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The effect of centre of mass location on sagittal plane moments around the centre of mass in trotting horses

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A B S T R A C T

The diagonal limb support pattern at trot provides pitch and roll stability, but little is known about the control of moments about the centre of mass (COM) in horses. Correct COM location is critical in the calculation of pitching moments. The objectives were to determine the effect of COM location on pitching moments in trotting horses and explore how COM location could influence balance.

Kinematic (120 Hz) and *GRF* (4 force plates, 960 Hz) data were collected at trot from three trials of eight horses. The position of the COM was determined from the weighted summation of the segmental COMs and this was then manipulated cranially and caudally to test the model. Sagittal-plane moments around the COM were calculated for each manipulation of the model and their relationship determined using reduced major axis regression.

Over the stride, the moments must sum to zero to prevent accumulation of rotational motion. This was found when the weight on the forelimbs in standing was 58.7% ± 3% (mean ± 95% C.I.), which corresponded closely to the COP ratio in standing. Moments were typically nose-up at foot strike changing to nose-down prior to midstance, and then reversing to nose-up in late stance. Mean moments were larger in the hindlimbs and more sensitive to COM location changes.

Divergence of the COM from the COP creating a vertical force moment arm prior to midstance may assist the hindlimb in relation to propulsive effort. A similar effect is seen in the forelimb during single limb support.

1. Introduction

One of the intriguing differences between quadrupedal gaits relates to how the different limb support patterns provide concurrent *GRF* that maintain balance dynamically while moving the body mass. The diagonal limb support pattern at trot is considered to provide both pitch and roll stability (Hildebrand, 1985), which implies that the moments about the body axes will stay close to zero over a whole stride. For a steady state trot in dogs Lee et al. (1999) suggested that the vertical impulse was distributed between forelimbs and hindlimbs in a similar proportion to the weight on the limbs when standing. When moderately accelerating or decelerating, pitch stability and hence balance around the transverse body axis was maintained by redistributing the proportion of vertical impulse between forelimbs and hindlimbs.

Pitching of the body has been reported at gallop (Biewener et al., 2009; Pfau et al., 2006; Walter and Carrier, 2009; Williams et al., 2009). To limit collisional losses and maintain forward momentum, an asymmetrical footfall pattern is used to gradually deflect the centre of mass (COM) trajectory from downwards and forwards at hindlimb landing to upwards and forwards at leading forelimb lift off (Bertram and Gutmann, 2009). Moments around the COM are also controlled by the timing and distribution of fore and hind limb *GRF* during each stance phase, which are minimized by allowing the combined centre of pressure (COP_{BODY}) to track the COM closely (Biewener et al., 2009).

During steady state gaits COM moments have been measured at trot and gallop in dogs and goats (Biewener et al., 2009), but little is known about COM moments in horses. The COM of horses may be calculated using a link model based approach (Buchner et al., 2000), by integration of force platform data (O'Neill and Schmitt, 2012) or by estimating the COM from a fixed marker or other segmental or geometric method (Lammers and Zurcher, 2011; Ting et al., 1994). Correct COM location was expected to be critical with regards to the calculation of moments, and therefore further study of stability and balance, but little is known about the sensitivity of COM location on moments around the COM. The objectives were to determine the effect of COM location on pitching moments in trotting horses and explore how COM location could influence balance.

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2. Materials and methods

The study was performed with approval from the institutional animal care and use committee, Michigan State University, USA under protocol number 02/08-020-00.

2.1. Experimental data collection

Eight horses of mixed horse breed (predominantly Arabian): 3 mares, 5 geldings with (mean ± s.d.), height 1.49 ± 0.04 m and mass 448 ± 48 kg were judged by a veterinarian to be sound at trot with lameness grade < 1 on a 5 point grading scale (American Association of Equine Practitioners, 1991). All were accustomed to the data collection runway and trained to trot in hand at a consistent speed and stride rate. Mean total braking impulse was measured to confirm that steady state trot was achieved (Hobbs and Clayton, 2013). Reflective cubic markers (6 mm edge length) were attached to the skin on the dorsal midline overlying the dorsal spinous processes of thoracic (T6, T10, T12, T14, T16, T18), lumbar (L2, L6), and sacral (S2 and S4) vertebrae. Markers were placed bilaterally on the rostral facial crests, the transverse processes of cervical (C1, C6) vertebrae, the *tuber spinae scapulae*, the ventral *tuber coxae* and over the centers of rotation of the joints of the fore and hind limbs. In addition, three markers were attached to each hoof wall. Additional virtual markers, which are markers constructed during data analysis that are not present during data collection, were created 2 cm medial to the *tuber spinae scapulae*, the ventral *tuber coxae* and the markers over the centers of rotation of the joints of the limbs. So, for example, the scapula was defined by the *tuber spinae scapulae* and corresponding virtual marker proximally and by the gleno-humeral joint centre and corresponding virtual marker distally. Virtual markers were also created 3.3 cm caudal to C6 to represent the C6/C7 junction and 7.25 cm from S4 to represent the position of the first mobile intervertebral joint caudal to the sacrum at the second coccygeal vertebra (CA2). Proximal and distal end markers were used to construct and track each segment, except for the trunk where the C6/C7 junction and CA2 were used as the segment endpoints and T14, T16, T18, L2, L6, S2, S4, and left and right *tuber coxae* were used as tracking markers.

Kinematic data were recorded at 120 Hz using a ten-camera (Eagle cameras, Motion Analysis Corp.) motion analysis system with proprietary software (Cortex 1.1.4.368, Motion Analysis Corp.) as described by Hobbs and Clayton (2013). Ground reaction forces were recorded at 960 Hz by four synchronized force platforms (FP60120 and FP6090, Bertec Corporation) arranged linearly, with their long axes parallel with the runway. A stationary trial representing a snapshot of each horse standing square was recorded for identification of the marker template. This was followed by 20–30 trotting trials, from which three were selected that had clean strikes of the diagonal hooves on the force plates. The raw data were filtered using a low pass 4th order zero lag Butterworth digital filter with cutoff frequency 10 Hz for kinematic data.

Kinematic and kinetic data were analysed using Visual 3D (C-Motion Inc.) and a full body model was created using inertial parameters from Buchner et al. (1997), see Table 1. The model included 25 segments in total; head, neck, trunk, two forelimbs (scapula, brachium, antebrachium, metacarpus, pastern, hoof), and two hindlimbs (thigh, crus, metatarsus, pastern, hoof). The pastern was the part of the ungulate digit between the metacarpo(-tarso-) phalangeal joint and the coronet (Nomina Anatomica Veterinaria, 2012). The trunk mass included the mass of the tail and fluid/saw cut losses (Buchner et al., 1997) and the trunk COM location was moved 4 mm caudally to take account of the tail. Angular inertial properties of each segment were scaled using the method of Forwood et al. (1985), except that height was substituted for trunk length. Consequently scaling was carried out as follows,

$$I = I_B \frac{(Ml_t^2)}{(M_B l_{Bt}^2)} \tag{1}$$

where I is the COM inertia of the segment, M is the mass of the horse and l_t is the trunk length and I_B, M_B and l_{Bt} are the corresponding mean values provided by Buchner et al. (1997). The pose of all segments except the neck and trunk were estimated for each frame of the kinematic data (Spoor and Veldpaus, 1980).

$$f(R, \vec{O}) = \sum_{i=1-n}^{t} ((\vec{p}_i - R\vec{a}_i) - \vec{O})^2 \tag{2}$$

where R is the rotation matrix from the segment coordinate system (SCS) to the laboratory coordinate system (LCS), $\vec{O}$ is the translation between the SCS and the LCS, $\vec{a}_i$ is the marker vector in the SCS of the standing trial, and $\vec{p}_i$ is the marker vector in the LCS of the ith frame of the movement trial and t is the number of tracking markers on the segment. To reduce the effect of translational artefacts in the trunk (Bobbert et al., 2007), global optimization was used (Lu and O'Connor, 1999; Van den Bogert and Su, 2007). An optimal least squares fit was found so that only rotational mobilization was permitted between the neck and trunk for each frame of data and noise was reduced with a low pass 4th order zero lag Butterworth digital filter with cutoff frequency 6 Hz (Robertson and Dowling, 2003).

$$f(R, \vec{O}) = \sum_{i=1-n}^{tt} ((\vec{p}_i - R(q)\vec{a}_i) - \vec{O}(q))^2 \tag{3}$$

where q are set coordinates based on the configuration of these segments together and tt is the total number of targets on the chain of segments.

Table 1
Segmental parameters for the group (mean and standard error (s.d.)). Mass proportions based on Buchner et al. (1997) except for the trunk, which was the remaining mass when all other segments had been accounted for. Length (m) is segment length taken from the model. COM inertia based on Buchner et al. (1997), scaled using the method of Forwood et al. (1985). Segment residuals (mm) describe the maximum least squared difference in fit of the tracking markers for each segment compared to the standing trial.

	Mass (kg)	Length (m)	COM Inertia (kg/m^2)	Residual (mm)
Trunk	303.2 (32.4)	1.363 (0.04)	43.0 (5.5)	*
Head	19.2 (2.1)	0.276 (0.01)	0.46 (0.01)	5.96 (2.79)
Neck	22.3 (2.4)	0.525 (0.03)	0.61 (0.08)	*
Scapula	9.6 (1.0)	0.279 (0.03)	0.18 (0.02)	4.19 (1.60)
Brachium	7.2 (0.8)	0.216 (0.01)	0.07 (0.01)	6.51 (1.55)
Antebrachium	5.6 (0.6)	0.479 (0.02)	0.08 (0.01)	21.01 (5.24)
Metacarpus	1.3 (0.1)	0.258 (0.01)	0.01 (0.001)	7.09 (2.26)
Fore Pastern	0.6 (0.1)	0.144 (0.01)	0.001 (< 0.001)	11.36 (4.36)
Fore hoof	0.9 (0.1)	0.04 (< 0.001)	0.001 (< 0.001)	3.80 (4.09)
Thigh	15.5 (1.7)	0.334 (0.01)	0.22 (0.03)	5.71 (2.60)
Crus	6.9 (0.7)	0.460 (0.02)	0.09 (0.01)	27.08 (6.07)
Metatarsus	2.4 (0.3)	0.325 (0.01)	0.03 (0.004)	4.90 (1.53)
Hind pastern	0.7 (0.1)	0.139 (0.02)	0.001 (< 0.001)	13.40 (5.51)
Hind hoof	0.8 (0.1)	0.05 (< 0.001)	0.001 (< 0.001)	3.92 (4.03)

* Residuals are not available for the trunk and neck, as they were optimized.

The body's COM was determined as the weighted summation of the segmental COMs for the standing trial and then applied to each frame of movement data.

$$COM = Md = \sum_{i=1-n}^{N=25} (md)_i \tag{4}$$

where m=segment mass, M=mass of horse, N=number of segments, d=distance to the origin of the LCS.

Sagittal plane moments around the COM were calculated for moments due to *GRF*s, the rate of change of angular momentum of each segment around its COM (M_{SEG}), the rate of change of angular momentum of each segment around the body COM (M_{BODY}). Vertical and longitudinal *GRF* components from individual limbs were multiplied by their perpendicular distance to the COM from their corresponding COP distance (COP_{LIMB}), and then summed together to obtain the moments due to *GRF*s acting on the COM.

$$M_{GRF} = \sum_{i=1-n}^{F} ((GRF_z l_y) - (GRF_y l_z))_i \tag{5}$$

where F=number of external forces applied, l=distance from the COP_{LIMB} to the COM of the body, M_{SEG}=the product of angular inertia and angular acceleration with the values being summed over all segments.

$$M_{SEG} = \sum_{i=1-n}^{N=25} (I_{COM}\alpha_{COM})_i \tag{6}$$

where I_{COM}=inertia about the segment COM, α_{COM}=angular acceleration of the segment, M_{BODY} was calculated for each segment as mass multiplied by the relative linear acceleration of the segment COM to the acceleration of the body COM (a), and perpendicular distance of the segment COM to the body COM (r) with the values being summed over all segments.

$$M_{BODY} = \sum_{i=1-n}^{N=25} ((ma_z r_y) + (ma_y r_z))_i \tag{7}$$

As moments due to segment weight are zero at the COM of the body, the angular momentum balance equation was therefore defined as Ruina and Pratap (2010).

$$\sum_{i=1-n} (M_{GRF})_i = \sum_{i=1-n} (M_{SEG} + M_{BODY})_i \tag{8}$$

A sign convention was established for moments, which is described when viewing the right side of the horse in the sagittal plane. A clockwise (nose-down) rotation about the COM was considered as positive and an anticlockwise (nose-up) rotation about the COM was considered negative.