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Ground Reaction Force Analysis of Horses Ridden at the Walk and Trot

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ABSTRACT. Riding by a skilled and an unexperienced rider were evaluated using ground reaction force measurements of 13 Dutch Warmblood horses at the normal walk and slow trot. The influence of the weight was studied by loading the horses with a sandbag with a mass equivalent to that of the rider. The additional mass increased the ground reaction forces produced by the forelimbs more than those of the hind limbs. At the walk, the force patterns of ridden horses could hardly be distinguished from those loaded with a sandbag. At the ordinary trot, an asymmetry occurred due to sitting in the saddle during the stance phase of the left forelimb and the right hind limb. Comparing sandbag with riding data, the riders were able to shift part of the weight towards the hind limbs. The skills of the riders had minimal influence on the ground reaction force patterns

Key words. Riding; horses; limb loading; force plate; biokinetics.

INTRODUCTION

The weight of the rider will increase the loads on the limbs of the horse and will shift the position of the centre of mass towards the forelimbs. Neither the timing, coordination of limb movement, stride frequency, stride length or vertical acceleration of the body changed significantly when horses were ridden by riders of different mass at the walk, trot or gallop.[1] Carrying loads of 20–30% of the horse's body mass only affected the ground reaction force amplitudes.[7] However, in horse riding, not only the mass of the rider plays a role in the additional load on the limbs, but the skills of the rider may also be important. Although many statements are made about the "proper" way to ride a horse, almost no quantitative studies have been carried out to evaluate these statements.[2]

The purpose of this study was to determine the influence of the mass and the skills of a rider on the loading of all 4 limbs of the horse. The limb loading is quantified on the basis of GRF patterns. This study is focused on GRF obtained during normal walk and slow trot.

MATERIALS AND METHODS

Ground reaction forces were obtained from 13 Dutch Warmblood horses and were measured using a 60×90 cm^2 Kistler type Z4852C quartz crystal piezoelectric force plate. The procedure and equipment to determine the vertical (Fz) and forward/backward (Fy) horizontal GRF have been described.[5,6] At least 8 visually acceptable runs in which both a forelimb, and after a short interval, the ipsilateral hind limb loaded the force plate, were recorded. After normalization of GRF amplitudes to the body mass of the horse (i.e. without the saddle and the rider) and to the duration of the stance phase, an averaged GRF pattern of each limb was constructed and the characteristic peak amplitudes and times of occurrence of each peak were determined. The selected force and peak-time variables are indicated in graphs of representative GRF patterns of horses at the walk (Fig. 1) and the trot (Fig. 3), and are listed in Tables 1 and 2. The variables derived from GRF patterns were the stance phase duration and the area under the force-time curves (force impulses; Py and Pz) of Fy and Fz. Py was separated in its positive retardatory and negative propulsory part. The fractions fPy and fPz of total impulse, produced by each limb, were calculated on the basis of the sum of the impulses of all limbs together.

The influences of mass or skills of a rider were studied by taking measurements during the following recording sessions, both at the walk (approximately 2 m s^{-1}) and the ordinary, slow trot (approximately 4 m s^{-1}): unloaded, guided by hand (baseline); ridden by a skilled rider A (mass 82 kg); loaded by a sandbag with mass equivalent to rider A (sandbag A); ridden by an unexperienced rider B (mass 94 kg); and loaded by a sandbag with mass equivalent to rider B (sandbag B).

The walk of the horse is a symmetrical gait. Either 2 or 3 limbs have simultaneous ground contact, and the left and right limbs are loaded almost identically.[4] Therefore, GRF patterns of the contralateral limbs were combined, and the effect of riding was studied in the fore- and hind limbs.

While unloaded or loaded with a dead weight (i.e. a sandbag), the trot is also a symmetrical gait. Under these conditions GRF patterns of the forelimbs and hind limbs could be analyzed without a separation between left and right. However, when the horses were ridden at the trot, the rider was sitting in the saddle when the left forelimb and the right hind limb had ground contact. This caused an asymmetry in the limb loading pattern and required that data of left and right limbs be presented separately.

During the measurements of GRF parameters, the velocity of the horses was not measured. Analysis of the stance phase duration revealed that slight differences occurred comparing the various recording sessions. These differences may be partially responsible for differences in GRF amplitudes and force impulses.

Differences in GRF parameters between unloaded horses and horses loaded with sandbags A or B were tested for statistical significance using Student's paired *t*-test at the level of $p<0.05$. The differences between GRF parameters of horses loaded with sandbags and horses with riders A or B were tested using Student's unpaired *t*-test at $p<0.05$.

RESULTS

Ground reaction force patterns at the walk

The mean ±1 SD GRF patterns of the 13 unloaded horses at the walk, are plotted in Fig. 1. The symmetry of all selected GRF amplitude and peak-time position parameters exceeded 93%. Combined forelimb and hind limb data are listed in Table 1.

After loading the animals with a sandbag, GRF patterns changed markedly (Fig. 1; Table 1). The most pronounced increases in GRF amplitudes were found in Fy, Fz, Py and Pz. Although the duration of the stance phase tended to decrease, the force impulses increased markedly ($p<0.05$) as compared to baseline values. In the forelimbs, GRF peak amplitudes occurred later in the stance phase. The effects on the amplitudes and the peak-time positions in the hind limbs were less pronounced. The fraction impulse values indicated that the forelimbs contributed relatively more to both retardation and propulsion of the body (Fy) and the support of the body mass (Fz) than the hind limbs.

No differences ($p>0.05$) were found in GRF patterns, peak amplitudes, or peak-time positions between horses ridden by rider A and rider B (Fig. 2; Table 1). Comparing GRF patterns during riding and those while loaded with a sandbag, only the impulses produced by the forelimbs were lower ($p<0.05$; Table 1). Part of the reduction in force impulses may be attributed to the reduction in stance phase duration. During riding the fraction impulses decreased in the forelimbs, and increased in the hind limbs.

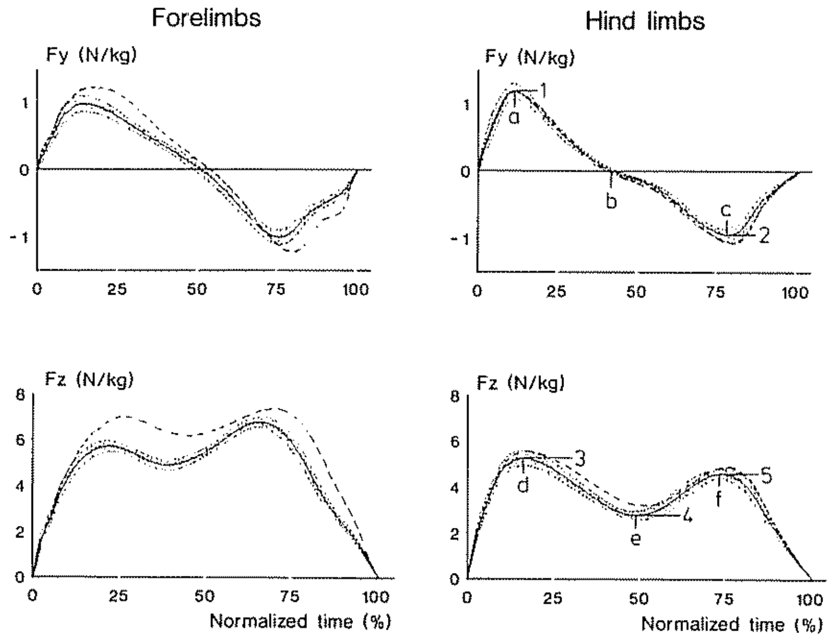

Fig 1. Mean ±1 SD normalized ground reaction force (GRF) patterns of 13 unloaded horses at the walk. Fy is the forward/backward GRF and Fz the vertical GRF. GRF are expressed in N kg^{-1} body mass of the horse; the stance phase duration is normalized to 100%. The selected peak amplitudes are: 1) Fymax; 2) Fymin; 3) Fzmax1; 4) Fzdip; 5) Fzmax2, and the corresponding peak-time positions are: (*a*) tFymax; (*b*) tFy=0; (*c*) tFymin; (*d*) tFzmax1; (*e*) tFzdip; (*f*) tFzmax2. The dashed lines are GRF patterns when the horses were loaded with a sandbag equivalent to the mass of the experienced rider A

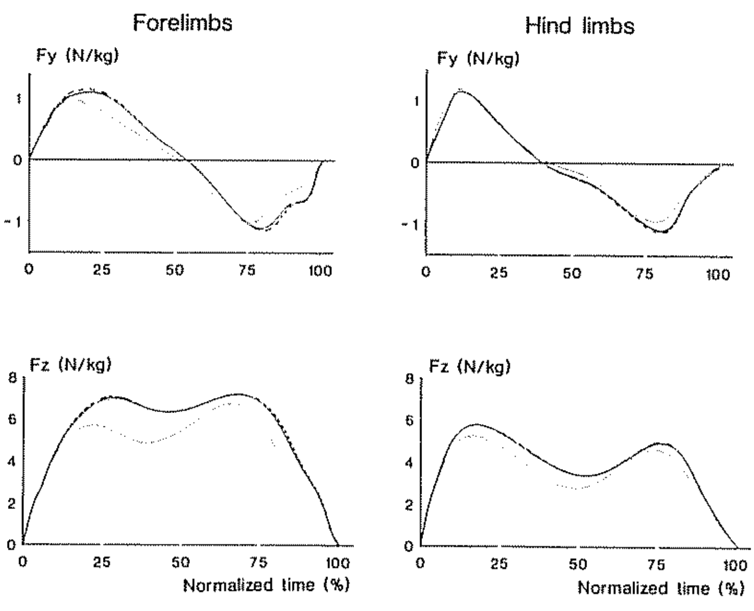

Fig 2. GRF patterns of unloaded horses (thin lines), and the same horses ridden by an experienced rider A (thick line), and an unexperienced rider B (dashed line), at the walk

Table 1. *Mean ground reaction force (GRF) parameters of 13 horses at the walk, and per cent changes versus baseline values produced by a sandbag of the mass equivalent to that of rider A, and per cent changes between GRF parameters of riders A and B compared to sandbags equivalent to their own masses*

	Forelimbs				Hind limbs			
Parameter	Baseline value	Sand A vs bsln	A vs sand A	B vs sand B	Baseline value	Sand A vs bsln	A vs sand A	B vs sand B
Fymax	0.98	26*	−9*	−5	1.19	−1	−2	1
Fymin	−1.02	22*	−9*	1	−0.96	14*	3	9
Fzmax1	5.75	22*	0	−1	5.29	6*	4	8*
Fzdip	4.88	25*	3	−3	2.77	15*	6*	−3
Fzmax2	6.81	9*	−2	−1	4.70	6*	1	2
Py	0.40	23*	−11*	−11*	0.37	6*	−4	−7
Py+	0.20	32*	−11*	−16*	0.18	−2	−8*	−13*
Py−	−0.19	14*	−10*	−4*	−0.19	14*	0	0
Pz	3.23	15*	−5*	−9*	2.47	6*	−1	−6*
fPy	26.0	7*	−3*	−2*	24.1	−8*	4*	3*
fPz	28.3	4*	−2*	−1*	21.7	−5*	2*	2*
tFymax	14.5	5*	1	−1	11.0	1*	0	0
tFy=0	51.1	3*	0	−2*	42.3	−2*	−1	−2*
tFymin	76.1	4*	−1	0	78.4	1*	0	0
tFzmax1	22.2	4*	2*	−3	16.6	1*	0	1
tFzdip	39.0	7*	0	−1	49.4	2*	1	3*
tFzmax2	66.0	3*	−2*	−0	73.7	1*	1*	2*
stance dur	0.70	−3	−4*	−8*	0.70	−2	−4*	−8*

GRF amplitudes (F, see Fig. 1 for definition of peaks used) are expressed in N kg^{-1} body mass, force impulses (P) in N s kg^{-1}, fraction impulses (fP) in per cent of total impulse of all limbs together, time of peaks during the normalized stance phase in per cent stance phase duration, and the stance phase duration (stance dur) in s. The changes from baseline values are in per cent (peak amplitudes), or in per cent stance phase duration (peak-time positions). Abbreviations: sand A vs bsln = changes between horses loaded with sandbag A vs baseline values; A vs sand A = rider A vs sandbag A. An asterisk = significant ($p<0.05$; Student's t-test) differences from baseline values, or comparing riders A and B with sandbags with masses equivalent to their own.

Ground reaction forces at the trot

In unloaded horses at the trot, the symmetry in contralateral limb GRF patterns, GRF peak amplitudes, peak-time positions and force impulses was almost complete. The same holds for horses loaded by a sandbag. Therefore, only GRF curves and numerical data of contralateral limbs combined are presented (Fig. 3, Table 2) for these experimental conditions. The stance phase duration of the forelimbs was longer ($p<0.05$) than that of the hind limbs. After loading, the symmetry in GRF patterns remained. It should be noted that in all limbs the retardatory forward/backward impulse Py+ was greater than the propulsory Py−. This may indicate that the horses were slowing down while hitting the force plate. All GRF amplitude parameters increased after loading. This increase was greater in the forelimbs than in the hind limbs. The positions of Fy=0, Fymin and Fzmax shifted towards the end of the stance phase in the forelimbs, but remained constant or shifted to the be-

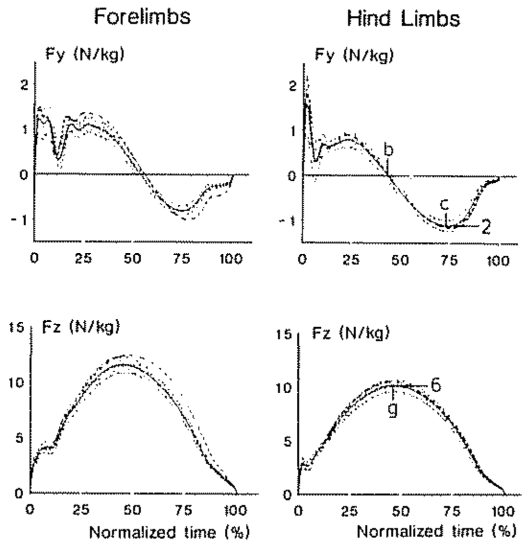

Fig 3 Mean GRF patterns of 13 horses at the trot. See also the legend to Fig. 1. GRF patterns of left and right forelimbs and left and right hind limbs have been averaged. The selected parameters are: 2) Fymin; 6) Fzmax; (*b*) tFy=0; (*c*) tFymin; g) tFzmax.

ginning of the stance phase in the hind limbs. The stance phase duration tended to increase, which may reflect a slower trotting speed of the loaded horses. The fraction of total Fy and Fz-impulses produced by the forelimbs increased ($p<0.05$), while those of the hind limbs decreased ($p<0.05$).

During riding, limb loading was no longer symmetrical. Because the riders were sitting in the saddle during left fore and right hind ground contact, and were standing during ground contact of the other diagonal limb pair, relative increases in left fore and right hind peak amplitudes and decreases in right fore and left hind occurred, especially in Fz and Pz (Fig. 4; Table 3). In all limbs Py+ decreased and Py− increased, comparing riding with sandbag data ($p<0.05$). The timing of GRF peaks changed ($p<0.05$) mainly in the right hind limb.

Comparing of GRF data for riding by rider A and rider B, few differences were found in all GRF parameters studied (Table 3, Fig.

Table 2. *Mean ground reaction force parameters of 13 horses at the trot, unloaded and loaded with a sandbag equivalent to the mass of rider A*

	Forelimbs		Hind limbs	
Parameter	Baseline value	Sandbag A vs bsln	Baseline value	Sandbag A vs bsln
Fymin	−0.81	25*	−1.12	5
Fzmax	11.6	7*	10.2	4*
Py	0.178	34*	0.156	13*
Py+	0.119	37*	0.066	17*
Py−	−0.059	38*	−0.090	12*
Pz	1.95	21*	1.59	9*
fPy	26.7	9*	23.3	−10*
fPz	27.6	5*	22.4	−6*
tFy=0	53.9	2*	43.4	1
tFymin	74.8	3*	73.9	1
tFzmax	45.3	3*	46.6	−1*
stance dur	0.274	9*	0.246	5*

GRF peak amplitudes (Fymin, Fzmax) are in N kg^{-1}, impulses (Py, Py+, Py− and Pz) in N s kg^{-1} (fPy, fPz) in per cent absolute summed impulse of all limbs, peak-time positions in per cent of the stance phase duration, and the stance phase duration (stance dur) in s. Changes in parameter values after loading the horses with sandbag A are expressed in per cent. Statistically significant ($p<0.05$; Student's paired *t*-test) changes are indicated with an asterisk

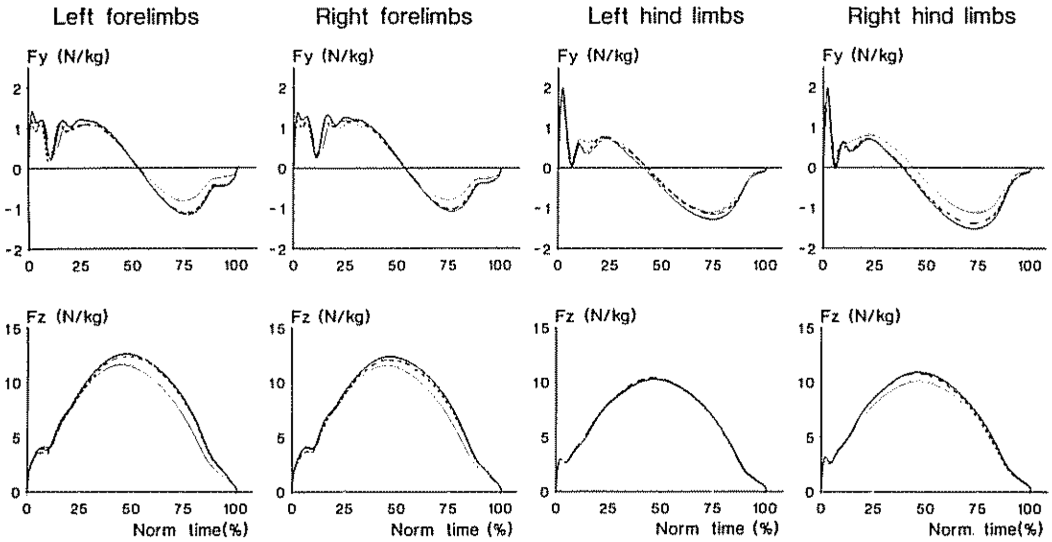

Fig 4 GRF patterns obtained from all limbs of unloaded horses (thin lines), and the same horses ridden by an experienced rider A (thick lines), and an unexperienced rider B (dashed lines), at the trot.

4). Only Pz in the left hind limb, and the stance phase duration of both hind limbs were different ($p<0.05$).

DISCUSSION

Applying force plate data analysis it was possible to determine small differences in limb loading of horses at walk.[3] However, certain conditions need to be fulfilled before the force plate system can be applied successfully. The horses must be guided over the plate so that their walking speed is constant: when a decrease occurs, the (positive) retardatory Fy-forces become larger than the (negative) propulsory forces. The vertical Fz-forces depend mainly on the mass of the horse and the rider and were not related ($p<0.05$) to walking speed.[5] At the walk these conditions could be met, but at the trot, they were more difficult to fulfil. First, the man guiding the horse has to run with considerable speed compared to normal human locomotion. Under these circumstances it is difficult to ensure both a constant trotting speed, and a straight path while the horse is hitting the force plate. When the horses are ridden, the rider can better control the gait, speed and line of trotting. Secondly, the probability of hitting the force plate decreases from about one in two at the walk to about one in four at the trot. Eight good hits on the force plate of each limb, are preferred to obtain a reasonable average of GRF patterns of a particular horse. To achieve this it is necessary to collect data from about 50 to 80 runs, which is tedious for both the man and the horse. It was also concluded that measurement of speed is necessary when collecting force plate data, or even better to record biokinematics.

Statements are made about how to ride a horse correctly and how to relieve load on the forelimbs and ensure that the horse will better use the hind quarters. If a rider is capable of inducing such a change in limb loading, it is possible to measure this effect using a force plate. In this study, the effect of an additional load was measured after loading the horses with a sandbag of a mass equivalent to that of the rider. Any changes between sandbag and riding data must then

Table 3. *Per cent changes in ground reaction force parameters of horses ridden at the ordinary, slow trot, produced by an experienced rider A, and an unexperienced rider B, with respect to sandbags with masses equivalent to those of the riders*

	Rider A				Rider B			
Parameter	LF	RF	LH	RH	LF	RF	LH	RH
Fymin	17*	11*	16*	31*	9	3	5	23*
Fzmax	1	−1	−3*	5*	2	−1	−2	3*
Py	0	−7*	0	12*	−5*	−10*	0	10*
Py+	−10*	−12*	−21*	−26*	−15*	−16*	−11	−27*
Py−	23*	8	24*	45*	18*	7	15*	48*
Pz	0	−4*	−2[a]	6*	4	−1	4	8*
fPy	−1	−7*	0	12*	−3	−8*	3	13*
fPz	0	−3*	−2	6*	1	−4*	0	4*
tFy=0	−3*	−2*	−3*	−6*	−2*	−2*	−2	−6*
tFymin	−1*	−2*	0	−1*	−1	−1*	0	−1*
tFzmax	−1	−1*	3*	1	1	1	2*	0
stance dur	0	−2	1[a]	1[a]	4	2	6*	6*

Significant ($p<0.05$, Student's paired t-test) changes indicated with an asterisk. Significant ($p<0.05$; Student's unpaired t-test) changes comparing both riders are indicated with [a]

be attributed to skills of the rider. It was found that the experience of the rider, and the effects on the limb loading of the horse, were not dramatic. At the normal walk, GRF patterns obtained from horses loaded with a sandbag and from horses ridden are almost indistinguishable. The data collection took place on different days, and GRF patterns are constructed from different numbers of runs of each animal. Therefore, some biological variation may be expected. This effect is hard to quantify precisely, but a reasonable estimate would be about 3–5% in GRF amplitudes, and 1–2% in peak-time positions.

One interesting comparison involves the sandbag and riding data of the fraction impulses in the fore and hind limbs. The additional loading by the sandbag increased the fraction of the total Fy and Fz-impulses in the forelimbs, and decreased that in the hind limbs. However, when ridden, the contribution of both the Fy and the Fz-force impulses decreased in the forelimbs, while those in the hind limbs increased. This supported the contention that a rider is able to shift some of the loading of the forelimbs to the hind limbs.

From this study the following conclusions can be drawn. The changes in GRF patterns produced by the loading due to the rider's mass are more pronounced in the forelimbs than in the hind limbs. The GRF patterns of a loaded horse and a ridden horse are difficult to distinguish, but the rider is able to shift part of the load to the hind limbs. This is possible for both experienced and unexperienced riders. Measurement of GRF is easy to perform and gives an accurate indication of the loading of all limbs of the horse, but comprehensive changes in the biokinematics of the horse are not taken into account. For this purpose automated biokinematic movement analysis equipment is necessary.

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Ground Reaction Force Analysis of Dutch Warmblood Horses at Canter and Jumping

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ABSTRACT. Ground reaction forces of all limbs of 7 Dutch Warmblood horses were recorded at right fore lead canter. The highest peak vertical forces were found in the nonlead left forelimb (14.8 N kg^{-1}), followed by the lead right forelimb (11.6 N kg^{-1}), right hind limb (11.1 N kg^{-1}) and left hind limb (9.4 N kg^{-1}). The lead right forelimb and the ipsilateral hind limb generated mainly retardatory impulses, while the left hind limb caused mainly propulsion. Retardatory and propulsory impulses in the left forelimb were approximately equal. In 5 horses jumping over a 0.8 m fence, the distribution of retardatory/propulsory, and vertical impulses changed considerably. Although the peak vertical forces mainly increased in the right forelimb and left hind limb, they did not exceed the highest peak vertical forces in the nonlead left forelimb at straight canter.

Key words: Horses; force plate; biokinetics; limb loading.

INTRODUCTION

In the past four decades the measurements of forces acting between the limbs and the ground has been an area of active research, and proved to be important in basic locomotion analysis.[3] Ground reaction force (GRF) data were used for a quantitative evaluation of the locomotion of sound and lame horses at the walk[5,6] and the trot.[13] In these symmetrical gaits the loading of the right and left limbs is almost identical. At canter, a three beat asymmetrical gait, both the sequence of limb placement and the loading of the limbs is asymmetrical.[7] In the right fore lead canter the hoofs are placed in the following sequence: left hind; right hind and left fore diagonal; lead right fore followed by a short suspension period without ground contact.[2] Adams[1] stated that the lead forelimb and the diagonal nonlead hind limb bear the most weight and are subject to more fatigue than the diagonal paired limbs. Previous studies presenting GRF patterns of one forelimb[8,10] or all limbs,[7] could not support this statement.

Horses clearing an obstacle change their footfall pattern considerably.[4] At take-off from right fore lead canter the nonlead left forelimb is placed on the ground just before the right forelimb. Both forelimbs are used to initiate the vertical movement of the forequarters. After a short suspension phase both hind limbs hit the ground in unison and at a similar distance from the fence and generate a powerful push-off, after which the flight over the obstacle starts. At landing the nonlead left forelimb hits the ground first, followed by the right forelimb, and after a short suspension phase the nonlead left hind limb and the lead right hind limb make ground contact. It is hypothesized that jumping is associated with higher loads on the limbs. However, studies in which the loads on the limbs at take-off and landing are quantified on the basis of the propulsory/retardatory and vertical ground reaction