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Comparison of speed-dependent time, force and spatial parameters between Franches-Montagnes and European Warmblood horses walking and trotting on a treadmill

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ABSTRACT

Speed alterations affect many gait analysis parameters. How horses adapt to speed is relevant in many equestrian disciplines and may differ between breeds. This study described changes in gait parameters in 38 Warmblood (WB) and 24 Franches-Montagnes (FM) horses subjected to an incremental speed test at walk (1.35–2.05 m/s) and trot (3.25–5.5 m/s). Time, force and spatial parameters of each limb were measured with an instrumented treadmill and analysed with regression analysis using speed as the independent variable. With higher speeds, stride rate, length, over-tracking distance and vertical ground reaction forces increased while the impulses decreased. The parameters followed the same linear or polynomial regression curves independent of breed, while the slope (linear) or incurvation (polynomial) often differed significantly between breeds. Some differences between the breeds were associated with height and speed (e.g. stride length at walk), and would disappear when scaling the data. The main differences between the breeds seem to stem from the movement of the hind limbs, with the FM obtaining long over-tracking distances despite the shorter height at withers. Some parameters relevant to gait quality could be improved in the FM to resemble WB movement by strict selection using objective measurements systems.

1. Introduction

A major interest in the domestication and breeding of horses is their capacity for variation in their movement patterns, both between and within gaits. To increase their traveling speed, horses have been shown to adapt specific time, force and spatial parameters, such as stride length, stride and stance duration, limb impulses and peak vertical ground reaction forces within a gait [1–5], until a combination of musculoskeletal force levels [6–8], metabolic cost of movement [7–10], and potentially an unsustainably high inter-stride variability [11,12] would induce an animal to switch gaits.

Consistently with higher speeds, limb impulses, stride and stance duration (absolute and relative, i.e. duty factor) decreased, while stride length, vertical ground reaction forces and stride frequency (in Hz) increased, at least towards the peak speed of the horse [1–5,13,14]. However, it is not understood in what proportion the individual parameters change depending on the breed or the discipline. In many equestrian disciplines, one performance indicator is the ability to increase the travel speed while staying in the same gait. Dressage horses for example that were being ridden from a collected (slow) to an extended walk [15], trot [16] or canter [17], were becoming faster through an increase in stride length, while maintaining cadence, i.e. keeping a similar stride rate [18]. Racehorses, whether for harness (trotters, pacers) or flat races (gallopers), must remain in the same gait during the competition and increase both stride length and stride rate to win. At a high-speed gallop, Thoroughbred horses winning high-class flat races took fewer strides in general, and only increased stride rate in the final section of the race [19]. Therefore, how horses adapt to an increase in speed is relevant when breeding for various equestrian disciplines.

In Switzerland, three-year old WB horses have to pass a field test, during which they are shown in hand, ridden in the three gaits and pass

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a free jumping test. The height at withers should be at least 160 cm [20]. In contrast, the Franches-Montagnes (FM), the last native horse breed of Switzerland and one of the last light European draught breeds, should have a height at withers between 150 and 160 cm, and pass a carriage driving test instead of a free jumping test during their field test [21].

In Warmblood (WB) horses, time, force and spatial parameters have been analysed in relation to speed using an instrumented treadmill [5]. The aim was to establish normative standards for Warmblood horses. European WB horses are used in leisure riding and competitions, mainly in the equestrian disciplines of dressage and show jumping, and the breeding goals and selection processes are adapted to the requirements of these disciplines. Few studies have concentrated on the driving discipline, but there were some differences in the stride length, over-tracking distance and swing duration when horses were driven [22]. This may indicate that the biomechanical demands for draught horses are slightly different from those of riding horses. Since the 1970′s, WB stallions have been introgressed into the FM population to breed for a lighter type of leisure horse, and many breeders consider the movements of WB horses as the goal to achieve with regards to gait quality. However, the biomechanics of the two breeds have not been compared objectively and gait quality traits are notoriously subjective. Objective parameters that have been previously associated with gait quality or sports performance, such as stride rate, stride length, over-tracking distance, suspension duration and time of advanced placement (at trot) could be used to improve gait quality [18,23–25].

This study aimed to determine how time, force and spatial parameters respond to changes in speed in sound FM breeding stallions compared to WB leisure horses at walk and trot during an incremental speed test on a treadmill. A further aim was to investigate how parameters associated with gait quality compared between FM and WB horses. We hypothesised that the time, force and spatial parameters would behave analogously, but with different linear regression slopes, and that the WB would show lower stride rates, longer strides, over-tracking distances, suspension duration and time of advanced placement at trot, as WB are considered better "movers".

2. Material and methods

2.1. Animals

This dataset was composed of two separate studies on sound horses (WB and FM horses).

2.2. Warmblood horses

The first dataset, detailed in Weishaupt et al. [5], consisted of 38 sound WB horses. The horses competed in jumping and dressage events of different levels. The experimental protocol had been approved by the Animal Health and Welfare Commission of the Canton of Zurich.

The horses were accustomed to walk and trot on the treadmill and trained to easily adjust their speed of movement to a range of velocities within each gait, following the guidelines of Buchner et al. [26]. After the habituation phase, the horses were measured on the high-speed instrumented treadmill (Mustang 2200) extracting time, force and spatial variables [27] at the Equine Performance Lab of the University of Zurich. The walking speeds ranged from 1.1 to 2.1 m/s at 0.1 m/s increments, and the trotting speeds from 2.5 to 5.8 m/s at 0.3 m/s increments. Horses were measured for 30 s at steady state, with a sampling frequency of 433 Hz. For more details, refer to Weishaupt et al. [5].

2.3. Franches-Montagnes horses

The second dataset included 24 sound FM breeding stallions which were part of a larger project quantifying objective kinematic parameters determining gait quality traits in the FM horse breed [24,25]. Most (20 out of 24) horses were regularly ridden or driven in competitions up to the international level (for driving). The experimental protocol was approved by the Animal Health and Welfare Commission of the canton of Vaud (permission number VD 3164, approved 17.08.2016).

After a similar habituation to the treadmill as the Warmblood horses, the stallions were measured on the same high-speed instrumented treadmill (Mustang 2200) as the other dataset [5]. The walking speed ranged from 1.4 to 2.0 m/s at 0.1 m/s increments; the trotting speeds were 3.3, 4.0, 4.5, 5.0, 5.5, 6.0 and 6.5. The speeds which all FM stallions reached were 1.7 and 1.8 m/s at the walk and 3.3, 4.0, 4.5 and 5.0 m/s at the trot. The stallions were measured during 20 s for each speed increment at 400 Hz. For more details, refer to Gmel et al. [24,25].

2.4. Data processing

For both datasets, the time, force and spatial parameters measured by the instrumented treadmill were calculated by the treadmill software (HP2) [27]. Temporal parameters were normalised as a percentage of stride duration. Force and impulse parameters were normalised to the horses' body mass as Newton per kg body mass. Stride segmentation was performed using the hoof-on moments of the left forelimb as previously described [27]. Data of contralateral limbs were pooled as all horses were sound based on the evaluation of a clinical expert (MAW) during the warmup phase before the measurements took place. To improve the comparability between the two datasets, the data were cut for both breeds to the overlapping speed range of $1.35 < \text{walk speed} < 2.05$ m/s and $3.25 < \text{trot speed} < 5.55$ m/s accounting for minor belt speed variation. The number of measurements at each speed increment are represented in Supplementary Fig. S1.

2.5. Parameter selection

We selected the time, force and spatial parameters first investigated by Weishaupt et al. [5]. Certain parameters were only determined at the walk: diagonal step duration, ipsilateral step duration, overlap duration of tripedal support – 2 fore-, one hind limb, overlap duration of lateral bipedal support, overlap duration of tripedal support – 2 hind-, one forelimb, overlap duration of diagonal bipedal support. There were three parameters describing the vertical force curve at walk: first vertical force peak; second vertical force peak and the vertical force dip. At the trot, there was only one vertical force peak. Additionally, the following time parameters at the trot were determined: suspension duration, time of advanced placement and time of advanced completion. We excluded the previously considered parameters related to stance length and step width from the analysis, which have no relevance for either gait quality or lameness evaluations. The Froude number, a dimensionless value considering both speed and height of an animal, was calculated as follows: $\frac{speed}{\sqrt{wither's\ height\ \times g}}$.

2.6. Data transformation and analysis

Further analyses were based on "mean-normalised data" as in Weishaupt et al. [5]: for each parameter, gait and horse, the mean value over the full range of velocities was computed and the speed-dependent changes were expressed as delta values to this mean (ΔVar). Delta velocities (Δv) were calculated in the same way. This procedure enabled the investigation of the speed dependence of each parameter within a breed regardless of the individual levels of the absolute data. To understand the relationship between mean normalised parameters and speed for each breed, the best matching regression function (linear or second-order polynomial) was determined visually from the residual plots, and based on the coefficient of determination (R^2).

Statistical analyses and visualisations were performed in Matlab (version R2022b). To highlight differences between breeds, the variables' mean across all speeds were compared with a t-test. Level of significance was set at $p < 0.05$. To account for scaling differences between the two breeds, the mean value for each variable was interpolated at the common mean Froude number for each breed and also compared using a t-test. The common mean Froude number was the mean of the overlapping Froude numbers between both breeds.

3. Results

The FM sample was slightly older, approximately 10 cm shorter and less heavy than the WB sample (Table 1). The FM sample contained only breeding stallions, whereas the WB sample consisted of one stallion, 28 geldings and 9 mares.

3.1. Walk

At the mean across all speeds for walk, most of the parameters were significantly different between breeds (Table 2). The FM group had a faster mean speed, higher stride rate and shorter stance duration than the WB. Due to the shorter stride duration, the vertical impulses were also lower for the FM, though the peak vertical forces were generally higher. The FM had a higher proportion of vertical impulse on the forelimbs. The vertical force dip was higher for the forelimbs but lower for the hind limbs. The overlap duration was longer during lateral and diagonal bipedal support for the FM than WB, which had longer tripedal support phases. The absolute stride length was shorter in the FM compared to the WB but was significantly longer when normalised to wither's height. Both the absolute and normalised over-tracking distance were longer for the FM than for the WB.

When comparing the means of the variables at the mean common Froude number (adjusting for withers' height and speed), most of the variables were not significantly different between breeds. At the common Froude number, the FM had significantly higher stride rate, shorter absolute stance duration, longer overlap duration of lateral bipedal support, lower proportion of diagonal vertical impulse carried by the forelimbs, higher first force peak and force dip in the front limbs than WB. At the mean common Froude number, the absolute stride length was shorter for FM than WB, but the height-normalised stride length was equal between the two breeds.

The parameters consistently followed either a linear or second-order polynomial regression for both breeds (Table 3, Fig. 1). With increasing speed, stride rate, the overlap duration of the lateral bipedal support, the mean vertical force during stance duration (front and hind limbs), the first vertical force peak in the front and hind limbs, the second vertical force peak of the forelimbs, stride length, height-normalised stride length, over-tracking distance and height-normalised over-tracking distance increased, while the other parameters decreased. Only few parameters followed a second-order polynomial regression: the relative stance duration, the overlap duration of tripedal support phases, the overlap duration of the lateral bipedal support, the proportion of diagonal vertical impulse carried by the forelimbs, the mean vertical force during stance duration in the forelimbs, the second vertical force peak in the front and hind limbs, and the absolute and height-normalised over-tracking distance. The absolute stride length followed a polynomial regression, but the height-normalised stride length was linear. Generally, the coefficients of determination (R^2) were higher for WB than for FM, except for the diagonal and ipsilateral step duration, the forelimb impulse, the second vertical force peak of the hind limbs and stride length (Table 3). Most models were significant ($p < 0.05$), except for the diagonal step duration (both breeds), the ipsilateral step duration (both breeds), and the mean vertical force in the hind limbs (FM), meaning that these parameters were independent of speed. The first order regression slopes were mostly steeper in absolute values for WB than for FM, except in the case of speed independent variables (diagonal and ipsilateral step duration) and for the first vertical force peak, the second vertical force peak (only in the front limbs), the vertical force dip and the height-normalised stride length. The second order regression curves were more strongly bent for FM than WB, meaning that the FM reached their minima or maxima earlier than the WB (Fig. 1).

Table 1
Sampling-related differences in age, height at withers, and body weight between the Warmblood (WB) and Franches-Montagnes (FM) datasets using a t-test.

Variable	FM	WB	Mean difference	p-value
Age (y)	8.8 ± 4.1	7.2 ± 3.4	1.6	0.16
Height at withers (m)	1.57 ± 0.03	1.68 ± 0.06	0.11	0.00
Body weight (kg)	526.3 ± 32.7	565.0 ± 51.8	38.7	0.00

3.2. Trot

On average across all trotting speeds, FM were faster, with higher Froude number, higher stride rate and shorter absolute stance duration especially in the hind limbs (Table 4). The relative stance duration (duty factor) however, was significantly different in the front limbs (higher in FM than WB) and equivalent in the hind limbs. The time of advanced placement was shorter in FM but time of advanced completion was longer. This means that on average the hind limb of the FM touched the ground before the diagonal front limb but slightly later during the stride than in WB (shorter time of advanced placement) and left the ground earlier (longer time of advanced completion), leading to a shorter absolute stance duration in the hind limbs. The suspension duration was slightly shorter in the FM than the WB. Similar to the walk, with a shorter stance duration, the vertical impulse was lower for FM than WB. However, mean vertical force during stance duration and the vertical force peak were not significantly different between the two breeds. Absolute stride length was shorter in FM than WB, but height-normalised stride length was shorter in WB than in FM. Both absolute and height-normalised over-tracking distance were longer in FM than WB.

At the common interpolated Froude number, FM still had a significantly higher stride rate, shorter absolute stance duration of the hind limbs, and relative stance duration (duty factor) of the front limbs. The relative stance duration of the hind limbs was also significantly higher in FM at the same Froude number. There was no significant difference for time of advanced placement and time of advanced completion between FM and WB at the same Froude number, however, the standard deviation was very high in both breeds. The suspension duration remained significantly shorter for FM than WB. The total vertical stride impulse was significantly higher in WB than FM, and impulse in both front and hind limbs were higher for WB, although only statistically significant in the front limbs. However, there was no significant difference in the proportion of diagonal vertical impulse carried by the forelimbs. The vertical force peak at the common Froude number was significantly different only in the front limbs (higher in the WB), but not in the hind limbs. Absolute and height-normalised stride length were longer in the WB than the FM, and there was no significant difference in over-tracking distance (absolute or height-normalised) between the two breeds.

The regression functions for all but one parameter were significant and followed the same patterns in both breeds (Table 5, Fig. 2). Time of advanced completion was not significant for FM and appeared independent of speed, whereas for WB this parameter followed a linear regression function with a determination coefficient of $R^2 = 0.51$. The stride rate, time of advanced placement, suspension duration, proportion of diagonal vertical impulse carried by the forelimbs, mean vertical force (front and hind), vertical force peak (front and hind), stride length, height-normalised stride length, over-tracking distance and height-normalised over-tracking distance increased with speed while the other parameters decreased. For WB, the proportion of diagonal vertical impulse carried by the forelimbs had the lowest coefficient of determination ($R^2 = 0.36$), suggesting that speed had only a very small effect on that parameter in this breed. The absolute and relative stance duration

Table 2
Summary statistics of the time, force, and spatial variables at walk for both breeds (mean ± standard deviation), and at the interpolated Froude Number 0.431. Unless stated differently, time parameters are expressed as percentage of stride duration (%SD). Significant differences between the means were investigated using a t-test.

Variable	Abbreviation	Concerned limbs	Mean across all speeds		Interpolated at Froude N:0.431	
			FM	WB	FM	WB
Speed [m/s]	V	-	1.73 ± 0.15***	1.66 ± 0.18***	-	-
Froude Number	FRN	-	0.44 ± 0.04***	0.41 ± 0.04***	-	-
Stride rate [1/min]	SR	-	55.13 ± 3.64***	51.46 ± 3.78***	54.93 ± 3.45 *	52.80 ± 3.30 *
Stance duration [s]	StD_{abs}_front	Forelimbs	0.68 ± 0.05***	0.74 ± 0.07***	0.69 ± 0.04*	0.71 ± 0.05*
	StD_{abs}_hind	Hind limbs	0.67 ± 0.04***	0.73 ± 0.06***	0.67 ± 0.03***	0.71 ± 0.04***
Duty factor (StD_{abs} relative to the stride duration) [%SD]	StD_{rel}_front	Forelimbs	62.27 ± 1.36**	62.85 ± 1.66**	62.50 ± 0.83	62.04 ± 1.09
	StD_{rel}_hind	Hind limbs	61.38 ± 1.14***	62.57 ± 1.21***	61.62 ± 1.28	62.10 ± 0.99
Diagonal step duration [%SD]	$StpD_{diag}$	Diagonal limbs	25.70 ± 2.02	26.02 ± 1.93	25.51 ± 2.41	26.18 ± 1.81
Ipsilateral step duration [%SD]	$StpD_{ipsi}$	Ipsilateral limbs	24.30 ± 2.03	23.98 ± 1.93	24.48 ± 2.42	23.82 ± 1.81
Overlap duration of tripedal support – 2 fore-, one hind limb [%SD]	OD_{2F1H}	Tripedal support	11.37 ± 1.14***	12.57 ± 1.22***	11.60 ± 1.27	12.10 ± 0.98
Overlap duration of lateral bipedal support [%SD]	OD_{lat}	Ipsilateral support	13.43 ± 2.57	13.17 ± 2.69	13.03 ± 2.53	14.14 ± 2.22
Overlap duration of diagonal bipedal support [%SD]	OD_{diag}	Diagonal support	12.98 ± 1.74***	11.40 ± 1.83***	12.94 ± 1.95 *	11.72 ± 1.55 *
Overlap duration of tripedal support – 2 hind-, one forelimb [%SD]	OD_{2H1F}	Tripedal support	12.25 ± 1.37***	12.85 ± 1.66***	12.47 ± 0.85	12.04 ± 1.08
Vertical stride impulse (sum of the 4 vertical limb impulses during an entire motion cycle) [Ns/kg]	Iz_{SD}	Sum of all limbs	10.85 ± 0.71***	11.50 ± 0.84***	10.89 ± 0.70	11.20 ± 0.68
Vertical limb impulse [Ns/kg]	Iz_front	Forelimbs	3.21 ± 0.23***	3.34 ± 0.23***	3.23 ± 0.26	3.26 ± 0.18
	Iz_hind	Hind limbs	2.21 ± 0.16***	2.41 ± 0.21***	2.22 ± 0.12**	2.34 ± 0.18**
Proportion of diagonal vertical impulse carried by the forelimbs [%Iz_{SD}]	Iz_{fore}	Forelimbs	59.26 ± 1.58***	58.11 ± 1.17***	59.22 ± 1.64 *	58.29 ± 1.17 *
Mean vertical force during StD [N/kg]	Fz_{mean}_front	Forelimbs	4.69 ± 0.21***	4.54 ± 0.16***	4.67 ± 0.18	4.61 ± 0.12
	Fz_{mean}_hind	Hind limbs	3.27 ± 0.12	3.28 ± 0.11	3.26 ± 0.12	3.30 ± 0.11
First vertical force peak [N/kg]	Fz_{P1}_front	Forelimbs	6.00 ± 0.31***	5.68 ±0.26***	5.91 ± 0.32*	5.75 ± 0.21*
	Fz_{P1}_hind	Hind limbs	5.11 ± 0.48***	4.79 ± 0.45***	4.99 ± 0.30	4.99 ± 0.23
Second vertical force peak [N/kg]	Fz_{P2}_front	Forelimbs	7.15 ± 0.46***	6.76 ± 0.39***	7.11 ± 0.42	6.93 ± 0.34
	Fz_{P2}_hind	Hind limbs	4.46 ± 0.29	4.43 ± 0.28	4.51 ± 0.24	4.48 ± 0.28
Vertical force dip [N/kg]	Fz_{dip}_front	Forelimbs	5.13 ± 0.40**	4.97 ± 0.38**	5.16 ± 0.25***	4.88 ± 0.35***
	Fz_{dip}_hind	Hind limbs	2.43 ± 0.33***	2.75 ± 0.40***	2.49 ± 0.23	2.53 ± 0.16
Stride length [m]	SL	-	1.89 ± 0.14**	1.93 ± 0.17**	1.86 ± 0.12**	1.99 ± 0.13***
Height-normalised stride length	SL_{norm}	-	1.20 ± 0.08***	1.15 ± 0.10***	1.18 ± 0.07	1.19 ± 0.08
Over-tracking distance [m]	OTD	-	0.29 ± 0.12***	0.23 ± 0.14***	0.26 ± 0.12	0.28 ± 0.11
Height-normalised over-tracking distance	OTD_{norm}	-	0.18 ± 0.08***	0.14 ± 0.08***	0.17 ± 0.08	0.17 ± 0.07

* $p < 0.05$,
** $p < 0.01$,
*** $p < 0.001$

for front and hind limbs, time of advanced placement, suspension duration, mean and peak vertical force of the front limbs were following a second order polynomial regression. The curves of the mean and peak vertical force of the front limbs and the impulse of the hind limbs were not statistically different between the two breeds. The mean and peak force of the hind limbs had steeper slopes for FM, while for the vertical stride impulse and the vertical front limb impulse the slopes were steeper for WB. The linear increase in stride rate, absolute and normalised stride length and over-tracking distance was slightly but significantly steeper in WB than FM.

4. Discussion

In agreement with our hypotheses, nearly all parameters followed the same linear or polynomial regression curves independent of breed, while the slope (linear) or incurvation (polynomial) were significantly different between breeds. The only exception was time of advanced completion which was seemingly independent of speed in FM, but presented with considerable standard deviations suggesting that this effect could have been mitigated with additional data. The coefficients of determination were generally higher in the WB than the FM group as

Table 3
Functional relationship of time, force, spatial and kinematic variables to speed at walk. Unless stated differently, time parameters are expressed as percentage of stride duration (%SD). The dependent and independent variables are expressed as differences to the respective mean (ΔVar, Δv).

Variable	FM				WB			
	a_0	a_1	a_2	R^2	a_0	a_1	a_2	R^2
SR	0.00	10.416***		0.70	0.00	14.175***		0.90
StD_{abs}_front	0.00	-0.221***		0.85	0.00	-0.299***		0.94
StD_{abs}_hind	0.00	-0.186***		0.89	0.00	-0.247***		0.94
StD_{rel}_front	-0.117	-8.119	7.813*	0.94	-0.089	-8.075	3.147*	0.96
StD_{rel}_hind	-0.164	-5.201***	10.946*	0.68	-0.155	-3.700***	5.478*	0.79
$StpD_{diag}$	0.00	1.606***		0.05	0.00	-0.719***		0.02
$StpD_{ipsi}$	0.00	-1.564***		0.05	0.00	0.716***		0.02
OD_{2F1H}	-0.162	-5.231***	10.795	0.67	-0.155	-3.708***	5.489	0.79
OD_{lat}	0.294	10.072***	-19.553	0.68	0.307	7.410***	-10.845	0.75
OD_{diag}	0.00	3.661		0.43	0.00	4.386		0.60
OD_{2H1F}	-0.107	-8.275	7.153*	0.95	-0.088	-8.062	3.109*	0.96
Iz_{SD}	0.00	-1.935***		0.64	0.00	-3.182***		0.89
Iz_front	0.00	-0.382***		0.30	0.00	-0.864***		0.85
Iz_hind	0.00	-0.585***		0.77	0.00	-0.727***		0.91
Iz_{fore}	0.171	3.750***	-11.394*	0.38	0.125	1.077***	-4.414*	0.31
Fz_{mean}_front	0.023	0.969***	-1.560**	0.77	0.014	0.664***	-0.497**	0.90
Fz_{mean}_hind	0.00	0.036**		0.01	0.00	0.111**		0.35
Fz_{P1}_front	0.00	1.478***		0.72	0.00	0.988***		0.74
Fz_{P1}_hind	0.00	2.516***		0.95	0.00	2.207***		0.96
Fz_{P2}_front	0.061	1.715*	-4.053***	0.85	0.020	1.497*	-0.721***	0.85
Fz_{P2}_hind	0.056	-0.262***	-3.754***	0.28	0.028	0.272***	-0.981***	0.23
Fz_{dip}_front	0.00	-1.098		0.46	0.00	-1.012		0.55
Fz_{dip}_hind	0.00	-1.954*		0.83	0.00	-2.138*		0.95
SL	0.011	0.729***	-0.758	0.94	0.012	0.636***	-0.410	0.93
SL_{norm}	0.00	0.458***		0.92	0.00	0.377***		0.92
OTD	0.013	0.582***	-0.849	0.83	0.014	0.488***	-0.499	0.88
OTD_{norm}	0.008	0.370***	-0.541	0.83	0.008	0.291***	-0.298	0.88

Polynomial regression function: $\Delta Var = a0 + a_1\,\Delta v + a_2\,\Delta v^2$; R^2, coefficient of determination.
* $p < 0.05$,
** $p < 0.01$,
*** $p < 0.001$. SD, stride duration; SR, stride rate; StD_{abs}, stance duration; StD_{rel}, duty factor (StD_{abs} relative to SD); $StpD_{diag}$, diagonal step duration; $StpD_{ipsi}$, ipsilateral step duration; OD_{2F1H}, overlap duration of tripedal support – 2 fore-, one hind limb; OD_{lat}, overlap duration of lateral bipedal support; OD_{2H1F}, overlap duration of tripedal support – 2 hind-, one forelimb; OD_{diag}, overlap duration of diagonal bipedal support; Iz_{SD}, vertical stride impulse (sum of the 4 vertical limb impulses during an entire motion cycle); Iz, vertical limb impulse; Iz_{fore}, proportion of diagonal vertical impulse carried by the forelimbs; Fz_{mean}, mean vertical force during StD; Fz_{P1}, first vertical force peak; Fz_{P2}, second vertical force peak; Fz_{dip}, vertical force dip; SL, stride length; OTD, over-tracking distance. Unless stated differently, time parameters are expressed as percentage of SD (%SD).

there were more data points for the WB sample. This is also demonstrated by the fact that R^2 values in this study were slightly lower in the WB compared to the original study [5] although we were working with the same collected data, because of the cuts made on both extremities of the speed range to compare WB and FM data. The WB were measured at more increments and lower speeds, especially at the trot, compared to the FM. This affected the mean across all speeds despite the common range of speeds. Using a scaling value such as the Froude number to compare the two breeds showed that many differences between the breeds were associated with height and speed, and most would disappear when scaling the data. However, some differences remained.

4.1. Breed-specific differences at walk

Stride length had a polynomial relationship to speed for both breeds at walk, while stride rate increased and stance duration decreased linearly, consistent with previous studies [2]. However, when normalising for withers' height, stride length was also increasing linearly, suggesting that the peak speed indicated by the polynomial curve was due to the biological limitations of size. The absolute stride length at walk was significantly shorter for FM than for WB, however, the height-normalised stride length was higher in the FM at the mean across all speeds, and equal at the same Froude number. Simultaneously, the absolute and height-normalised over-tracking distance were always higher in the FM compared to WB, except for the height-normalised over-tracking distance at the same Froude number. This means that while the height of the horse essentially limits stride length at walk, the FM were compensating by increasing the over-tracking distance, reaching the same absolute over-tracking distance than WB at the same Froude number, and surpassing WB at higher mean speed. The over-tracking distance has been positively associated with stride length in the ridden horse, so that longer over-tracking distances were also associated with the FEI dressage prerequisites for the medium and extended walk, while horses failed to cover their tracks at the collected walk [15]. Unridden Iberian horses of three different breeds also showed negative over-tracking distances on the treadmill [28], suggesting that long over-tracking distances may be specific to the FM. Theoretically, walking the average WB and average FM side by side at the same speed, an observer would see the FM taking more strides, but with better hind limb engagement (essentially determined by the over-tracking distance [24]) than the WB. If the breeding goal for the FM would be to increase stride length, either the breeding goal for withers' height needs to be changed to allow withers' heights over 160 cm, or the movement of the forelimbs needs to be further improved (e.g. by selecting for larger forelimb protraction and retraction angles [24]). The longer over-tracking distance in FM compared to WB might also be related to the conformation of the horses: the FM tends to be a more compact horse with a relatively shorter back compared to the WB. A longer back conversely is associated with shorter over-tracking distance in young WB horses, and even after a certain growth period, the increased height at withers did not entirely compensate for the longer distance between front and hind limbs due to the longer back [29]. Limb length itself could also have affected stride length and over-tracking distance as it was shown to affect stance duration [30]. While it stands to reason that horses with longer limbs would be taller, the proportions would not necessarily be maintained to scale. Miniature Shetland and Falabella for

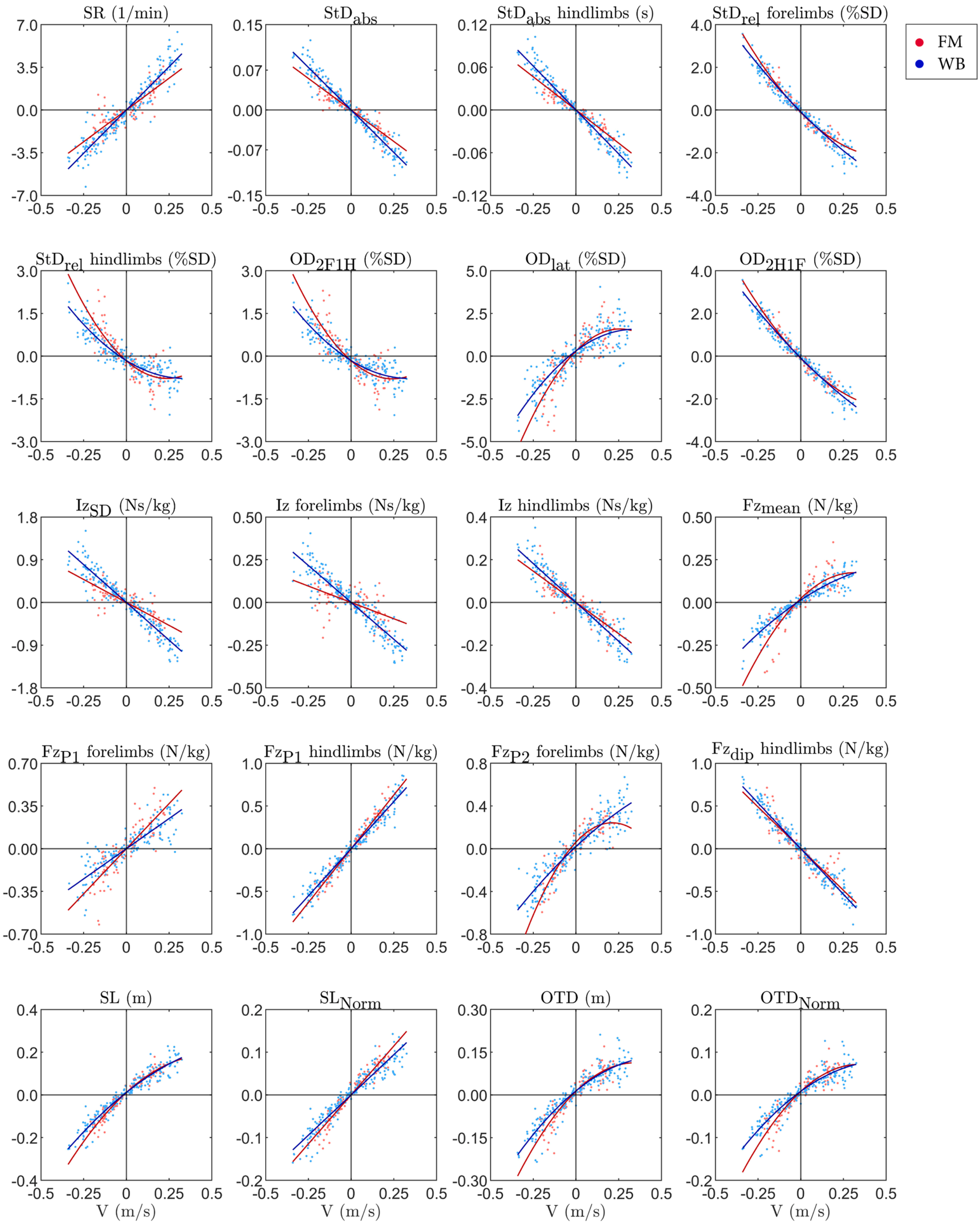

Fig. 1. Speed dependencies of selected time, force and spatial parameters at walk for Warmblood (WB) horses in blue and Franches-Montagnes (FM) horses in red. Dependent and independent variables are represented as the difference (delta) to the respective mean value. The variable's mean values and abbreviations are listed in Table 2. SR, stride rate; StD_{abs}, absolute stance duration; StD_{rel}, relative stance duration or duty factor (StD_{abs} relative to SD); OD_{2F1H}, overlap duration of tripedal support – 2 fore-, one hind limb; OD_{lat}, overlap duration of lateral bipedal support; OD_{2H1F}, overlap duration of tripedal support – 2 hind-, one forelimb; Iz_{SD}, vertical stride impulse (sum of the 4 vertical limb impulses during an entire motion cycle); Iz, vertical limb impulse; Fz_{mean}, mean vertical force during StD; Fz_{P1}, first vertical force peak; Fz_{P2}, second vertical force peak; Fz_{dip}, vertical force dip; SL, stride length; OTD, over-tracking distance.

Table 4
Summary statistics of the time, force, and spatial variables at trot for both breeds and at the interpolated Froude Number 0.963 (mean ± standard deviation). Unless stated differently, time parameters are expressed as percentage of stride duration (%SD). Significant differences between the means were investigated using a t-test.

Variable	Abbreviation	Limb	Mean across all speeds		Interpolated at Froude N:0.963	
			FM	WB	FM	WB
Speed	v	-	4.35 ± 0.72*	4.16 ± 0.58*		
Froude Number	FRN	-	1.11 ± 0.18***	1.03 ± 0.15***		
Stride rate [1/m]	SR	-	89.58 ± 6.12***	82.44 ± 5.39***	85.56 ± 3.32***	81.07 ± 4.29***
Stance duration [s]	StD_{abs}_front	Forelimbs	0.27 ± 0.03***	0.28 ± 0.03***	0.29 ± 0.01	0.29 ± 0.02
	StD_{abs}_hind	Hind limbs	0.24 ± 0.03***	0.26 ± 0.02***	0.26 ± 0.01**	0.27 ± 0.01**
Duty factor (absolute stance duration relative to the stride duration) [% SD]	StD_{rel}_front	Forelimbs	39.54 ± 3.05*	38.79 ± 3.15*	41.39 ± 1.52***	39.62 ± 1.87***
	StD_{rel}_hind	Hind limbs	35.39 ± 2.04	35.29 ± 1.95	36.58 ± 1.32*	35.77 ± 1.61*
Time of advanced placement [%SD]	TAP	Mean left/ right	0.48 ± 1.87	0.71 ± 1.52	-0.24 ± 1.70	0.35 ± 1.06
Time of advanced completion [%SD]	TAC	Mean left/ right	4.62 ± 1.10**	4.22 ± 1.03**	4.56 ± 1.05	4.20 ± 0.97
Suspension duration [%SD]	SpD	Mean left/ right	9.43 ± 2.50*	10.05 ± 2.46*	8.01 ± 1.17***	9.61 ± 1.57***
Vertical stride impulse (sum of the 4 vertical limb impulses during an entire motion cycle) [Ns/kg]	Iz_{SD}	Sum of all limbs	6.83 ± 0.45***	7.17 ± 0.47***	7.06 ± 0.34*	7.28 ± 0.38*
Vertical limb impulse [Ns/kg]	Iz_front	Forelimbs	1.92 ± 0.14***	2.02 ± 0.12***	1.97 ± 0.13*	2.05 ± 0.10*
	Iz_hind	Hind limbs	1.49 ± 0.12***	1.56 ± 0.12***	1.56 ± 0.08	1.59 ± 0.10
Proportion of diagonal vertical impulse carried by the forelimbs [$\%Iz_{SD}$]	Iz_{fore}	Forelimbs	56.27 ± 1.80	56.42 ± 1.10	55.76 ± 1.86	56.33 ± 0.99
Mean vertical force during StD [N/kg]	Fz_{mean}_front	Forelimbs	7.13 ± 0.69	7.18 ± 0.59	6.67 ± 0.33***	6.99 ± 0.30***
	Fz_{mean}_hind	Hind limbs	6.15 ± 0.39	6.08 ± 0.38	5.96 ± 0.29	6.00 ± 0.34
Vertical force peak [N/kg]	Fz_{peak}_front	Forelimbs	12.13 ± 1.26	12.08 ± 1.06	11.31 ± 0.66*	11.74 ± 0.65*
	Fz_{peak}_hind	Hind limbs	10.38 ± 0.70**	10.17 ± 0.59**	10.06 ± 0.50	10.05 ± 0.52
Stride length [m]	SL	-	2.90 ± 0.35**	3.02 ± 0.35**	2.65 ± 0.11***	2.90 ± 0.18***
Height-normalised stride length	SL_{norm}	-	1.85 ± 0.22	1.80 ± 0.21	1.69 ± 0.06*	1.73 ± 0.09*
Over-tracking distance [m]	OTD	-	0.20 ± 0.14*	0.16 ± 0.14*	0.10 ± 0.05	0.11 ± 0.07
Height-normalised over-tracking distance	OTD_{norm}	-	0.13 ± 0.09**	0.09 ± 0.08**	0.06 ± 0.03	0.07 ± 0.04

* $p < 0.05$,
** $p < 0.01$,
*** $p < 0.001$

example had shorter limbs than expected compared to other horse breeds in a previous study [11]. The breeding goal for the Franches-Montagnes requires horses of a quadratic format, with limb length and trunk length roughly equal when observing the horse standing from the side [21], while WB are selected to be more rectangular, with shorter limbs compared to the trunk (although taller than FM), which should affect stride length and over-tracking distance. Unfortunately, we did not have limb length data from the initial WB study, so that the effect of limb length compared to withers' height could not be assessed here.

The hind limb duty factor (relative stance duration) was shorter compared to the front in the FM, meaning there was a longer hind limb swing phase to account for longer over-tracking distance. This longer swing phase affected the four-beat rhythm of the walk, suggesting that the FM had a more "pacey" walk, i.e. a shorter ipsilateral step duration as described in Icelandic horses [31]. WB horses had a slightly more "trotty" walk, with shorter diagonal step duration (not significant). This caused differences between the overlap durations as well: FM had significantly longer overlap in diagonal support, while WB had longer tripedal support phases. For gait quality, a clear four beat rhythm as required in dressage would require a 25 % relative step duration or 12.5 % overlap duration. This has not been achieved by either breed in this study, nor even by Grand Prix dressage horses under the saddle [15]. Step duration might be an easily measured trait to improve walk regularity in all breeds (such as Pura Raza Español [23]), those involved in dressage more generally, and even gaited horses such as the Icelandic horse [31].

4.2. Breed-specific differences at trot

The mean stride rate was higher in FM both across the mean of all speeds and at the common interpolated Froude number, and while the absolute stride length was longer in WB, the height-normalised stride length was actually longer in FM. Stride length at trot is mainly determined by the extent of the airborne phase. Accordingly adaptations to faster trotting speeds are reflected longer suspension durations and over-tracking distances [25]. Longer over-tracking distances at the trot were related to greater propulsive work and better scores in dressage horses [18,32]. The suspension duration increased with speed as in [33], but showed a polynomial regression plateauing for both breeds. The suspension duration was longer in WB, suggesting that the FM again compensate for their height and their shorter suspension duration by increasing over-tracking distance, as both the absolute and height-normalised over-tracking distance were significantly higher in FM when comparing mean speeds. At the same Froude number though, absolute and normalised stride length and over-tracking distance were

Table 5
Functional relationship of time, force, spatial and kinematic variables to speed at trot (24 Franches-Montagnes stallions). Unless stated differently, time parameters are expressed as percentage of stride duration (%SD). The dependent and independent variables are expressed as differences to the respective mean (ΔVar, Δv).

Variable	FM				WB			
	a_0	a_1	a_2	R^2	a_0	a_1	a_2	R^2
SR	0.00	6.664***		0.93	0.00	5.610***		0.91
StD_{abs}_front	-0.005	-0.043***	0.010	0.98	-0.003	-0.051***	0.010	0.97
StD_{abs}_hind	-0.003	-0.033**	0.006***	0.99	-0.001	-0.031**	0.002***	0.97
StD_{rel}_front	-0.500	-3.451***	1.007	0.95	-0.314	-4.348***	1.044	0.96
StD_{rel}_hind	-0.282	-2.194***	0.569**	0.86	-0.044	-1.896***	0.147**	0.88
TAP	0.263	1.181***	-0.530	0.76	0.243	1.836***	-0.809	0.81
TAC	0.00	-0.064***		0.01	0.00	-0.615***		0.51
SpD	0.400	2.800**	-0.806	0.90	0.248	3.143**	-0.825	0.89
Iz_{SD}	0.000	-0.402***		0.88	0.00	-0.487***		0.92
Iz_front	0.00	-0.077***		0.64	0.00	-0.123***		0.91*
Iz_hind	0.00	-0.124		0.90	0.00	-0.120		0.90
Iz_{fore}	0.00	1.058***		0.55	0.00	0.404***		0.36
Fz_{mean}_front	0.074	0.829	-0.149	0.97	0.038	0.857	-0.125	0.97
Fz_{mean}_hind	0.00	0.322**		0.78	0.00	0.272**		0.79
Fz_{peak}_front	0.146	1.469	-0.294	0.97	0.077	1.426	-0.255	0.97
Fz_{peak}_hind	0.00	0.581***		0.83	0.00	0.402***		0.76
SL	0.00	0.460***		0.98	0.00	0.521***		0.98
SL_{norm}	0.00	0.292***		0.98	0.00	0.311***		0.98
OTD	0.00	0.177***		0.96	0.00	0.204***		0.96
OTD_{norm}	0.00	0.112***		0.96	0.00	0.122***		0.96

Polynomial regression function: $\Delta Var = a0 + a_1 \Delta v + a_2 \Delta v^2$; R^2, coefficient of determination.
* $p < 0.05$,
** $p < 0.01$,
*** $p < 0.001$. SD, stride duration; SR, stride rate; StD_{abs}, stance duration; StD_{rel}, duty factor (StD_{abs} relative to SD); TAP, time of advanced placement; TAC, time of advanced completion; SpD, suspension duration; Iz_{SD}, vertical stride impulse (sum of the 4 vertical limb impulses during an entire motion cycle); Iz, vertical limb impulse; Iz_{fore}, proportion of diagonal vertical impulse carried by the forelimbs; Fz_{mean}, mean vertical force during StD; Fz_{peak}, vertical force peak; SL, stride length; OTD, over-tracking distance.

shorter in FM compared to WB, although the difference was not significant for over-tracking distance (absolute and normalised). If the FM breeding goal were to increase stride length to a comparable level without increasing withers' height, the selection should mainly focus on prolonging the suspension duration. Time of advanced placement was longer in WB than FM, and was previously associated with better scores in dressage horses. Selecting for longer time of advanced placement could indirectly improve the balance of the horse from "downhill" to "uphill", more adapted for collected work [34–36]. Time of advanced placement in this study had very large standard deviations seemingly due to the differences between the horses (Supplementary Fig. S2). This would mean that time of advanced placement could be a good trait for selection. However, each horse also had a high standard deviation for the mean of all of its measurements, which might partially have been caused by differences between the left and right diagonal time of advanced placement increasing over faster speed [37]. Furthermore, time of advanced placement is a parameter that is strongly dependent on the accuracy determining the hoof-on and hoof-off moments, which is good under laboratory conditions but difficult in the field e.g. with inertial measurement units [38]. Overall, time of advanced placement is a relevant parameter, but difficult to measure accurately, so that the breeding progress might therefore be rather small unless measurement accuracy improves.

For both breeds, time of advanced completion was positive, which is consistent with a hind-first lift-off that was previously defined as both very common and also unrelated to gait quality [33,37]. While there was no difference for the mean stance duration at the common Froude number between the two breeds in the front limbs, hind limb stance duration was longer in WB which would indicate better gait quality for WB compared to FM [39]. The duty factor (relative stance duration) was in the previously reported range (35–42 % for the trot [36]), and decreased with speed in both breeds in concordance with [16]. The duty factor was lower in WB than FM, which again indicates better gait quality in the former [39], but this parameter is also influenced by the level of training (more muscular horses have shorter duty factors) [40], so that the slight differences are not entirely attributable to a breed effect. The total vertical stride impulse was higher in the front limbs than the hind limbs, which is consistent with previous studies on overground locomotion in horses [4,41,42]. At higher speeds, the front limbs take on more vertical ground reaction force compared to the hind limbs, especially in the FM, which could be due to the FM being built "downhill", with more body mass having to be supported by the front limbs.

4.3. Limitations

It is a well-established fact that locomotion on the treadmill is different from overground locomotion due both to the treadmill and to varying surfaces [43–46], therefore the results presented here are only applicable to treadmill locomotion. However, as we have used the same instrumented treadmill and a comparable level of treadmill adaptation for all horses, the comparison between the two breeds remains sound. Further research is needed comparing different horse breeds under field conditions (overground locomotion), bearing in mind that the data will need to be standardised for size and speed for example using the Froude number. While we have used wither's height to calculate the Froude number, it might be more accurate to use the front limb length, with a more direct relation to stride length but without excessive joint angulation differences due to conformation. Unfortunately, we could not explore a potential sex effect in this study, as the sex groups were not well distributed: all FM were stallions, but only one WB was, while there were very few mares compared to geldings in the WB sample. There is a lack of evidence that the sex has an effect on kinematics or kinetics in the horse, but it could be expected that approved stallions generally would "move better", as they should be better than average to improve the breed. Therefore, it is possible that breed comparisons with a more even sex distribution might yield different results than presented here. It should also be noted that as many horses were lent for the purpose of the study, we could not control for the fitness condition of the horses, only for the habituation to the treadmill itself.

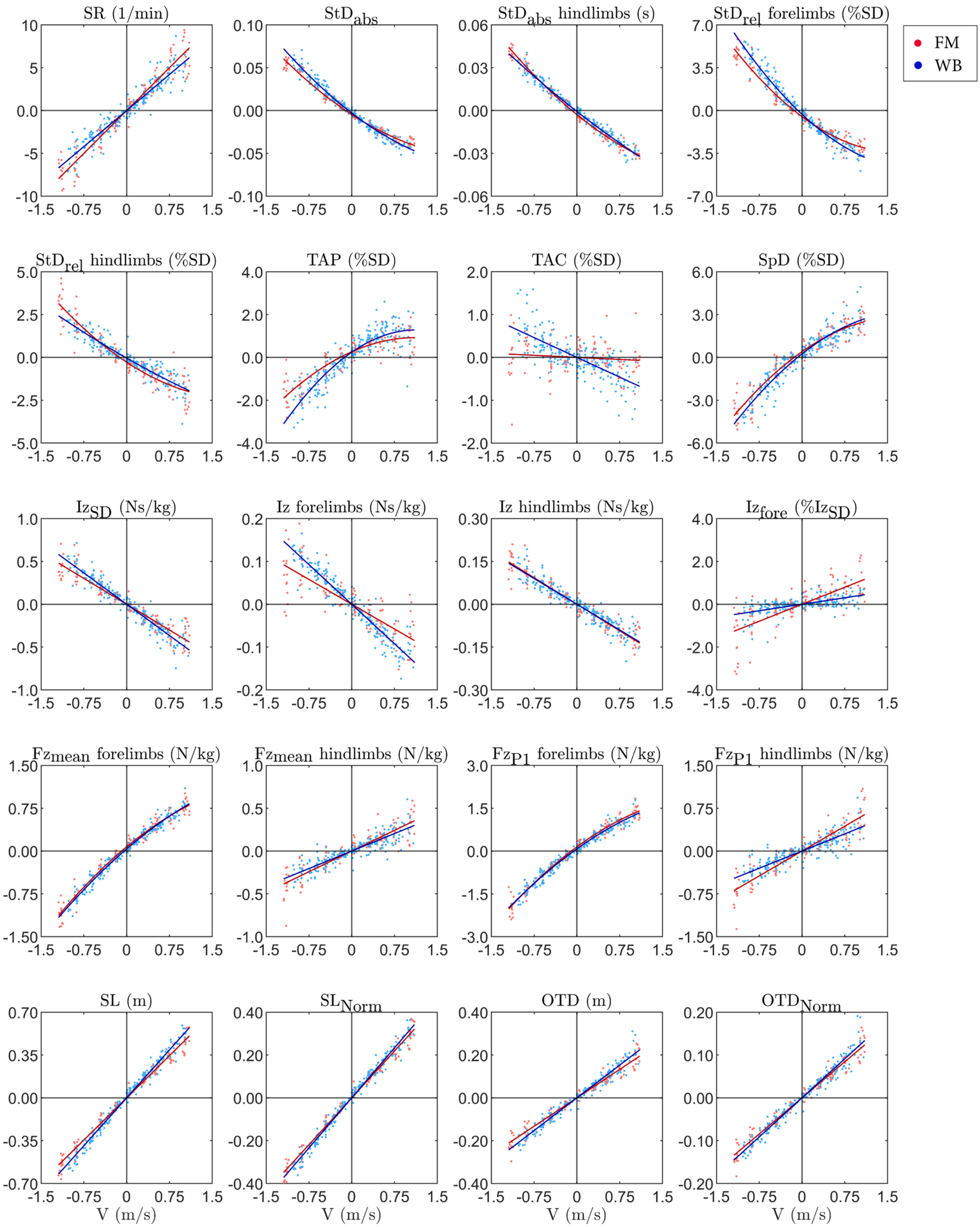

Fig. 2. Speed dependencies of selected time, force and spatial parameters at trot for Warmblood (WB) horses in blue and Franches-Montagnes (FM) horses in red. Dependent and independent variables are represented as the difference (delta) to the respective mean value. The variable's mean values and abbreviations are listed in Table 4. SR, stride rate; StD_{abs}, absolute stance duration; StD_{rel}, duty factor (StD_{abs} relative to SD); TAP, time of advanced placement; TAC, time of advanced completion; SpD, suspension duration; Iz_{SD}, vertical stride impulse (sum of the 4 vertical limb impulses during an entire motion cycle); Iz, vertical limb impulse; Iz_{fore}, proportion of diagonal vertical impulse carried by the forelimbs; Fz_{mean}, mean vertical force during StD; Fz_{peak}, vertical force peak; SL, stride length; OTD, over-tracking distance.

5. Conclusions

In general, time, force and space parameters for FM followed the same regression patterns as for WB. The main differences between the breeds seem to stem from the movement of the hind limbs, with the FM obtaining long over-tracking distance despite their shorter height at withers. However, other parameters related to gait quality were better in WB, which could potentially be improved in the FM by rigorous selection.

Ethical statement

The data for this study were collected complying to Swiss Federal legislation under permit number VD 3164. No animals were harmed during the experiment.

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CRediT authorship contribution statement

A.I. Gmel: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition. **E.H. Haraldsdóttir:** Methodology, Formal analysis, Data curation, Writing – review & editing. **F.M. Serra Bragança:** Conceptualization, Investigation, Writing – review & editing. **A.M. Cruz:** Conceptualization, Investigation, Writing – review & editing. **M.A. Weishaupt:** Conceptualization, Methodology, Investigation, Resources, Data curation, Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jevs.2024.105005.

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