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Short communication

Ground reaction forces of elite dressage horses in collected trot and passage

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ABSTRACT

In this study, sagittal plane ground reaction forces (GRFs) in ridden elite dressage horses performing 'collected trot' and in 'passage' over ground were determined. In-ground force plates captured GRF data from four Dutch Warmblood and four Lusitano horses ridden by their trainers. At least three stance phases were analysed for forelimbs and hind limbs per horse. The variables extracted were vertical and longitudinal (braking, propulsive) force maxima, their times of occurrence and the respective impulses for forelimbs and hind limbs. Lusitanos had lower vertical impulses than Dutch Warmbloods in collected trot. Across all horses, passage had larger vertical impulses than collected trot in the forelimbs and hind limbs. Propulsive impulse increased in the hind limbs in passage. Prolonged stance durations in passage contributed to higher vertical impulses that are needed to increase the vertical excursions of the centre of mass.

Dressage horses maintain an uphill longitudinal balance by adjusting limb protraction/retraction and ground reaction forces (GRFs) (Hobbs and Clayton, 2013). Vertical GRFs for 'collected trot' and in 'passage' (Fédération Equestre Internationale, 2016) have been compared in horses ridden on a treadmill (Weishaupt et al., 2009); however, treadmill locomotion differs from over ground both physiologically and kinematically (Barrey et al., 1993; Sloet van Oldruitenborgh-Oosterbaan and Barneveld, 1995). In the present study, we compared vertical and longitudinal GRFs and impulses during collected trot and in passage in elite dressage horses ridden over ground. The experimental hypothesis was that, in passage, both forelimbs and hind limbs generate higher vertical impulses to provide greater vertical oscillation of the centre of mass (COM) and lower longitudinal impulses, to align the GRF vector with the smaller ranges of limb protraction/retraction.

The protocol was approved by the Michigan State University institutional animal care and use committee (approval number 02/08-020-00; date of approval February 2008). Eight sound Grand Prix dressage horses were ridden by their regular trainers. Four Dutch Warmbloods (550–745 kg) were 'warmed up' and then ridden along a 20 m rubberised runway with an embedded force plate (Type Z4852C, Kistler Corporation; 300 Hz). Four Lusitanos (597–613 kg) were 'warmed up' and ridden along a 30 m rubberised runway with four embedded force plates (FP60120 and FP6090, Bertec Corporation, 960 Hz). Trials of collected trot and passage were recorded in a predetermined random order using an online randomisation tool[1]. Trials assessed as inadequate by the riders or by an experienced observer were discarded. In successful trials, the horse moved straight at consistent velocity, making one or more valid force plate contacts.

At least three stance phases for a forelimb and a hind limb were analysed per horse/gait. Since trot and passage are symmetrical gaits, left and right limbs were grouped (Weishaupt et al., 2009). GRFs were normalised by dividing the forces by the combined mass of horse and rider. Variables derived from the GRFs were stance duration (threshold value 50 N for contact and lift off), peak values and times of occurrence of vertical and longitudinal braking and longitudinal propulsive GRFs, and their respective impulses, along with time of zero longitudinal force. Data are presented as means ± standard deviations (SDs).

A Kolmogorov–Smirnov test indicated that variables were normally distributed, except for times to peak hind limb vertical GRF and peak forelimb propulsive GRF. Values for the two breeds were compared using *t* tests for independent samples and then data were

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[1] See: http://www.randomizer.org (accessed 24 January 2017).

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Table 1
Mean ± standard deviation (SD) of forelimb and hind limb vertical impulses (N s/kg) in Dutch Warmblood and Lusitano horses performing collected trot and passage.

	Collected trot		Passage	
	Dutch Warmbloods	Lusitanos	Dutch Warmbloods	Lusitanos
Forelimb vertical impulse [a]	2.57 ± 0.13*	2.21 ± 0.02*	2.85 ± 0.07	2.81 ± 0.15
Hind limb vertical impulse [a]	1.90 ± 0.08*	1.64 ± 0.02*	2.49 ± 0.11	2.31 ± 0.07

* Values that differ significantly between breeds ($P < 0.05$).
[a] Forces are standardised to the combined body masses of horse and rider.

combined. Repeated measures analysis of variance (for normally distributed variables) or the Wilcoxon signed rank test (for non-normally distributed variables) was used for comparisons between gaits (collected trot versus in passage) and between limbs (forelimbs versus hind limbs).

In collected trot, but not in passage, Dutch Warmbloods had significantly higher vertical impulses than Lusitanos in both forelimbs and hind limbs (Table 1). In all limbs, stance durations were significantly longer in passage compared to in collected trot. Peak vertical forces did not differ, but the longer stance duration resulted in significantly higher vertical impulses in all limbs in passage (Table 2; Fig. 1A). Hind limb peak propulsive force (percentage stance) occurred relatively earlier and was accompanied by a large and significant increase in propulsive impulse in passage due to the prolonged stance duration and earlier transition from braking to propulsion (Table 2; Fig. 1B). When forelimbs and hind limbs were compared, there were no significant differences in peak vertical force and its time of occurrence in passage, whereas other variables differed significantly ($P < 0.05$).

Coordinated forelimb and hind limb GRFs provide gravitational support, together with inertial forces, to accelerate the COM, maintain forward progression and control trunk orientation (Hobbs and Clayton, 2013). Detailed knowledge of GRFs is needed to evaluate the musculoskeletal effects of postural modifications shown by dressage horses performing highly collected movements. In accordance with our first hypothesis, all four limbs contributed significantly to the higher vertical impulse in passage compared with collected trot, but the increase was relatively greater in the hind limbs (+32%) than in the forelimbs (+17%), similar to the increases (forelimbs +24.8%; hind limbs +39.9%) reported on a treadmill by Weishaupt et al. (2009). The smaller vertical impulses in the Lusitanos in collected trot were associated with smaller COM vertical oscillations (unpublished data), which may explain why riders subjectively find Iberian horses easy to sit at trot.

The summed GRF of all grounded limbs is represented by a vector acting at the centre of pressure (COP). During trotting, the COP initially corresponds with the first hoof to contact the ground. It remains almost stationary through most of diagonal stance, in a position closer to the forelimb, which has a higher vertical GRF than the hind limb. In terminal stance, the COP moves towards the fore-hoof, which is the last limb to lift off (Hobbs and Clayton, 2013). The COM moves forward continuously during trotting at a fairly constant speed relative to the diagonal base of support (Hobbs and Clayton, 2013). On a treadmill, the forelimbs provided 57.4% of the vertical impulse in collected trot and 54.0% in passage, which was interpreted as moving the COM closer to the hind limbs in passage (Weishaupt et al., 2009). In the present study, the decrease in forelimb impulse contribution and the resulting change in forelimb:hind limb vertical GRF ratio is interpreted as shifting the COP (but not the COM) towards the hind limbs in passage. Changes in pro-retraction angles of the supporting limbs and their position relative to the COM determine the moment arm lengths of the forelimb and hind limb vertical GRFs (Hobbs and Clayton, 2013).

The hypothesis that passage would have a lower longitudinal impulse associated with reduced limb protraction–retraction was not supported. The higher hind limb propulsive impulse in passage could contribute to a nose-up moment around the COM that would lift the forehand (Hobbs et al., 2016). In passage, the forelimb exerts a braking force, while the hind limb simultaneously exerts a propulsive longitudinal force through much of stance (Fig. 1B), which results in a marked convergence of the sagittal plane GRF vectors (Fig. 2).

In conclusion, Dutch Warmbloods had higher vertical impulses than Lusitanos in all limbs in collected trot, but the two breeds did not differ in passage. In all horses, vertical impulses were larger in passage than in collected trot, especially in the hind limbs, and this was associated with increased vertical oscillations of the COM. The increased hind limb propulsive impulse is thought to maintain balance by increasing the nose-up moment around the COM.

Conflict of interest statement

None of the authors of this paper has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of the paper.

Table 2
Mean ± standard deviation (SD) of forelimb and hind limb data during collected trot and passage.

Variable [a]	Forelimbs		Hind limbs	
	Collected trot	Passage	Collected trot	Passage
Peak vertical force (N/kg)	10.06 ± 0.54	9.74 ± 1.16	8.28 ± 0.79	8.48 ± 1.09
Time of peak vertical force (% stride)	53.25 ± 3.57 *	47.83 ± 4.81 *	46.76 ± 1.32	43.33 ± 4.77
Vertical impulse (N s/kg)	2.44 ± 0.20 *	2.85 ± 0.08 *	1.81 ± 0.14 *	2.43 ± 1.03 *
Peak braking force (N/kg)	−1.07 ± 0.11	−0.95 ± 0.29	−0.51 ± 0.16 *	−0.24 ± 0.23 *
Time of peak braking force (% stride)	30.10 ± 2.46	29.02 ± 4.63	22.34 ± 1.77 *	18.22 ± 4.13 *
Braking impulse (N s/kg)	−0.16 ± 0.03	−0.16 ± 0.06	−0.05 ± 0.02	−0.03 ± 0.03
Peak propulsive force (N/kg)	0.77 ± 0.28 *	0.48 ± 0.32 *	1.04 ± 0.16	0.92 ± 0.23
Time of peak propulsive force (% stride)	82.25 ± 2.88	84.29 ± 5.73	70.07 ± 1.35 *	64.11 ± 4.17 *
Propulsive impulse (N s/kg)	0.07 ± 0.03	0.06 ± 0.05	0.13 ± 0.02 *	0.19 ± 0.05 *
Time of zero longitudinal force (% stride)	60.71 ± 3.48	64.05 ± 9.16	39.85 ± 4.08 *	21.27 ± 3.92 *
Stance duration (ms)	0.38 ± 0.03 *	0.47 ± 0.04 *	0.36 ± 0.03 *	0.49 ± 0.08 *

* Values that differ significantly between collected trot and passage ($P < 0.05$).
[a] Values are standardised to the combined body masses of horse and rider (forces) or to time (percentage stride).