Thoracic geometry changes during equine locomotion

G Robert Colborne*, Rebecca J Allen, Rosanna JR Wilson, David J Marlin and Samantha H Franklin

Equine Centre, University of Bristol, Langford, Somerset BS40 5DU, UK
Equine Centre, Faculty of Medical & Veterinary Sciences, University of Bristol, Langford, N. Somerset, BS40 5DU, UK
* Corresponding author: bob.colborne@bristol.ac.uk

Equine and Comparative Exercise Physiology 3(2): 53–59
DOI: 10.1079/ECP200686

Abstract

Classic descriptions of rib motion during ventilation include three-dimensional movements that are tied to the locomotor pattern. It is still not clear how chest wall and diaphragmatic movements contribute to ventilation. The purpose of this paper was to evaluate how gait affects local thoracic geometry in horses. Hemispherical markers were placed on the skin over the ribs and spine to calculate thoracic hemi-diameter. Ventilatory airflows were recorded using an ultrasonic flowmeter system. Airflow and kinematic data were collected synchronously at walk (1.8 m s⁻¹), trot (4 m s⁻¹), canter and gallop (6, 8 and 10 m s⁻¹) on the treadmill. At walk and trot, the changes in right and left hemi-diameter were approximately symmetric. At walk, mean hemi-diameter changes were 40 mm (rib 10) and 47 mm (rib 16). At trot, they were 33 mm (rib 10) and 34 mm (rib 16). Across the three canter and gallop speeds, leading (right) side hemi-diameter change increased from 25 to 30 to 35 mm (rib 10) and from 23 to 37 to 46 mm (rib 16). The trailing (left) side hemi-diameter increased from 50 to 67 to 70 mm (rib 10) and from 36 to 48 to 54 mm (rib 16) (P < 0.01). At canter and gallop, the non-lead side of the thorax is subjected to larger amplitude changes in hemi-diameter than the lead side, which tends to be more compressed overall and demonstrates smaller amplitudes of change in diameter.

Keywords: rib movement; locomotion; ventilation; thoracic geometry

Introduction

Classic descriptions of ventilation of the mammalian lungs include movements by the ribs, which change the transverse and dorso–ventral diameters of the thorax, and movements of the diaphragm, which change the cranio–caudal dimension. In most mammals, inspiration is usually described as an active process starting from functional residual capacity, involving contraction of the diaphragm and the intercostal muscles and expiration is thought to be largely passive, returning the lungs to their functional residual capacity. The horse breathes with a biphasic flow pattern around, rather than from, its functional residual capacity¹. Inhalation and exhalation each have active and passive phases and the relative proportion of these varies across horses, and from breath to breath².

During locomotion, the horse tends to couple its breathing to its stride pattern, especially in the asymmetric gaits where 99% of breaths are 1:1 coupled, to minimize the mechanical constraints to ventilation imposed by limb movements³. An impact loading theory⁴ proposed that phases in the respiratory cycle were related to events in the locomotor cycle. As the forelimb is rotated forward during terminal swing phase, the ribs would be pulled upwards and forwards, causing lateral expansion of the chest and inspiration. Forces imparted by the scapulae to the chest wall during stance would cause compression and thereby aid expiration. The ‘visceral piston’ mechanism has also been proposed as a contributor to alterations in intra-thoracic pressure. In theory, movements of the abdominal viscera in phase with accelerations and decelerations of the trunk should affect the motion of the diaphragm, but Young et al.⁵ have

©CAB International 2006
shown that forward displacement of the abdominal viscera does not coincide completely with expiration.

The equine thorax is thought to be a relatively rigid structure\(^5,^7\) and, until recently, the contribution of chest expansion to ventilation in the horse has not been described. Marlin \textit{et al.}\(^8\) used respiratory inductance plethysmography to show that chest circumference increased and decreased a very small amount with inspiration and expiration at rest, walk and trot. At canter and gallop, the ventilatory pattern was paradoxically out of phase and thoracic circumference changed by only 1–2 cm despite a 4–5-fold increase in tidal volume. Lobeline-induced hyperpnoea at rest caused a 4–6-fold increase in tidal volume and large excursions of the chest wall in phase with the airflows, illustrating that the thoracic expansion is not limited by stiffness of the ribcage.

The mechanics of ventilation in the exercising horse are still not clear. The purpose of this study was to evaluate the symmetry of thoracic wall movements during locomotion to determine whether ventilation can be more precisely linked to the motion of individual limbs in both the symmetric and asymmetric gaits.

**Methods**

Two Thoroughbred horses underwent a standard exercise test (SET) on the high-speed treadmill. They were at a medium level of fitness and were habituated to the treadmill and to the respiratory airflow collection system prior to collection of data. As these were treadmill-habituated horses, they did not wear a safety surcingle as this would have interfered with data collection and might have interfered with the natural motion of the thoracic wall. Simultaneous airflow measurements, limb contacts and thoracic wall movements were recorded during the SETs. Hemispherical retro-reflective markers were glued to the horse’s skin over spinous processes T10 and T16 and to the skin over ribs 10 and 16 at their most lateral projections. Markers were also applied to the fore hooves to identify their stance times in the stride cycle.

**Standard exercise test**

The horses were warmed up for 20 min on a mechanical horse walker. Reflective markers were then applied to the horse for kinematic data capture and a mask was fitted for measurement of ventilatory airflow. The horse was led onto the treadmill and data were captured for two 5-s periods while the horse was standing still. The treadmill was started and the horse walked for 2 min at 1.8 m s\(^{-1}\), trotted for 4 min at 4.0 m s\(^{-1}\) and cantered for 1 min each at 6.0, 8.0 m s\(^{-1}\) and galloped at 10.0 m s\(^{-1}\). The treadmill was level throughout testing. An assistant recorded lead limb during canter and gallop. Just before the end of each incremental level, two 5-s data captures were taken. The treadmill was stopped after the 10.0 m s\(^{-1}\) increment and two final standing measurements were captured. The treadmill was then restarted at walking speed and the horse was cooled down for at least 3 min before removal from the treadmill.

**Kinematic data collection**

Motion data were captured using a four-camera ProReflex\(^\circledast\) kinematic system (Qualisys Medical AB, Esperantoplatsen 7–9, S-411 19 Göteborg, Sweden). The four cameras were set up near the four corners of the treadmill, such that marker positions on both sides of the horse could be collected for simultaneous evaluation of the right and left hemithorax. To achieve good accuracy of marker position in the transverse plane, the two cranially located cameras were situated at angles of about 20\(^\circ\) from the mid-sagittal plane and about 3 m above the ground on telescoped tripods, aiming down at the horse. The two caudal cameras were likewise elevated and positioned about 45\(^\circ\) from the mid-sagittal plane for viewing the markers on the trunk and on the limbs. The calibrated volume of space was c. 1.2 m wide, 3.0 m long and 2.0 m high and measurement accuracy was estimated at \(\pm 2\) mm. Kinematic data were captured at 200 Hz for two 5-s period at each incremental speed.

**Airflow data collection**

Ventilatory airflow was measured using a breath-by-breath flowmeter system. Inspiratory and expiratory flow rates were recorded online at 200 Hz simultaneously with kinematic data capture through additional analogue channels. Ultrasonic flow transducers (BRDL, Flowmetrics Division, Birmingham Research, Birmingham, UK) were mounted into a lightweight, close-fitting plastic mask worn by the horse, such that they were positioned in line with the nostrils and ventilatory airflow was calculated according to the technique described by Woakes \textit{et al.}\(^9\). The transducers were individually calibrated before and after each run using fixed flow rates up to 601 s\(^{-1}\). The system has been shown to have minimal effect on the horse’s ventilatory parameters\(^10\).

**Data analysis**

The markers on the skin over the spinous processes and on the lateral thoracic wall were identified and tracked through the 5-s sampling period along with the markers on the hooves, such that multiple stride cycles were analysed per trial. Tracked three-dimensional data were exported to a spreadsheet for calculation of thoracic hemi-diameter as the transverse distance between the markers on the spinous processes and the equivalent markers on the lateral body wall over the ribs. Airflows were calculated from calibration of the voltages.
from each of the two ultrasonic flow transducers, which were then arithmetically summed to yield a total flow rate. Positive airflow represented expiration and negative airflow represented inspiration. Paired t-tests were used to compare changes in thoracic hemi-diameter between right and left sides.

### Results

The measured changes in thoracic hemi-diameter are presented in Table 1. Values represent the mean amplitude of change in transverse hemi-diameter through the ventilatory cycle (spine marker to rib marker) for right and left ribs 10 and 16, standing at rest before and after exercise and for each of the gaits. During pre-exercise standing, too few breathing cycles were collected for determination of standard deviations, and therefore no statistical comparisons were possible. Horse 1 demonstrated some thoracic wall motion asymmetry during standing pre-exercise, but no asymmetry in amplitudes of rib motion during walk and trot. There were, however, significant (\(P < 0.01\)) differences between right and left thoracic wall motions during canter and gallop. The thoracic hemi-diameter varied through a significantly wider range on the side of the trailing forelimb, in comparison to the leading forelimb side. Following exercise, the standing values were symmetric. Horse 2 demonstrated smaller standing values both before and after exercise and these were not significantly different between right and left sides. There were asymmetric amplitudes of change in hemi-diameter at trot, canter and gallop. At trot, the largest thoracic wall motions occurred on the right side at both rib sites, while at canter and gallop the largest motions occurred on the side of the trailing forelimb.

As a representative complete dataset, Figs 1–7 illustrate the changes in hemi-diameter (as calculated from spine marker T10 and right and left 10th ribs) occurring in Horse 1 during pre-exercise standing, at walk, trot, canter and gallop and during post-exercise standing. They also illustrate changes in total thoracic diameter (TTD) as the distance between markers on the right and left 10th ribs. This is plotted with inspiratory and expiratory airflow. Flow values greater than zero are expiratory and flows below zero are inspiratory. During standing pre-exercise (Fig. 1) changes in TTD of c. 3 cm were roughly in phase with inspiration and expiration, and motions of the right and left sides were asymmetric in amplitude. At walk (Fig. 2), ventilatory airflow was not completely linked to changing chest diameter. The hemi-diameter of one side increased and decreased entirely out of phase with motions of the other side, yielding net changes in TTD of about 2 cm through the stride cycle. Airflow was linked to trot kinematics (Fig. 3) and stance of one forelimb occurred coincident with an increase in

<table>
<thead>
<tr>
<th>Horse</th>
<th>Rib</th>
<th>Stand (pre-)</th>
<th>Walk (1.8 m s(^{-1}))</th>
<th>Trot (4.0 m s(^{-1}))</th>
<th>Canter (6.0 m s(^{-1}))</th>
<th>Canter (8.0 m s(^{-1}))</th>
<th>Gallop (10.0 m s(^{-1}))</th>
<th>Stand (post-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R10</td>
<td>27 (–)</td>
<td>29 (6.1)</td>
<td>32 (5.1)</td>
<td>28 (8.4)</td>
<td>35 (6.9)</td>
<td>43 (4.5)</td>
<td>30 (6.8)</td>
</tr>
<tr>
<td></td>
<td>L10</td>
<td>12 (–)</td>
<td>32 (5.1)</td>
<td>31 (7.4)</td>
<td>64** (5.9)</td>
<td>73** (3.6)</td>
<td>76** (3.2)</td>
<td>32 (5.1)</td>
</tr>
<tr>
<td></td>
<td>R16</td>
<td>22 (–)</td>
<td>45 (7.2)</td>
<td>30 (5.1)</td>
<td>40 (4.8)</td>
<td>39 (3.9)</td>
<td>49 (2.5)</td>
<td>21 (10.1)</td>
</tr>
<tr>
<td></td>
<td>L16</td>
<td>13 (–)</td>
<td>48 (6.5)</td>
<td>31 (5.9)</td>
<td>49** (7.7)</td>
<td>54** (4.9)</td>
<td>56** (4.4)</td>
<td>22 (17.8)</td>
</tr>
<tr>
<td>2</td>
<td>R10</td>
<td>4 (–)</td>
<td>35 (6.2)</td>
<td>37** (5.8)</td>
<td>22 (5.4)</td>
<td>25 (4.6)</td>
<td>27 (2.6)</td>
<td>15 (3.2)</td>
</tr>
<tr>
<td></td>
<td>L10</td>
<td>8 (–)</td>
<td>35 (6.5)</td>
<td>29 (3.4)</td>
<td>36** (2.5)</td>
<td>48** (4.3)</td>
<td>60** (2.1)</td>
<td>23 (5.3)</td>
</tr>
<tr>
<td></td>
<td>R16</td>
<td>5 (–)</td>
<td>51 (6.8)</td>
<td>39** (5.0)</td>
<td>23 (4.3)</td>
<td>36 (3.5)</td>
<td>44 (2.9)</td>
<td>22(4.0)</td>
</tr>
<tr>
<td></td>
<td>L16</td>
<td>8 (–)</td>
<td>45 (5.4)</td>
<td>34 (4.3)</td>
<td>24 (5.1)</td>
<td>36 (3.0)</td>
<td>43 (2.3)</td>
<td>21 (4.4)</td>
</tr>
</tbody>
</table>

Significant differences between corresponding right and left ribs are \(^*P < 0.05\) and \(^{**}P < 0.01\).
hemi-diameter on that side. Changes in hemi-diameter were approximately symmetric and mean amplitude was about 3.5 cm. The TTD pattern was biphasic, with the larger increase in TTD occurring during right forelimb stance, but this occurred paradoxically during the first half of the expiratory phase. At canter and gallop, hemi-diameter increased with forelimb stance on the same side (Figs 4–6) and TTD gradually decreased during most of the expiratory phase. At the end of stance of the leading fore, TTD rapidly decreased and then quickly reversed shortly after the beginning of the inspiratory phase, which was initiated during early suspension. The post-exercise standing traces (Fig. 7) show bilaterally symmetric changes in hemi-diameter that combined to yield changes in TTD that were in phase with the inspiratory and expiratory airflows.

Figure 8 illustrates a serendipitous change of lead from right to left lead canter. The data trace is from the left side, which was the trailing forelimb side until the lead change, at which point it became the side of the leading fore. The amplitude decreased after the lead change and the frequency of the oscillations increased.

Discussion

In this preliminary study, total transverse thoracic diameter varied through 2–3 cm at all gaits, agreeing with
the small circumference changes observed by Marlin et al. However, the right and left hemi-diameters were often observed to be out of phase with one another during locomotion; as one side increased the other side decreased. The consistency of the kinematic and ventilatory patterns suggests a major influence by locomotor forces. Attenborough’s proposal that the stance limb causes compression of the chest and expiration is not supported by this study, in that thoracic hemi-diameter appears to increase during ipsilateral limb stance. The chest wall appears to be capable of active expansion to aid ventilation. Post-exercise changes in total transverse thoracic diameter occur with amplitude of 6–7 cm, agreeing with Marlin’s observations of horses breathing under the influence of lobeline. Figure 7 shows that these lateral chest wall motions occur in synchrony with inspiration and expiration and that they are not paradoxical to airflows.

The largest asymmetries were observed at canter and gallop, and the amplitudes of these thoracic wall excursions increased with speed. The change in hemi-diameter was approximately twice as large on the side of the trailing forelimb (Table 1), resulting in overall chest circumference of less than 2 cm at canter. Although short segments of the TTD profile are out of phase with the airflow trace, most expiratory flow occurred coincident with decreasing TTD at T10 and vice versa.

The respiratory inductance plethysmography technique used by Marlin et al. would have accounted for changes occurring in the dorso-ventral and transverse diameters of the thorax, whereas our measurement technique only accounted for lateral changes in chest geometry. It is entirely possible that changes in overall chest circumference are negligible, despite significant TTD ranges, if there is a concomitant compensatory change in the dorso-ventral distance between the spine and ventral thoracic wall. The forelimbs interact with the chest wall in such a way that the ribs could be driven upwards during limb loading, in addition to any other rib motions occurring as a result of locomotor muscle activity. The abdominal muscles contract to stabilize the trunk during weight bearing, but it is unknown whether this affects the dorso-ventral thoracic diameter. The if the upward forces acted to reduce the dorso-ventral dimension of the thorax at the same time as its transverse dimension was increasing, then the thoracic circumference, and therefore its cross-sectional area, might be minimally changed overall. Our canter data indicate paradoxical.
movements between the two sides of the thorax. It would appear that changes in hemi-diameter on the side of the leading fore are subtractive against changes on the side of the trailing fore, yielding a net TTD measurement that is smaller than the motion observed on the trailing side.

Merkens et al.\textsuperscript{11} reported that the ground reaction force amplitudes are substantially different at canter between the leading and trailing forelimbs. The vertical forces under the trailing forelimb at slow canter were 21% greater than under the leading forelimb, and the cranio-caudal forces and impulse were net propulsive. In contrast, the cranio-caudal forces under the leading fore were net braking. Our observation that thoracic hemi-diameter increased during trailing forelimb stance agrees with the notion that the extrinsic forelimb retractor muscles originating on the ribs pull the ribs forward while the foot is in contact with the ground, accomplishing the net propulsive effect. The larger braking forces on the side of the leading forelimb would have the overall effect of compressing the chest.

Confounding the measured amplitude changes would be the effects of skin movement and of muscles shortening under the skin and, in doing so, becoming thicker. The extrinsic forelimb muscles responsible for retraction of the limb (\textit{latissimus dorsi, serratus ventralis} and \textit{cutaneous trunci}) are situated in the region of the rib markers. As these muscles shortened and thickened during the retraction part of the stance phase, this could have introduced some artefactual amplitude change that would not affect internal thoracic hemi-volume. These same muscles, given that they originate from the ribs, would be pulling the ribs cranially as they contracted to retract the forelimb. Their action is to pull the trunk forward over the stance limb and, given the forces involved, cranial displacement of the ribs is a likely consequence. As the ribs are pulled forward, their spinal and sternal attachments result in the ‘bucket handle’ motion described in classical anatomy texts for a general animal thoracic model. The caudal motion of the scapula in retraction might also have introduced some increase in measured hemi-diameter in the region of T10, but this is not likely to have had an effect at T16. The caudal thorax is more likely to have been affected by movement of the abdominal viscera during acceleration and deceleration of the trunk, in the ‘visceral piston’ concept. The motion of the ribs appears to follow the same pattern at T10 and T16, despite local amplitude differences (Table 1).

This study has provided evidence that the equine thorax changes its transverse hemi-diameter asymmetrically during gait, and suggests that changes in total transverse diameter may be greater than previously reported. There are times in the ventilatory cycle when thoracic diameter changes in phase with airflow, but there are also paradoxical movements within the overall pattern. Future work should investigate how the full cross-sectional shape of the thorax changes under the influence of the various gaits and speeds.

\textbf{References}

Thoracic changes during equine locomotion


