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General Articles

Trunk deformation in the trotting horse

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Summary

Reasons for performing study: **Estimates of the position of the centres of mass (CM) of body segments are usually extrapolated relative to bony landmarks as determined in cadaver studies. This extrapolation assumes that segments are rigid bodies. Since the trunk represents a large percentage of the total body mass in horses, violation of the rigid body assumption by the trunk segment has important consequences for studying the biomechanics of equine locomotion.**

Objectives: **To assess the magnitude of error in CM position due to deformability of the trunk segment and the timing of these errors during the trotting stride. The hypothesis was that shape changes during a stride are repeatable and predictable.**

Methods: **Forty skin markers were attached in a grid pattern on the trunks of 6 adult horses, with an additional marker attached to each hoof. The markers were tracked using an 8 camera motion analysis system. Each horse was tested at 10 different velocities during trotting. The CM of the trunk was calculated under the assumption of a rigid body, based on 5 spine markers and from the volume encompassed by the 40 markers. The difference between the 2 calculation methods quantifies the effect of trunk deformation on the position of the CM.**

Results: **The trunk changed shape during locomotion in a repeatable manner resulting in cyclic changes in CM position. Amplitudes of the CM displacement due to trunk deformation were equal in magnitude in the transverse and longitudinal directions. In the vertical direction, the CM moved only at half the amplitude. Magnitudes were strongly horse-dependent.**

Conclusions and potential relevance: **Shape changes in the equine trunk segment in the horizontal plane should be taken into account when modelling locomotion of horses. Amplitudes are horse dependent, complicating the development of correction routines.**

Introduction

Most biomechanical analyses of equine locomotion use mathematical equations based on rigid-body dynamics, in which the horse is represented by a finite number of linked rigid segments (van den Bogert *et al*. 1989). The positions of the segmental centres of mass (CM) are usually calculated by extrapolating the relative location of the CM according to data reported in cadaver studies (Sprigings and Leach 1986; van den Bogert *et al*. 1989; Buchner *et al*. 1997). Such calculations imply a constant relative location of the CM. Although this is probably a fair assumption for the distal segments of the limbs, it has been shown that timing of the shape changes of the trunk were correlated with limb movements (Nauwelaerts *et al*. 2009). Errors in estimating the position of the CM as a consequence of ignoring changes in trunk shape are propagated through subsequent calculations causing errors in estimation of mechanical energy expenditure.

A trotting horse's movement patterns are different from those of a walking horse (Hildebrand 1965): interlimb coordination changes, stance durations decrease and ranges of joint motion increase (Back 2001), and each stride includes 2 suspension phases in trot. If changes in trunk shape vary with limb excursions, as suggested in the previous study (Nauwelaerts *et al*. 2009), trunk deformability may be expected to be larger during trotting than walking. On the other hand, stabilisation of the trunk becomes increasingly important during trot because of the increases in muscular and inertial forces. Such increases necessitate a stiffening of the spinal column during trot (Robert *et al*. 2001, 2002). The timing of the activation of *rectus abdominis* and *longissimus dorsi* suggests a role in limiting thoracolumbar motion (Robert *et al*. 2001, 2002) and hence stiffening of the trunk. If rigidity of the trunk segment increases, a decrease in the error caused by ignoring the deformability of the trunk may be expected.

In this report, deformability of the trunk segment was quantified during trot by comparing 2 calculation methods that estimate the position of the CM of the trunk. The first method uses a system of 3 equations describing the position of the CM relative to the positions of 5 spine markers, while the second method takes shape changes into account by calculating the centroid of a volume encompassed by a regular mesh of 40 trunk markers. Differences between the 2 calculation methods quantify the effect of shape changes on the position estimate of the CM. The working hypothesis is that the shape changes in the trunk during trot causes a difference in the CM location resulting in a difference in CM coordinates between the 2 calculation methods.

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Materials and methods

The experimental design of Nauwelaerts *et al*. (2009), was used for this study. Briefly, 6 horses of different breeds trotted at 10 speeds through a capture volume created by a motion analysis system[1] consisting of 8 calibrated infrared cameras recording at 120 Hz. Forty-five reflective markers were attached to the horse with carpet tape. Forty were spread uniformly over the trunk segment. Two markers were attached to the abdomen on the ventral midline at the most cranial (just caudal to the olecranon and *triceps* muscle in the standing position) and most caudal parts (just cranial to the patella) of the trunk segment. Three additional markers were placed at equal distances between the cranial and caudal abdominal markers. A similar approach was performed to place 5 spine markers vertically above the abdominal markers. The distance between corresponding spine marker and abdominal marker was divided equally to place 3 additional rows of markers on each side of the trunk. This resulted in 5 equally spaced rings of 8 markers around the trunk, which will be called 'levels 1–5' in a cranial to caudal direction in the remainder of this manuscript. To time the footfall patterns, one marker was placed on the lateral side of each hoof, plus a reference marker on the forehead. The positions of all markers were tracked for one entire locomotor cycle starting at ground contact of the right front hoof. Contact and lift-off times were determined for each hoof based on the trajectories of the hoof marker.

Prior to each trotting session, a static trial was recorded with the horse standing square in the middle of the capture volume. The centre of the trunk volume was used as the origin of a local coordinate system that moved with the horse and represented the centre of mass of the trunk in a rigid body (calculation method 1: rigid segment approach). A system of 3 linear least square regressions was defined based on the relative position of the CM of the trunk for the standing horse using the coordinates of the 5 spine markers. The directions of the axes of the local coordinate system were: X longitudinal and positive cranially, Z vertical and positive upward, and Y transverse, mutually perpendicular to the X and Z axes, and positive to the left. The system of equations was then used to find the trunk CM location in every time interval for one stride of the trotting horse.

The coordinates of the centre of mass of the deformable trunk segment were calculated on a frame-by-frame basis in 3DSMAX 9[2] as the centre of the volume encompassed by a linear mesh of 40 trunk markers assuming uniform density of the segment (calculation method 2: deformable segment approach). The coordinates of the centre of the volume were recalculated at each time point in the local coordinate system to quantify the effect of deformation on CM position; if the segment remains rigid during locomotion, the coordinates of the centre of the volume of the deformable trunk are indistinguishable from the origin of the local coordinate system (rigid trunk).

Differences between the 2 calculation methods along the 3 axes of the local coordinate system were plotted against time. Amplitudes of the differences in centre of mass coordinates between the 2 calculation methods quantify the maximal magnitude of the error caused by ignoring the deformation of the trunk segment. Amplitudes were determined along the 3 axes of the local coordinate system.

The timing of hoof contacts and lift-offs were added to the graphs to examine temporal correlations between the error amplitudes and limb movements. The dimensions of the trunk segment were calculated through the stride cycle as the height and width of the volume at 5 levels along the trunk, corresponding with the 5 marker levels, and the craniocaudal length was measured from the middle of the first ring of markers to the fifth one. Minimal and maximal values for the difference in centre of mass position using the 2 calculation methods were measured and the range expressed in absolute and percentage terms relative to the largest value in the stride.

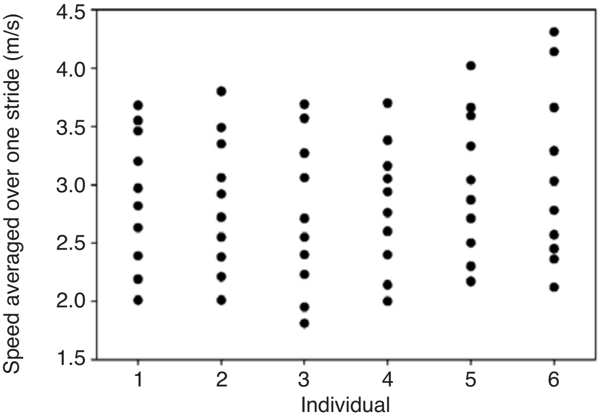

Fig 1: Speed range (in m/s) of trotting trials for each horse.

Statistical analyses[3] used a multivariate analysis of covariance (MANCOVA) with horse defined as a random factor and speed as a covariate. A similar model was built for the dimensional data with the levels (1–5) as fixed factors. To detect grouping in the variables, Tukey B tests were used as *post hoc* tests. To find an appropriate estimate for the CM shifts due to the deformation of the trunk, an ANOVA was performed on the change in linear dimensions of the 5 heights, 5 widths, total craniocaudal length of the volume and the CM shifts in all 3 directions. In addition, to find a good estimate for the time profiles of the CM shift, correlation coefficients between the CM position profiles in the local coordinate system and each of the dimensions and trunk markers were calculated for each trial.

Results

Trunk dimensions

Trunk dimensions changed during the locomotor cycle (Fig 2). Trunk height averaged over one locomotor cycle decreased progressively in a cranial to caudal direction. Percent changes in trunk height during the stride were significantly smaller at the 3 cranial levels (level 1: 2.9%; level 2: 2.1% and level 3: 3.3%) than at the 2 caudal levels (level 4: 4.5% and level 5: 5.5%). This corresponded to mean ± s.d. absolute changes in mm of, respectively, 11.5 ± 0.5, 15.1 ± 0.5, 23.0 ± 0.6, 30.8 ± 0.8 and 35.8 ± 1.0. Trunk width averaged over one locomotor cycle was smallest at the cranial level, increasing to level 3, then remaining quite consistent through level 4 and 5. Relative changes in width were significantly larger at the most cranial and most caudal levels (level 1: 4.3% and level 5: 4.0%), and smallest at level 2 (3.0%) and level 3 (3.0%), with level 4 as an intermediate at 3.6%. This corresponded to means ± s.d. absolute changes in mm of 21.7 ± 0.7, 17.0 ± 0.7, 18.8 ± 1, 23.3 ± 1 and 25.9 ± 0.9, respectively. Relative change in craniocaudal length was 4% (25.2 ± 2).

Trunk deformation

The trunk changed shape during locomotion in a repeatable manner resulting in cyclic changes in CM position between the 2 calculation methods (Fig 3). In the vertical direction, the difference between CM of the deformable trunk and CM of the

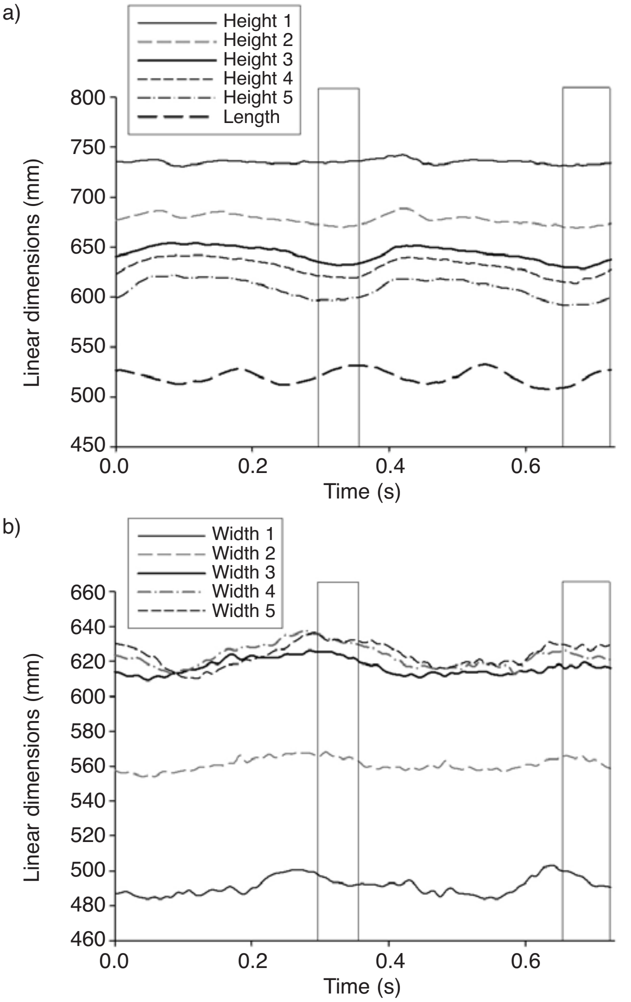

Fig 2: Changes in trunk dimensions throughout the locomotor cycle at trot. Suspension phase is shown as a white box. a) Changes in vertical trunk dimension at 5 levels along the trunk (height 1: most cranial to height 5: most caudal) and changes in trunk length. b) Changes in trunk width at 5 levels along the trunk (width 1: most cranial to width 5: most caudal).

rigid trunk was consistently positive, indicating that CM of the deformable trunk was higher than expected from its relative location during standing. The discrepancy was greatest during the suspension phase and least just before midstance. In the lateral direction, the CM calculated from the volume moved to the left throughout retraction of the left forelimb and to the right during retraction of the right forelimb. In the longitudinal direction, the difference in CM position was maximal caudally just before midstance and maximal cranially in terminal stance.

None of the correlation matrices of the time profiles of the CM error with any length measure between 2 markers gave a satisfactory correlation coefficient (r significant and larger than 0.8).

Amplitude of error

Mean ± s.d. amplitudes of the deformation effect were equal in magnitude (25.1 ± 6.4 and 25.1 ± 4.3 mm, relative to total movement of CM respectively 45% and 1%) in the transverse and longitudinal directions (Fig 3). In the vertical direction, the CM of the deformable trunk moved only at half the amplitude (12.7 ± 2.6 mm, relative to total movement of CM 16%) and was consistently above the CM of a standing horse.

Effect of horse

All dimensional variables, absolute and relative, except height change, were horse dependent. Timing of CM motion was consistent, but magnitudes were strongly horse-dependent causing the horses to fall into 2 distinct groups, the members of which were not different from each other in height or mass. Horse variability of the transverse and longitudinal amplitudes was mainly caused by *horse 6*, the youngest horse, and *horse 5*, the largest horse.

Effect of speed

The minimal height and minimal width averaged over all levels increased with speed, but none of the other dimensions were affected by speed. Speed had a small, but significant, negative effect on the magnitude of error in the longitudinal direction (F = 8.036; P = 0.006), but no effect on transverse (F = 3.959; P = 0.052) or vertical (F = 0.429; P = 0.515) magnitude of error.

Discussion

The horse's trunk changes shape in a consistent manner throughout the locomotor cycle and the shape change affects the position of the CM, supporting the hypothesis. As a result, the CM shifts maximally cranially, dorsally and laterally in the terminal part of the diagonal stance and is maximally caudally and ventrally prior to midstance. At the end of the suspension phase, the CM is in the neutral (middle) position in the transverse direction. At the end of the swing phase and throughout the suspension phase, the ribcage is pulled towards the side of the retracting forelimb probably due to the action of *serratus ventralis thoracis*, which suspends the thorax from the scapula (Payne *et al*. 2004). This causes the total CM to move laterally and dorsally towards the scapular attachment of the muscle. The caudal shift possibly coincides with extension of the

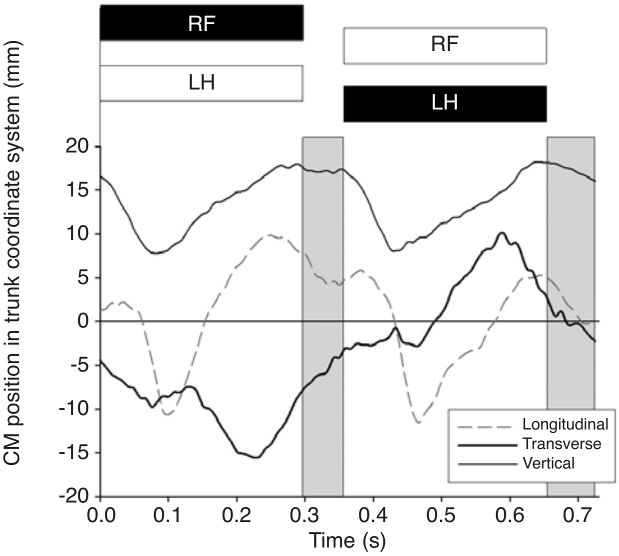

Fig 3: Patterns of CM movements calculated from the trunk volume in a local coordinate system for a horse trotting at 3 m/s. The origin of the local coordinate system is calculated from equations describing the relative position of the CM of the trunk volume of a standing horse based on 5 spine markers. X is the longitudinal axis (positive cranially), Y is transverse (positive left) and Z is vertical (positive up). Footfall patterns are shown as rectangular boxes representing the hoof on the ground (RF = right front, LF = left front, RH = right hind, LH = left hind). Suspension phases are shown as grey vertical boxes.

thoracolumbar spine, while the axial rotations of the vertebrae explain the transverse shift (Faber *et al*. 2001). One of the key moments in the CM shift profile seems to happen right before midstance, coinciding with a negative peak in the fore-aft ground reaction force in the forelimbs (Merkens *et al*. 1993), which may cause a large change in trunk shape due to the inertia of the trunk. Changes in spinal flexion and pelvic rotations add to the shape changes caused by movements of the forelimb and scapula. The length changes coincide with lateral bending of the spine (Faber *et al*. 2001). The cranial and caudal parts of the spine bend out of phase, causing the 4 peaks in the trunk length profile.

Changes in dimensions were of the same order of magnitude as a previous study in which reflective markers were attached over spinous processes T10 and T16 and at ribs 10 and 16 at their most lateral projections (Colborne *et al*. 2006; Thorpe *et al*. 2009). These authors were interested in changes in thoracic geometry relating locomotion to ventilation, so they did not study changes in movement of the caudal part of the trunk. We found larger changes caudally suggesting additional mechanisms for trunk shape changes than the loading of the forelimbs. The width changes at the most cranial level are probably artifacts of scapular motion and the consequent caudal movement of triceps as the forelimb is retracted during locomotion rather than a real increase in width of the thorax. The relatively large increase in width caudally likely reflects the deformability of the costal arch.

The effects of the deformation of the trunk segment are smaller during trotting than walking in all 3 directions, with the largest difference in the transverse direction (S. Nauwelaerts, unpublished data). The amplitude of the left to right swaying of the belly is reduced by about half during the trot compared with the walk as a result of the diagonal support patterns and intervening suspension phases. Due to larger inertial effects and larger ground reaction forces, there is more need for stabilisation of the trunk in trot than in walk. Lateral bending at the intervertebral joints is smaller during trotting compared with walking (Faber *et al*. 2001), which is a consequence of greater muscular activity in *rectus abdominis* (Robert *et al*. 2001) and in *longissimus dorsi* (Robert *et al*. 2001; Wakeling *et al*. 2007). Other muscles, such as *transversus abdominis* and the abdominal obliques, may act to reduce the swaying of the belly.

In this study, only shifts in CM due to a change in trunk shape were taken into account, which neglects the effect of changes in density distribution that can occur during breathing, or as a consequence of inertial effects on visceral tissues or possibly both (Lee and Banzett 1997). Mechanical linkage systems would work through displacement of the ribcage, movements at the intervertebral joints or ribcage loading by the forelimbs. Displacements of the ribcage coupled to locomotor movements would cause changes in dorsoventral (height) and lateral (width) diameters of the trunk. The relationship coupling between the impact of the forelimb and peak expiratory pressure proved to be inconsistent in walks and trots regardless of the ratio between breathing and stride frequency (Ainsworth *et al*. 1996). Moreover, at trot, breathing patterns can be variable, adding variability to the trunk changes. Relative changes in height were largest in the abdominal part of the trunk, which is bounded ventrally by deformable soft tissues, whereas changes at the thorax were only 2%. Although the relative width changes were greatest just behind the forelimbs, the magnitude was small in absolute terms. Absolute width changes were larger caudally perhaps reflecting a 'bucket handle' motion that could hypothetically cause respiration flows out of phase with abdominal visceral mass displacements (Lee and Banzett 1997).

In conclusion, shape changes in the equine trunk segment in the horizontal plane should be taken into account when modelling the mechanics of locomotion of horses. Unfortunately, there does not seem to be an easy correction routine for the trunk shape changes based on a small set of markers because amplitudes were horse dependent and attempts to describe trunk deformation based on a smaller set of markers failed.

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Manufacturers' addresses

[1]Motion Analysis Corp, Santa Rosa, California, USA.
[2]Autodesk, Inc, San Rafael, California, USA.
[3]SPSS Inc, Chicago, Illinois, USA.

References

Ainsworth, D.M., Eicker, S.W., Nalevanko, M.E., Ducharme, N.G., Hackett, R.P. and Snedden, K. (1996) The effect of exercise on diaphragmatic activation in horses. *Resp. Physiol*. **106**, 35-46.

Back, W. (2001) Intra-limb coordination: the forelimb and the hindlimb. In: *Equine Locomotion*, Eds: W. Back and H. Clayton, W.B. Saunders, London. pp 95-133.

Buchner, H.H.F., Savelberg, H.H.C.M., Schamhardt, H.C. and Barneveld, A. (1997) Inertial properties of Dutch warmblood horses. *J. Biomech*. **30**, 653-658.

Colborne, G.R., Allen, R.J., Wilson, R.J.R., Marlin, D.J. and Franklin, S.J. (2006) Thoracic geometry changes during equine locomotion. *Equine Comp. Exerc. Physiol*. **3**, 53-59.

Faber, M., Johnston, C., Schamhardt, H., van Weeren, R., Roepstorff, L. and Barneveld, A. (2001) Basic three-dimensional kinematics of the vertebral column of horses trotting on a treadmill. *Am. J. vet. Res*. **62**, 757-764.

Hildebrand, M. (1965) Symmetrical gaits of horses. *Science* **150**, 701-708.

Lee, H. and Banzett, R.B. (1997) Mechanical links between locomotion and breathing: Can you breathe with your legs? *News Physiol. Sci*. **12**, 273-278.

Merkens, H.W., Schamhardt, H.C., van Osch, G. and van den Bogert, A.J. (1993) Ground reaction force patterns of Dutch Warmblood horses at normal trot. *Equine vet. J*. **25**, 134-137.

Nauwelaerts, S., Kaiser, L., Malinowski, R. and Clayton, H.M. (2009) Effects of trunk deformation on trunk center of mass mechanical energy estimates in the moving horse, *Equus caballus*. *J. Biomech*. **42**, 308-311.

Payne, R.C., Veenman, P. and Wilson, A.M. (2004) The role of the extrinsic thoracic limb muscles in equine locomotion. *J. Anat*. **206**, 193-204.

Robert, C., Valette, J.-P. and Denoix, J.-M. (2001) The effects of treadmill inclination and speed on the activity of three trunk muscles in the trotting horse. *Equine vet. J*. **33**, 466-472.

Robert, C., Valette, J.-P., Pourcelot, P. Audigié, F. and Denoix, J.-M. (2002) Effects of trotting speed on muscle activity and kinematics in saddlehorses. *Equine vet. J., Suppl*. **34**, 295-301.

Sprigings, E. and Leach, D. (1986) Standardised technique for determining the centre of gravity of body and limb segments of horses. *Equine vet. J*. **18**, 43-49.

Thorpe, C.T., Marlin, D.J., Franklin, S.H. and Colborne, G.R. (2007) Transverse and dorso-ventral changes in thoracic dimension during equine locomotion. *Vet. J*. Epub ahead of print.

van den Bogert, A.J., Hartman, W. and Sauren, A.A.H.J. (1989) Measurement and computation of inertial parameters in the horse. In: *Computer Simulation of Locomotion in the Horse,* PhD thesis, University of Utrecht.

Wakeling, J.M., Ritruechai, P., Dalton, S. and Nankervis, K. (2007) Segmental variation in the activity and function of the equine *longissimus dorsi* muscle during walk and trot. *Equine Comp. Exerc. Physiol*. **4**, 95-103.

Author contributions Both authors contributed to the initiation, conception, planning and writing for this study. Its execution and statistics were by S.N.