that the increase in asymmetry with skilled riders is a repeatable finding. We suggest that it may be useful to monitor asymmetry quantitatively and objectively in horses during training, since riders are known to have difficulties in detecting and/or correcting asymmetries in a merely intuitive fashion.46

4.5 | Strengths and limitations of the study

An important limitation of this study is the low number of horses. Studies on larger populations including different ages and stages of training are needed to determine the degree of general applicability. Furthermore, skin markers were used, which are inherently prone to skin displacement errors. However, if the same marker locations are used, valid comparisons can be made between conditions.47 Furthermore, data were collected during treadmill locomotion which is not identical to over ground locomotion.48 Studying horses first in unridden condition and then in ridden condition may introduce systematic bias. In a study of asymmetry in unridden riding horses trotting overground, it was found that between-trial variation was larger on the first of two consecutive days.49 However, in the current study, the latter effect was likely not of major influence as horses were trained on the treadmill, both with and without rider, for several days before the recorded trials. The strength of this study was the large number of asymmetry variables that were analysed including movements in transverse, longitudinal and vertical directions, in combination with vGRF. Nevertheless, the (long-term) biological significance of the detected asymmetries remains to be addressed. The results for poll (atlas) movement asymmetries must be interpreted with considerable caution, in part because data quality was not optimal and therefore a number of trials had to be discarded, and also because the effects of rein tension applied in the ridden condition could conceivably affect head motion (a)symmetry [c.f. 20]. Rider kinematics were not evaluated in this analysis. *P* value correction for multiple comparisons was not applied, as statistical power was reduced through analysis of trial level data rather than stride level data.

5 | CONCLUSIONS

Sound, high-level dressage horses walked and trotted slightly more asymmetrically when ridden between the aids in a dressage frame compared with when moving freely in an unrestrained position.

ETHICAL ANIMAL RESEARCH

The study protocol was approved by the Animal Health and Welfare Commission of the canton of Zürich (188/2005).

OWNER INFORMED CONSENT

Horse owners gave verbal consent for the study.

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AUTHOR CONTRIBUTIONS

The study used data originally collected by L. Roepstorff, M. Rhodin, R. van Weeren and M.A. Weishaupt. Data were first organised by A. Byström, L. Roepstorff and M.A. Weishaupt. The present analyses was made by A. Byström and A. Egenvall. The paper was written by A. Byström, H. M. Clayton and A. Egenvall with support of all authors, who all gave their final approval of the manuscript.

CONFLICT OF INTERESTS

None of the authors has any financial or personal relationships that could inappropriately influence or bias the content of the paper.

DATA ACCESSIBILITY STATEMENT

The data are provided at https://doi.org/10.6084/m9.figshare.11432943.v1.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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