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# Effects of trunk deformation on trunk center of mass mechanical energy estimates in the moving horse, *Equus caballus*

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ABSTRACT

The estimation of the position of the center of mass (CM) is essential in a wide range of biomechanical analyses. In horses, the majority of the body mass is contained in the trunk and in most studies, the trunk is assumed to be rigid. However, this rigidity assumption has not been tested. We quantified changes in the position of the trunk CM due to external shape changes by measuring the kinematics of a mesh encompassing the trunk. Using a frame of reference fixed to the horse's spine, we described the shape deformation of the trunk during walking. In addition, we tested for speed and individual differences. The significance of any trunk deformation was illustrated by calculating mechanical energy profiles. Errors in the estimation of the trunk CM due to a rigid body approach were always small in the vertical direction, but can be significant in the transverse direction and in the longitudinal direction at high walking speeds. This is enough to change the mechanical energy expenditure estimates up to 25%. When extrapolating the position of the trunk CM from cadaver data, one should be aware of this extra source of error, separated from the measurement error of the cadaver CM. We also found considerable inter-individual variation, which complicates theoretical correction routines. We suggest using extra markers on the trunk during gait analysis to correct this CM shift experimentally.



## 1. Introduction

A wide range of biomechanical analyses, including balance, coordination, mechanical energy and inverse dynamics, rely on estimating the position of the center of mass (CM) accurately. In balance (e.g. Pai, 2003; Parker et al., 2006) and coordination (e.g. Robert et al., 2007; Patron et al., 2005; Lyon and Day, 2005) studies, trajectories of the CM are combined with information of center of pressure of the ground reaction force to elucidate the control of posture and balance (Lenzi et al., 2003). Estimates of mechanical energy expenditure during locomotion (e.g. Biewener, 2006; Gottschall and Kram, 2006) require information describing the position and the velocity of CM. Estimation of the position of the CM is essential in inverse dynamics analyses, a technique that uses the kinematic representation of movement to derive the kinetics responsible for that movement (van den Bogert, 1994; van den Bogert et al., 1996). The vast majority of current analytic techniques model the body segments as rigid bodies (Andriacchi and Alexander, 2000), which neglects the possibility of shape changes that affect the relative position of the CM during movement.

In horses, a large proportion of the body mass is contained in the trunk (van den Bogert et al., 1989; Buchner et al., 1997). The equine thorax is considered to be a relatively rigid structure (Leith and Gillespie, 1971; Bramble, 1989; Colborne et al., 2006) and overall trunk movement is considered as a good estimate of total CM displacement (Buchner et al., 2000; Pfau et al., 2006). However, it has never been explicitly tested whether CM position is consistent throughout a stride. In this paper, we quantify external shape changes and estimate their effect on the CM position by measuring the kinematics of a mesh encompassing the trunk and calculating its volume during a full gait cycle. To assess the relevance of the shape deformation in energy calculations, we compare mechanical energy profiles, first under the rigidity assumption and second taking shape changes into account.

## 2. Materials and methods

### 2.1. Experimental setup

#### 2.1.1. Animals

Data were obtained from six sound horses, with a mean ($\pm$S.D.) age of $10\pm5$ years and a mean mass of $502\pm98$ kg, ranging from 417 to 673 kg representing a variety of breeds, body shapes and sizes.

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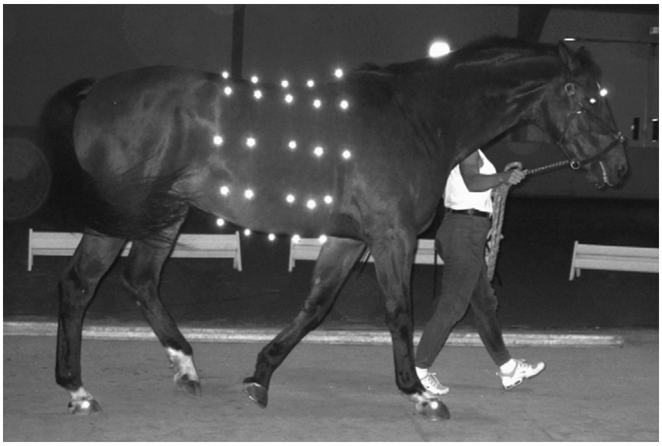

**Fig. 1.** Picture of markers attached to the trunk of the horse. Notice the regular grid pattern.

*2.1.2. Motion capture*

Forty-five reflective cubes of 6 mm were attached to each horse using double-sided tape. We attached 40 skin markers in a regular grid pattern on the trunk, placed geometrically rather than with respect to anatomical structures (Fig. 1). Additional markers were placed on the forehead and on the lateral side of each hoof.

Three-dimensional kinematic data were collected in the global coordinate system using eight Eagle infra-red cameras recording at 120 Hz using real-time 5.0.4 software (Motion Analysis Corporation, Santa Rosa, CA).

*2.1.3. Standing trial*

Each experiment started with recording a static 60 Hz trial of the horse standing square. A stick figure was built to facilitate automated recognition of the markers. The volume encompassed by the linear mesh of 40 trunk markers was calculated in 3DSMAX 9 (Autodesk, Inc., San Rafael, CA) and the coordinates of the CM were determined assuming uniform density of the segment. The axes of the local coordinate system were determined based on the trunk dimensions: $X$ is longitudinal, aligned with spinal markers using a least square linear fit and positive cranially, $Z$ is vertical and positive upward, and $Y$ is transverse, mutually perpendicular to the $X$ and $Z$ axes, and positive to the left. The origin of the local coordinate system was defined in the center of the volume of the mesh formed by the 40 trunk markers in the standing trial. A system of three linear equations based on the spatial relationships between the center of the mesh and the coordinates of the five spine markers was defined for each horse. This approach was similar to the Buchner et al. (2000) approach to allow for comparison between the two 3D models. The only difference is that we extrapolated the position of the CM not from the position as measured on a cadaver study but instead from the position estimated as the volume of the trunk in a standing trial. Variations in the equations of different standing trials were found to be small within one horse.

*2.1.4. Experimental trials*

During data collection, horses were led in hand until 10 trials had been conducted representing the entire range of speeds over which each horse was willing to walk and trot.

*2.2. Data analysis*

A trial consisted of a single stride starting with contact of the right forelimb. The cranial spine marker was used to determine speed. For each animal, ten sequences within the speed range of 0.7–1.9 m/s (walk) and 1.8–4.3 m/s (trot) were analysed. All speeds were converted to Froude numbers by squaring speed and dividing it by the product of the average leg length and gravitational acceleration. The position of the origin of the coordinate system based on the linear equations of the standing trial was calculated from the moving positions of the five spine markers ($CM_{rigid}$). $CM_{deformable}$ is the CM calculated as the center of the mesh based on the 40 trunk markers. Differences between the positions of both $CM_{rigid}$ and $CM_{deformable}$ were interpreted as being caused by changes in CM position due to trunk deformation.

*2.2.1. Energy calculations*

For the total trunk, kinetic energy in the three directions of the coordinate system ($\frac{1}{2}mv^2$ with $m$ = mass and $v$ = velocity) and potential energy ($mgh$ with $g$ = gravitational acceleration and $h$ = height) were calculated over one full gait cycle for $CM_{rigid}$ and $CM_{deformable}$. Rotational energy was negligible based on preliminary data and was ignored. Instantaneous total mechanical energy was the sum of all kinetic energies and potential energy. The instantaneous difference between the mechanical energy estimates for both CMs was calculated and the maximal and minimal value of the differences was plotted against the Froude number.

*2.3. Statistics*

A multivariate analysis of covariance (MANCOVA) was performed in SPSS 16.0.1 on the maximal and minimal differences in total mechanical energy calculated from $CM_{rigid}$ and $CM_{deformable}$. Fixed effects were horse and gait (walk, trot). The covariate was the Froude number. To test for individual differences between horses, the Froude number was removed as a covariate and a Tukey-B posthoc test was performed on horse as a fixed effect.

## 3. Results

Motion patterns of $CM_{deformable}$ described in the local coordinate system are consistent and repeatable. The origin of the local coordinate system attached to the horse's spine ($CM_{rigid}$) and $CM_{deformable}$ did not move together throughout the stride resulting in differences in mechanical energy profiles. Total mechanical energy profiles for the trunk segment (Fig. 2) showed that differences in absolute values of minimal and maximal peaks (Fig. 3) between the two approaches increased with the Froude number. Inter-individual differences were small and a posthoc test revealed that horse 5, the heaviest horse in the group, was significantly different from all other horses.

## 4. Discussion

Several mechanisms can cause the position of the CM of the trunk to shift relative to the position of the CM extrapolated from measurements on a cadaver trunk. The two most important mechanisms are changes in trunk dimensions or changes in trunk density distribution. This paper focuses on the effect of changes in trunk dimensions on trunk CM position and mechanical energy fluctuations. Asymmetric changes in trunk volume cause a change in trunk shape and therefore a change in the relative position of the trunk CM.

The energy calculations show that taking shape changes of the trunk segment into account has vast consequences for estimating the instantaneous total mechanical energy for the trunk segment. Since the trunk is the segment with the largest mass and since shape changes accentuate the movements of the limbs, it is highly likely that this difference will be reflected in the mechanical energy profile of the body CM. This might explain why some authors did not find a satisfactory match between the kinematic approach of estimating the position of the CM and the kinetic approach using force plate data (Arabian, unpublished).

Although shifts in CM position due to deformation are smaller in amplitude during trotting, the effect on forward kinetic energy is considerable, resulting in higher maxima and lower minima in the instantaneous total mechanical energy profile. This is especially true for horse 5. Being slightly overweight and large seems to increase this effect.

Since the CM is consistently higher during walking than during standing, it can be assumed that the abdominal muscles are engaged to elevate the ventral abdominal wall. Stabilization of the trunk by the abdominal muscles may also explain why the assumption of a rigid trunk works in the vertical direction: deviations from the rigid approach are small ($<1$ cm). Since the error in the vertical direction is small, it partly explains why accurate estimates of the vertical ground reaction forces from kinematic data can be obtained for trotting but less for walking (Bobbert et al., 2007). Since the Bobbert et al. (2007) paper used a

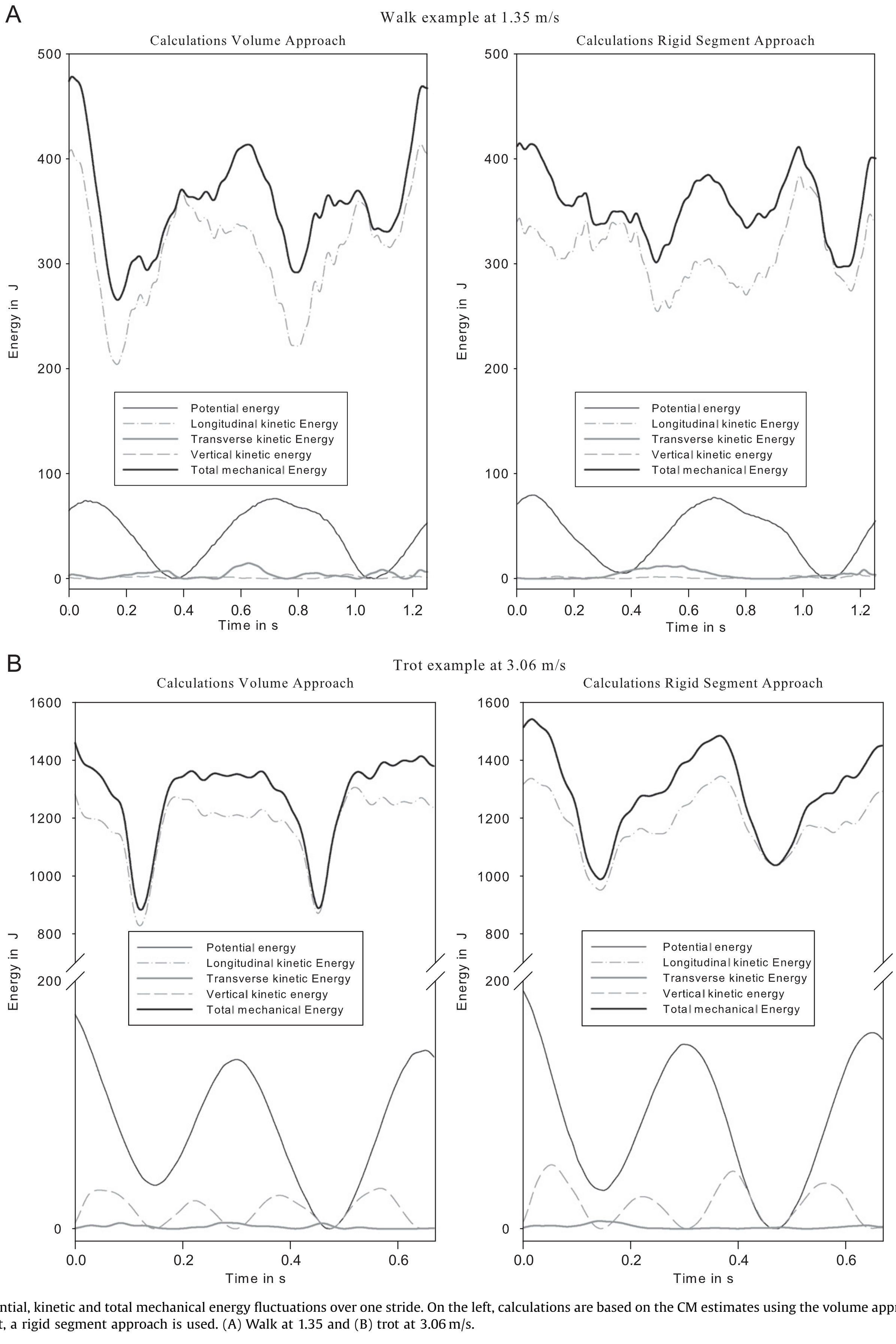


**Fig. 2.** Potential, kinetic and total mechanical energy fluctuations over one stride. On the left, calculations are based on the CM estimates using the volume approach, while on the right, a rigid segment approach is used. (A) Walk at 1.35 and (B) trot at 3.06 m/s.

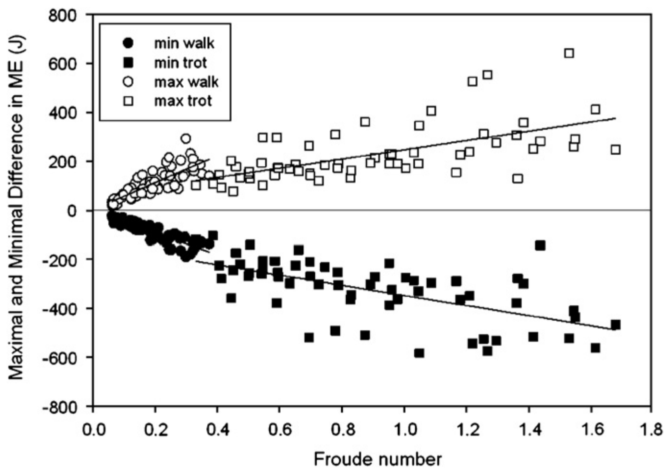


**Fig. 3.** Maximal and minimal difference between total mechanical energy (ME) calculated from $CM_{rigid}$ and $CM_{deformable}$ over one stride plotted against the Froude number (velocity$^2$/g limb length) for both walking (open symbols) and trotting (filled symbols).

2D model, this effect is enhanced by the more extensive mediolateral movements of the CM of the trunk during walking.

Apart from ignoring the deformation of the trunk, the rigid segment approach in horse locomotion has additional challenges. The local coordinate system was defined attached to the spine, which ignores its slightly flexible nature. Perhaps more importantly, the markers along the spine do not allow for all three rotational degrees of freedom equally well. Pitch and yaw can be taken into account but roll is difficult to incorporate.

Our configuration therefore gives only 5 degrees of freedom (3 translational and 2 rotational) to compare the deformable approach to. This error in fact is included in the error amplitudes we attribute to trunk deformation and our error estimates might be slightly overestimated. One solution would be the comparison of our findings to an inertial sensor system that allows 6 degrees of freedom attached to the spine, as described in Pfau et al. (2006) for galloping horses. This method is a vast improvement over the rigid body kinematic method, especially at high speeds, but the underlying assumption is that the CM does not move with respect to the attachment site of the sensor.

In conclusion, changes in the shape of the trunk volume alter the position of the trunk CM. When extrapolating the position of the CM of the trunk from cadaver data, one should be aware of this extra source of error, separate from the measurement error of the cadaver CM. We found considerable inter-individual variation, which complicates theoretical correction routines. However, since the CM of the trunk moves as one unit, estimates of trunk CM location can be improved using extra markers distributed over the trunk segment.

## Conflict of interest statement

All authors deny having any financial and personal relationships with other people or organisations that could inappropriately influence our work.


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