Basic three-dimensional kinematics of the vertebral column of horses trotting on a treadmill

Marjan Faber, PhD; Christopher Johnston, DVM, PhD; Henk Schamhardt, PhD†; René van Weeren, DVM, PhD; Lars Roepstorff, DVM, PhD; Ab Barneveld, DVM, PhD

Objective—To determine movements of the vertebral column of horses during normal locomotion.

Animals—5 young Dutch Warmblood horses that did not have signs of back problems or lameness.

Procedure—Kinematics of 8 vertebrae (T6, T10, T13, T17, L1, L3, L5, and S3) and both tuber coxae were determined, using bone-fixed markers. Measurements were recorded when the horses were trotting on a treadmill at a constant speed of 4.0 m/s.

Results—Flexion-extension and axial rotation were characterized by a double sinusoidal pattern of motion during 1 stride cycle, whereas lateral bending was characterized by 1 peak and 1 trough. Ranges of motion for all vertebrae were: flexion-extension, 2.8° to 4.9°; lateral bending, 1.9° to 3.6°; axial rotation, 4.6° to 5.8°, except for T10 and T13, where the amount of axial rotation decreased to 3.1° and 3.3°, respectively.

Conclusion and Clinical Relevance—During locomotion, 3 types of rotations are evident in the thoracolumbar vertebrae. Regional differences are observed in the shape and timing of the rotations. These differences are related to actions of the limbs. The method described here for direct measurement of vertebral column motion provides insights into the complex movements of the thoracolumbar portion of the vertebral column in trotting horses. Information on normal kinematics is a prerequisite for a better understanding of abnormal function of the vertebral column in horses. (Am J Vet Res 2001;62:757–764)

Dysfunction of the back is an important cause of poor performance and lameness in equine athletes. Despite the high prevalence of back problems, understanding of normal and abnormal function of the equine vertebral column and supporting tissues has been based solely on clinical experience and results of a few in vitro studies. Recently, a number of in vitro studies have increased our knowledge on the normal movements of the back of sound horses.1-4

Vertebrae can rotate in 3 planes. This leads to 3 types of motion: flexion-extension (FE), lateral bending (LB), and axial rotation (AR). The amount of rotation that is possible varies along the vertebral column and depends on the size, shape, and orientation of anatomic structures. In vitro studies use isolated dissected vertebral columns, and excessive loads are applied to determine movements of the vertebral column. In vivo assessment of vertebral column movements is more difficult, because the movements are complex and rather small. Therefore, an extremely sensitive and accurate measurement technique is required. In addition, the skin covering the vertebrae impedes direct observation and quantification of vertebral movements, and the mass of the epaxial muscles makes the vertebral column rather inaccessible.

On the basis of results of in vitro studies, it was concluded that the amount of rotation is limited (<5°) for most intervertebral joints, except in the cranial thoracic region and the lumbosacral joint (>20°).5 Investigators of only 1 in vivo study have successfully described interrelationships of the 3 rotations in the vertebral column of horses during walking on a treadmill.6 Flexion-extension had a bimodal pattern, whereas LB and AR were characterized by 1 peak and 1 trough. Range of motion for FE appeared to be constant (approx 7°) for vertebrae caudal to T10. With respect to LB, the cranial thoracic vertebrae and segments in the pelvic region had the maximal amount of motion (values up to 5.6°). For the vertebrae between T17 and L5, the amount of LB decreased to <3°. The amount of AR increased gradually from 4° for T6 to 13° for the tuber coxae.

The study reported here is a continuation of the aforementioned in vivo study7 and focuses on the thoracolumbar vertebral and pelvic movements in all 3 dimensions in a group of clinically normal horses during trotting on a treadmill. The techniques we used allowed us to perform an accurate 3-dimensional (3-D) analysis of the amount, type, and timing of all rotational movements in the vertebral column of horses during locomotion.

Materials and Methods

The materials and methods used in the study have been described in detail elsewhere. The experimental procedure was approved by the Utrecht University Ethical Committee and was in full compliance with the Act on Animal Experiments.

Animals—Five Dutch Warmblood horses (4 geldings and 1 mare) were used. Horses ranged from 2 to 4 years old, weighed (mean ± SD) 443 ± 46 kg, and had a height of 159
± 3 cm. Before the experiments started, horses were accustomed to locomotion on a treadmill.

**Procedure**—Exact locations of the dorsal spinous processes of T6, T10, T13, T17, L1, L3, L5, and S3 were determined, using fluoroscopy. The position of the left and right tuber coxae was determined by palpation. Horses were sedated, and the aforementioned sites were routinely prepared for surgery and infiltrated with a 2% solution of lidocaine hydrochloride. A stab incision was made through the skin and underlying tissue to the bone. A 4- to 8-cm-long, 3.0-mm-thick Steimann pin was driven into each dorsal spinous process or tuber coxae without prior drilling. The length of the pin depended on the thickness of the tissues between the bone and skin, because the pin protruded approximately 1 cm above the skin. After placing all Steimann pins, a custom-built lightweight marker device was attached to each pin; the device was constructed such that each vertebra and tuber coxae had a set of 4 markers. The device was approximately an equilateral triangle with an intermarker distance of 20 cm. Three markers (1 at each corner of the triangle) were glued to the device, and an additional marker was placed midway between the 2 markers that constituted the base of the triangle. Markers were lightweight reflective spherical balls, each of which was 9 mm in diameter. Additional markers (30 mm in diameter) were placed on the hooves of the hind limbs. Custom-made uniaxial accelerometers were affixed to all 4 hooves.

Horses were allowed to recover 4 hours before the treadmill experiments started. During that time and during the experiments, signs of discomfort were not detected. After finishing the experiment, pins were removed in the standing horses, and the stab incisions were sutured with interrupted sutures. All wounds healed by primary intention.

**Data collection**—A commercially available system was used to record the 3-D positions of the markers. Seven cameras were positioned around the treadmill in such a way that it was possible to simultaneously record markers on hooves of both hind limbs as well as the markers affixed to the vertebral column. Data for marker position and the accelerometer were collected at 240 and 3,600 Hz, respectively, during a 5-second period. Data were synchronized and stored on a personal computer for further processing. The experimental protocol included data collection while horses were walking (1.6 and 1.8 m/s), trotting (4.0 m/s), and cantering (7.0 m/s) during a single session. For this report, we considered only data obtained while horses were trotting.

**Calculation of the 3-D kinematics of the vertebral column**—To describe rotations of the vertebral column, a standard right-handed orthogonal Cartesian coordinate system was used. In the laboratory coordinate system, the positive y-axis was directed along the line of progression. The z-axis was perpendicular to the y-axis and was oriented vertically with the positive axis in the upward direction. The positive x-axis was perpendicular to these 2 axes. Consequently, FE was defined as rotation around the x-axis, LB was defined as rotation around the z-axis, and AR was defined as rotation around the y-axis (Fig 1).

The 3-D marker coordinates were filtered initially with a second-order low-pass Butterworth-filter (cutoff frequency, 10 Hz). Filtered coordinates subsequently were used to calculate 3-D angular rotations in accordance with the method described by Faber et al. To identify separate stride cycles, the starting point of each stride cycle was defined as the initial ground contact of the left hind limb. This moment in time was determined interactively by using the vertical displacement and the impact acceleration peak of the hoof of the left hind limb in accordance with the method of Schamhardt et al. In a resampling procedure, each stride cycle was adjusted to 101 data points (100 intervals), with 0% being hoof contact of the left hind limb and 100% being the subsequent hoof contact for the same limb. The resampling procedure uses a polyphase implementation and applies a low-pass filter to the data. The resulting angular movement patterns (AMP), defined as the diagram of time versus angle values during 1 stride cycle, were inspected visually. Stride cycles judged to have a deviant pattern or aberrant stride cycle duration (ie, when the stride cycle duration exceeded the mean ± 2 SD of the stride cycle duration) were excluded. For the remaining stride cycles, a mean AMP was calculated. Only mean AMP were reported, unless stated otherwise.

**Definitions of variables**—Several variables were used in the evaluation of vertebral column movements. Definition of these variables is necessary to ensure consistency among investigators.

**Angles**

All positive-slope segments in the AMP indicate clockwise rotations, and negative-slope segments indicate counterclockwise rotations. For FE, extension of the back is a dorsoventral movement that tends to straighten or decrease the normal curvature of the vertebral column, and flexion of the back represents movement that increases the normal curvature.

**Temporal gait characteristics**

The onset of each stride cycle was determined for the left hind limb, from which the stride cycle time (SCT) was calculated. Velocity of the stride cycle was calculated from displacement during full ground contact of the left hind limb. Stride time was calculated, using the regression equation described by Roepstorff. Distinct gait events were extracted from the ground reaction force (GRF) pattern during the stance phase. These included the concussion phase, which started at time of hoof contact and lasted until the second local maximum was seen in the vertical GRF; midstance, which started when the horizontal GRF was in transition from the braking to the propulsive phase; and maximal forward propulsion, which coincided with the horizontal GRF reaching its negative peak in the second half of the stance phase.

These gait events were extracted from the standard GRF pattern of trotting Dutch Warmblood horses described by Merkens et al. We did not measure the GRF during our study.
Variability

Repeatability of the AMP was calculated across the collected stride cycles within the same horse (within-horse variation [WHV]) and between the mean AMP of the 5 horses (between-horse variation [BHV]). The WHV and BHV were determined by calculating a SD for each data point over the available stride cycles. The root mean square of these SD was expressed as a percentage of the range of motion (ROM). This measure equals the coefficient of variation and is a measure for the exact agreement of AMP.

Kinematic variables

Several kinematic variables were calculated, including ROM, which was the difference between the maximal and minimal AMP value; timing of peak amplitudes in the vertebral AMP which were expressed as a percentage of SCT, the moment of transition, which was defined as the moment in time when the AMP crosses zero and was expressed as a percentage of SCT; and the correlation coefficient calculated between the AMP of the vertebrae, which served as a test for the degree of rigid-body behavior of successive vertebrae during locomotion. Values approaching 1 implied rigid body behavior.

All results, calculated for the number of available data points per vertebra, were reported as mean ± SD. For most vertebrae, 5 AMP were available for between-horse comparisons. However, for a number of vertebrae, the pin construction became loose during the study and had to be removed. This happened once for L3 and 4 times for L5.

In describing the AMP, we emphasized the first half of the stride cycle. We did this because the pattern is repeated (approximately) during the second half of the stride cycle.

Results

Error analysis—The motion analysis system provided that markers attached to the vertebrae and tuber coxae could be reconstructed with an accuracy of 0.3 mm. Residuals of the angle calculation procedure ranged from 0.09 ± 0.02 mm for T13 to 0.36 ± 0.45 mm for L3. This error included rigid-body deviations and modeling errors.

Temporal gait characteristics—We analyzed 6 to 7 stride cycles/horse. The 5 horses trotted at a speed of 4.06 ± 0.05 m/s, and the SCT of the left hind limb was 0.68 ± 0.02 seconds. The stance time was calculated as 0.29 seconds (42.4% of the SCT). The end of the concussion phase was reached at 11% of the SCT in the forelimb and 9% of the SCT in the hind limb. Midstance was at 22% of SCT for the forelimb and 18% of the SCT for the hind limb. Maximal forward propulsion was at 31% of the SCT in the forelimb and hind limb. After liftoff (42% of the SCT), the suspension phase started, ending at the moment of hoof contact of the right hind limb (50% of the SCT).

Variability—Consistency of vertebral AMP observed within each horse depended on the location of the vertebra and the rotation that was involved. Lateral bending was the most consistent motion, with values of 5.7 to 8.2% for WHV. The FE and AR had slightly larger values for WHV that ranged from 5.9 to 12.9%. Values for BHV were 4 to 5 times the values for WHV for all vertebrae and rotations (Fig 2).

Vertebral flexion-extension—The FE had a bimodal sinusoidal pattern during each stride cycle.
Throughout the stride cycle, T10 and S3 were out-of-phase by 180°, whereas L1 moved out-of-phase by ± 90°, compared with the pattern for T10 and S3. This implied that T10 and S3 reached their minimal and maximal FE angle while L1 was in transition. At the moment of hoof contact of the left hind limb, T10 rotated clockwise, whereas the rotation of S3 was in the opposite direction. As a result, the back was extending. This extension continued until midstance, when the rotation of T10 reversed from clockwise into a counterclockwise rotation. Flexion of the back lasted from midstance until 50% of SCT, coinciding with the moment of hoof contact of the right hind limb. There was simultaneous transition of T10 and S3 twice during the first 50% of the stride cycle (ie, at the end of the conclusion phase and at the moment of maximal propulsion [approx 10 and 31% of the SCT, respectively]).

The ROM was lowest for T6 (2.8 ± 0.8°) and S3 (2.8 ± 0.9°) and highest for T10 (4.9 ± 1.4°). The ROM for the vertebrae caudal to T10 gradually decreased until reaching the area of the tuber coxae, where the ROM was > + (Table 1).

The FE AMP of the lumbar vertebrae had a high intervertebral correlation (Table 2), indicating that these vertebrae move simultaneously and behave like a single rigid body. For the remaining vertebrae, analysis of correlations among the AMP revealed a tendency for correlations with adjacent vertebrae, but this correlation progressively decreased whenever the vertebrae were located further apart.

**Ventral lateral bending**—The LB was a single periodic motion (Fig 3). Vertebral T10 rotated out-of-phase by ± 180° relative to S3, with transitional bending in the segments between the cranial thorax and pelvis. At the moment of hoof contact of the left hind

---

Table 1—Mean ± SD values for vertebral range of motion (degrees) for flexion-extension (FE), lateral bending (LB), and axial rotation (AR) in 5 horses trotting on a treadmill

<table>
<thead>
<tr>
<th>Structure</th>
<th>FE</th>
<th>LB</th>
<th>AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertebral</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6</td>
<td>2.8 ± 0.8</td>
<td>4.9 ± 1.2</td>
<td>5.5 ± 1.1</td>
</tr>
<tr>
<td>T10</td>
<td>4.9 ± 1.4</td>
<td>4.4 ± 0.8</td>
<td>3.3 ± 1.1</td>
</tr>
<tr>
<td>T13</td>
<td>4.2 ± 1.8</td>
<td>3.7 ± 1.4</td>
<td>3.1 ± 1.3</td>
</tr>
<tr>
<td>T17</td>
<td>3.5 ± 1.3</td>
<td>3.6 ± 1.8</td>
<td>4.6 ± 1.2</td>
</tr>
<tr>
<td>L1</td>
<td>3.4 ± 0.6</td>
<td>4.5 ± 1.9</td>
<td>4.6 ± 1.3</td>
</tr>
<tr>
<td>L3</td>
<td>3.1 ± 0.3*</td>
<td>4.4 ± 2.1*</td>
<td>5.0 ± 1.9*</td>
</tr>
<tr>
<td>L5</td>
<td>4.1*</td>
<td>4.1</td>
<td>5.4*</td>
</tr>
<tr>
<td>S3</td>
<td>2.8 ± 0.9*</td>
<td>4.0 ± 1.3</td>
<td>5.7 ± 1.3</td>
</tr>
<tr>
<td>Tuber coxae Left</td>
<td>4.3 ± 1.3</td>
<td>4.1 ± 1.0</td>
<td>5.7 ± 0.9</td>
</tr>
<tr>
<td>Right</td>
<td>4.5 ± 1.3*</td>
<td>4.4 ± 1.1*</td>
<td>5.8 ± 1.1</td>
</tr>
</tbody>
</table>

‡Represents values for 1 horse. §Represents values for 3 horses.

---

Table 2—Mean ± SD values for intervertebral pattern symmetry* of vertebral angular motion patterns for flexion-extension of 5 horses trotting on a treadmill

<table>
<thead>
<tr>
<th>Structure</th>
<th>T6</th>
<th>T10</th>
<th>T13</th>
<th>T17</th>
<th>L1</th>
<th>L3χ</th>
<th>L5</th>
<th>S3</th>
<th>Left tuber coxae</th>
<th>Right tuber coxae†</th>
</tr>
</thead>
<tbody>
<tr>
<td>T6</td>
<td>—</td>
<td>0.74 ± 0.12</td>
<td>0.40 ± 0.28</td>
<td>0.12 ± 0.33</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>T10</td>
<td>0.74 ± 0.12</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.36 ± 0.42</td>
<td>0.63 ± 0.42</td>
<td>0.76 ± 0.23</td>
<td>0.37 ± 0.10</td>
<td>—</td>
</tr>
<tr>
<td>T13</td>
<td>0.40 ± 0.28</td>
<td>0.70 ± 0.40</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>T17</td>
<td>0.12 ± 0.33</td>
<td>0.30 ± 0.81</td>
<td>0.10 ± 0.30</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>L1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.90 ± 0.06</td>
<td>0.90 ± 0.06</td>
<td>0.37 ± 0.23</td>
<td>0.50 ± 0.32</td>
<td>0.61 ± 0.24</td>
</tr>
<tr>
<td>L3χ</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.90 ± 0.13</td>
</tr>
<tr>
<td>L5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>S3χ</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Left tuber coxae</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Right tuber coxae†</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.90 ± 0.13</td>
</tr>
</tbody>
</table>

*Intervertebral pattern symmetry is calculated as the coefficient of correlation between the angular motion patterns of successive vertebrae. †Represents values for 4 horses. ‡Represents values for 1 horse. §Represents values for 3 horses. — = Not applicable.

---

Table 3—Mean ± SD values for intervertebral pattern symmetry* of vertebral angular motion patterns for lateral bending of 5 horses trotting on a treadmill

<table>
<thead>
<tr>
<th>Structure</th>
<th>T6</th>
<th>T10</th>
<th>T13</th>
<th>T17</th>
<th>L1</th>
<th>L3χ</th>
<th>L5</th>
<th>S3</th>
<th>Left tuber coxae</th>
<th>Right tuber coxae†</th>
</tr>
</thead>
<tbody>
<tr>
<td>T6</td>
<td>—</td>
<td>0.82 ± 0.13</td>
<td>0.34 ± 0.32</td>
<td>—</td>
<td>0.28 ± 0.43</td>
<td>—</td>
<td>0.66 ± 0.24</td>
<td>0.85 ± 0.13</td>
<td>0.98 ± 0.09</td>
<td>—</td>
</tr>
<tr>
<td>T10</td>
<td>0.82 ± 0.13</td>
<td>—</td>
<td>—</td>
<td>0.69 ± 0.37</td>
<td>0.16 ± 0.54</td>
<td>0.27 ± 0.47</td>
<td>0.54 ± 0.32</td>
<td>0.58 ± 0.13</td>
<td>0.85 ± 0.11</td>
<td>0.86 ± 0.13</td>
</tr>
<tr>
<td>T13</td>
<td>0.34 ± 0.32</td>
<td>0.69 ± 0.37</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>T17</td>
<td>—</td>
<td>0.28 ± 0.43</td>
<td>0.16 ± 0.54</td>
<td>0.64 ± 0.24</td>
<td>0.30 ± 0.28</td>
<td>0.01 ± 0.21</td>
<td>0.12 ± 0.25</td>
<td>0.22 ± 0.45</td>
<td>0.50 ± 0.46</td>
<td>0.01 ± 0.46</td>
</tr>
<tr>
<td>L1</td>
<td>—</td>
<td>0.86 ± 0.24</td>
<td>0.27 ± 0.47</td>
<td>0.30 ± 0.28</td>
<td>0.89 ± 0.15</td>
<td>0.89 ± 0.08</td>
<td>0.52 ± 0.31</td>
<td>0.44 ± 0.26</td>
<td>0.43 ± 0.21</td>
<td></td>
</tr>
<tr>
<td>L3χ</td>
<td>—</td>
<td>0.85 ± 0.13</td>
<td>0.54 ± 0.32</td>
<td>0.01 ± 0.31</td>
<td>0.54 ± 0.25</td>
<td>0.89 ± 0.08</td>
<td>0.91 ± 0.16</td>
<td>0.68 ± 0.11</td>
<td>0.90 ± 0.02</td>
<td>0.91 ± 0.03</td>
</tr>
<tr>
<td>L5</td>
<td>—</td>
<td>0.86 ± 0.24</td>
<td>0.27 ± 0.47</td>
<td>0.30 ± 0.28</td>
<td>0.89 ± 0.15</td>
<td>0.89 ± 0.08</td>
<td>0.52 ± 0.31</td>
<td>0.44 ± 0.26</td>
<td>0.43 ± 0.21</td>
<td></td>
</tr>
<tr>
<td>S3χ</td>
<td>—</td>
<td>0.85 ± 0.13</td>
<td>0.54 ± 0.32</td>
<td>0.01 ± 0.31</td>
<td>0.54 ± 0.25</td>
<td>0.89 ± 0.08</td>
<td>0.91 ± 0.16</td>
<td>0.68 ± 0.11</td>
<td>0.90 ± 0.02</td>
<td>0.91 ± 0.03</td>
</tr>
<tr>
<td>Left tuber coxae</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Right tuber coxae†</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.90 ± 0.13</td>
</tr>
</tbody>
</table>

See Table 2 for key.
trotting on a treadmill vertebrae

Table 4—Mean 180° out-of-phase rotation relative to each other. The negative correlation was reflected in a strong correlation (R > 0.97) for the AMP of these vertebrae (Table 3). All lumbar vertebral AMP had a strong correlation with adjacent vertebrae (R > 0.89; eg, L1 vs L3, L3 vs L5) but not for vertebral further apart. For all thoracic vertebrae, a high correlation was not found, suggesting that these vertebrae rotate individually. The negative correlation that was found for many vertebrae was caused by the 180° out-of-phase rotation of each other.

Vertebral ROM for LB was similar for all vertebrae (Table 1), ranging from 3.6° to 4.9°. The pelvic segments (ie, S3 and both tuber coxae) and L5 moved as a single segment, which was reflected in a strong correlation (R > 0.97) for the AMP of these vertebrae (Table 3). All lumbar vertebral AMP had a strong correlation with adjacent vertebrae (R > 0.89; eg, L1 vs L3, L3 vs L5) but not for vertebral further apart. For all thoracic vertebrae, a high correlation was not found, suggesting that these vertebrae rotate individually. The negative correlation that was found for many vertebrae was caused by the 180° out-of-phase rotation relative to each other.

Vertebral axial rotation—The AMP for axial rotation had various minimal and maximal AR angles during 1 stride cycle (Fig 3). For most vertebrae, 3 periods of clockwise and 3 periods of counterclockwise rotation were seen. At the moment of hoof contact of the hind limb, all vertebrae rotated counterclockwise toward the supporting hind limb. Vertebra S3 started changing the direction of rotation during the concussion phase, and L1 and T10 followed at the end of the concussion phase and immediately before midstance, respectively. Vertebrae S3 and L1 did not reach the transition point before changing the direction of rotation. The clockwise rotation lasted until after midstance for S3, and L1 and T10 followed. The counterclockwise rotation of S3 lasted until the end of the stance phase of the left hind limb. The AR of L1 and S3 were highly related, although the movement of S3 was greater. Therefore, the angular velocity of S3 was larger. All moments of transition for T10 corresponded to GRF-derived gait events: at the end of the concussion phase, at the moment of maximal propulsion, and at liftoff.

The ROM for all vertebrae, except T10 and T13, were in the range of 4.6° to 5.8° (Table 1). However, T10 and T13 had a slightly smaller ROM, with values between 3.1° and 3.3°.

With respect to AR, the segment from L3 to the pelvis acted almost like a rigid body, because the corre-

Table 4—Mean ± SD values for intervertebral pattern symmetry* of vertebral angular motion patterns for axial rotation of 5 horses trotting on a treadmill vertebrae

<table>
<thead>
<tr>
<th>Structure</th>
<th>T6</th>
<th>T10</th>
<th>T13</th>
<th>T17</th>
<th>L1</th>
<th>L3t</th>
<th>L5t</th>
<th>S3</th>
<th>Left tube coxae</th>
<th>Right tuber coxae</th>
</tr>
</thead>
<tbody>
<tr>
<td>T6</td>
<td>—</td>
<td>0.71 ± 0.17</td>
<td>0.22 ± 0.35</td>
<td>0.21 ± 0.47</td>
<td>0.29 ± 0.64</td>
<td>0.46 ± 0.59</td>
<td>0.77 ± 0.43</td>
<td>0.43 ± 0.40</td>
<td>—</td>
<td>0.42 ± 0.42</td>
</tr>
<tr>
<td>T10</td>
<td>0.71 ± 0.17</td>
<td>—</td>
<td>0.71 ± 0.32</td>
<td>0.35 ± 0.59</td>
<td>0.18 ± 0.59</td>
<td>0.10 ± 0.61</td>
<td>0.63 ± 0.04</td>
<td>0.04 ± 0.55</td>
<td>0.12 ± 0.62</td>
<td>0.09 ± 0.55</td>
</tr>
<tr>
<td>T13</td>
<td>0.22 ± 0.35</td>
<td>—</td>
<td>0.71 ± 0.32</td>
<td>—</td>
<td>0.81 ± 0.12</td>
<td>0.62 ± 0.22</td>
<td>0.59 ± 0.29</td>
<td>0.37 ± 0.15</td>
<td>0.63 ± 0.18</td>
<td>0.53 ± 0.21</td>
</tr>
<tr>
<td>T17</td>
<td>0.21 ± 0.47</td>
<td>0.35 ± 0.59</td>
<td>0.81 ± 0.12</td>
<td>—</td>
<td>0.82 ± 0.26</td>
<td>0.81 ± 0.15</td>
<td>0.92 ± 0.04</td>
<td>0.08 ± 0.08</td>
<td>0.90 ± 0.09</td>
<td>0.80 ± 0.18</td>
</tr>
<tr>
<td>L1</td>
<td>—</td>
<td>0.20 ± 0.64</td>
<td>0.18 ± 0.59</td>
<td>0.62 ± 0.22</td>
<td>0.82 ± 0.26</td>
<td>0.89 ± 0.11</td>
<td>0.90 ± 0.03</td>
<td>0.76 ± 0.40</td>
<td>0.76 ± 0.37</td>
<td></td>
</tr>
<tr>
<td>L3t</td>
<td>—</td>
<td>—</td>
<td>0.10 ± 0.61</td>
<td>0.50 ± 0.29</td>
<td>0.81 ± 0.15</td>
<td>0.88 ± 0.11</td>
<td>—</td>
<td>0.94 ± 0.06</td>
<td>0.90 ± 0.10</td>
<td>0.84 ± 0.10</td>
</tr>
<tr>
<td>L5t</td>
<td>0.77</td>
<td>—</td>
<td>0.63 ± 0.37</td>
<td>0.92 ± 0.37</td>
<td>0.90 ± 0.04</td>
<td>0.94 ± 0.09</td>
<td>—</td>
<td>0.97 ± 0.03</td>
<td>0.91 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>—</td>
<td>0.43 ± 0.40</td>
<td>0.04 ± 0.55</td>
<td>0.54 ± 0.15</td>
<td>0.84 ± 0.08</td>
<td>0.79 ± 0.39</td>
<td>0.90 ± 0.06</td>
<td>0.99 ± 0.09</td>
<td>0.97 ± 0.03</td>
<td>—</td>
</tr>
<tr>
<td>Left tube coxae</td>
<td>—</td>
<td>0.42 ± 0.42</td>
<td>0.12 ± 0.62</td>
<td>0.63 ± 0.18</td>
<td>0.50 ± 0.09</td>
<td>0.78 ± 0.35</td>
<td>0.90 ± 0.10</td>
<td>0.97 ± 0.03</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Right tuber coxae</td>
<td>—</td>
<td>0.39 ± 0.40</td>
<td>0.09 ± 0.55</td>
<td>0.53 ± 0.21</td>
<td>0.80 ± 0.18</td>
<td>0.76 ± 0.37</td>
<td>0.84 ± 0.10</td>
<td>0.94 ± 0.05</td>
<td>0.84 ± 0.12</td>
<td></td>
</tr>
</tbody>
</table>

See Table 2 for key.

Figure 4—Angle-angle diagram illustrating the coupling between 2 rotations for flexion-extension versus axial rotation in S3 (left), flexion-extension versus axial rotation in L1 (middle), and lateral bending versus axial rotation in T10 (right). Distinct gait events are indicated as follows: hoof contact (I), midstance (II), and liftoff (III) of the left diagonal stance phase (IV); midstance (V) and liftoff (VI) of the right diagonal stance phase.
Relationships between rotations—The 3-D character of vertebral rotations can be illustrated in an angle-angle diagram that shows the coupling between 2 rotations within 1 vertebra. For S3 and L1, the FE-AR interrelationship was analyzed, and for T10, we analyzed the LB-AR interrelationship.

The FE-AR angle-angle plot for S3 was a butterfly-shaped pattern (Fig 4). After hoof contact of the left hind limb, FE initially traveled through a large ROM, whereas the AR angle remained fairly constant. Before midstance, the AR angle also started to change. After midstance until liftoff, a period followed in which a linear relation was evident between the FE and AR movement (FE increased, and AR decreased); however, AR decreased more rapidly than FE increased. Between hoof contact and hoof contact of the right hind limb, FE remained fairly constant while AR increased. After hoof contact of the right hind limb, a short period followed in which FE decreased while AR remained constant, which was followed by a period in which the AR angle decreased, and FE remained constant. After midstance, a linear relation again was seen between the change in FE angle and AR angle that lasted until liftoff of the right hind limb. During the last period of the stride cycle, FE remained constant, and the AR angle decreased.

Another pattern was seen in the FE-AR angle-angle plot for L1. In this case, we saw a C-shaped plot (Fig 4). After ground contact of the left hind limb, the AR angle increased initially, and there was a limited amount of FE rotation. Then, 2 periods followed in which FE moved through a greater range while AR remained constant, and AR subsequently moved through a greater range while FE remained fairly constant. During the suspension phase, AR angle remained constant, but there was a considerable amount of FE rotation. This ended at the moment of hoof contact of the right hind limb. The pattern then was repeated for the second half of the stride cycle. The pattern was not perfectly symmetric because of small asymmetries for each pattern.

For T10, the LB-AR relationship was fairly symmetric (Fig 4). After hoof contact of the hind limb, a linear relation was evident between LB and AR that lasted until immediately before midstance. The same applied, in inverse direction, for the period between hoof contact of the right hind limb and midstance of the right hind limb. At midstance and liftoff of both hind limbs, AR was in transition for both halves of the stride cycle.

Relationships between movement of the hind limbs and rotation of the vertebral column—The correlation between protraction and retraction of the left hind limb (PR) and lateral bending (LB) of the vertebral column (VC) for T10 and S3 was analyzed by using the x-, y-, and z-coordinate data of the markers affixed to the left hind hoof and tuber coxae. These pins could be placed in standing sedated horses without the use of additional forms of restraint. All horses were sound for all gait data collection.

Interrelationships between the PR and FE for T10 and S3 were perfectly mirrored. They were identical for both vertebrae, except the FE for T10 had a greater ROM (Fig 5). At hoof contact of the left hind limb, the FE angle was in an extreme position. There was a rapid change in FE angle, which lasted until midstance, while the PR angle also changed, resulting in a linear relationship between FE and PR. At midstance, the FE angle changed direction. A similar period of rapid change in the FE angle, with a simultaneous change in the PR angle, followed from midstance until liftoff. During the suspension phase, the FE angle again changed direction, and the cycle was repeated for the second half of the stride cycle.

For LB, open loop figures were found in the interrelationship between PR of the left hind limb and LB (Fig 5). For both T10 and S3, a comparable relationship existed between LB and PR movements. During the first half of the stance phase, there was a linear change in LB angle, relative to the PR angle. At midstance in S3 and at liftoff in T10, LB started to change direction, whereas PR did not change direction before liftoff in either vertebra. After the suspension phase, the process was repeated again during the second half of the stride cycle.

Discussion
Kinematics of the vertebral column were measured in trotting horses, using an invasive technique that involved implantation of Steinmann pins in the dorsal spinous processes of a number of vertebrae and both tuber coxae. These pins could be placed in standing sedated horses without the use of additional forms of restraint. All horses were sound for all gaits during data collection.

Certain data for the tuber coxae were not used, because the horses' movements were outside the calibrated range. When this took place, angular symmetry

---

**Figure 5**—Angle-angle diagram illustrating the coupling between protraction and retraction of the left hind limb and vertebral column rotations. Diagrams represent flexion-extension versus protraction and retraction of the left hind limb for T10 (A) and S3 (B) and lateral bending versus protraction and retraction of the left hind limb for T10 (C) and S3 (D). See Figure 4 for key.
was low, and results were considered to be inadequate. Also, as mentioned previously, some pins became loose and were removed during the experiment.

Results of the study reported here were compared with those of Audigié et al.,2 who described FE movements during a slow trot (3.16 ± 0.15 m/s). Similar to our results, they also reported that the nature of the FE rotation is biphasic, but distinct differences were seen in ROM and timing of the minimal and maximal FE angles. In our study, the ROM of the FE of the thoracic angle (T6-T13-L1) was calculated to be 5.3 ± 2.2° and 3.7 ± 1.2° for the thoracolumbar angle (T13-L1-S3). Audigié et al.2 reported similar values for the thora-

columbar angle (3.8°) but lower values for the thoracic angle (3.9°). In our study, the maximal FE angle was detected at 6.6 and 24.8% of SCT for the thoracic angle and at 19.0 and 36.0% for the thoracolumbar angle. In the study by Audigié et al., the maximal FE angle was detected much later in the stride cycle (11.6 and 36.3% for the thoracic angle and 22.9 and 47.1% for the thoracolumbar angle). These differences could be attributable to the difference in trotting speed. However, when the thoracic and thoracolumbar angles from our data were calculated on the basis of T6-L1 and T13-S3 angles, our results were comparable to theirs. This illustrates that errors are introduced when using skin markers and calculating spinal angles that include multiple vertebrae. This should be considered when interpreting results of studies that use skin markers to describe kinematics of the vertebral column.

In a horse that is not lame, an efficient locomotion pattern is achieved by the interaction between movements of the limbs and vertebral column. After hoof contact, the initial effect of inertia will tend to continue the forward and downward movement of the body. However, muscular activity will resist this motion and stabilize the vertebral column. Major muscular activity at the moment of hoof contact is seen in the rectus abdominis, biceps femoris, and gluteus medius muscles.9-11 Actions of the rectus abdominis muscle will prevent excessive extension of the vertebral column, which is induced by downward movement of the viscera mass. This downward force will induce the counterclockwise rotation of S3 at 0% of the SCT. In addition to activity of the rectus abdominis muscle, activity of hip extensors (biceps femoris and gluteus medius muscles) during landing also may limit the amount of counterclockwise FE rotation of S3. At midstance, the FE of S3 reverses into a clockwise rotation as a result of the forward- and upward-directed push-off force.4 Also, after lift off of the left hind limb, S3 rotates clockwise for FE as the limb is still retracting. The longissimus dorsi muscle, which induces extension, is active during the second half of the stance phase; because S3 then is rotating clockwise, this muscle will not actively initiate FE rotations but, rather, will limit the amount of clockwise rotation of S3. During the first part of the stance phase, AR of S3 is counterclockwise until the end of the concusion phase. At the end of the concussion phase, the stance limb is stabilized in length, and AR subsequently changes direction. The pelvis then drops toward the side of the unsupported hind limb, but this is only for a short period that lasts until immediately after midstance. After midstance, the push-off force and hip extension will rotate the pelvis toward the side of the supporting hind limb. This facilitates clearance of the opposite hind limb that is in protraction. During the suspension phase (42 to 50% of the SCT), the AR of S3 reverses again into a clockwise rotation for a short period as the right hind limb is preparing for landing and is reaching forward. The LB rotation from hoof contact until midstance is clockwise. The forward velocity of the horse at 0% of the SCT will partly be absorbed into the left stance limb, but it also will cause forward movement of the right hind limb and subsequently explain the clockwise LB rotation of S3. After midstance, the left hind limb generates a push-off force, exerting an oblique force on the vertebral column, including a forward and sideways component. Musculature of the vertebral column will mainly absorb these sideways forces to promote forward movement.10 However, muscular activity cannot prevent that part of the sideways force that will push the vertebral column toward the opposite right side and cause the counterclockwise LB rotation.

Vertebra T10 has different time-dependent rotation patterns, compared with patterns for L1 and S3. For FE and LB, T10 and S3 are rotating out-of-phase by approximately 180°. Because the FE and LB rotations of S3 and T10 are influenced by the hind limb and forelimb, respectively, and because these limbs also are moving 180° out-of-phase, it is understood that similar mechanisms will play a role in the regulation of the FE and LB rotations for both vertebrae. However, movement of the head also influences thoracic vertebrae, in particular the FE rotation of these vertebrae. In an in vitro study, it was noticed that lowering of the neck provoked a flexion or counterclockwise rotation along the thoracic portion of the vertebral column.13 In the study reported here, clockwise FE rotation of T10 during the first half of the stance phase coincided with downward movement of the head.11 Similarly, the counterclockwise FE rotation of T10 was detected simultaneously with upward movement of the head during the second half of the stance phase. Thus, we concluded that the passive linkage between thoracic FE and head position for in vitro situations is not responsible for initiating the FE rotations in vivo during trotting. However, it may be that downward movement of the head during the first half of the stance phase limits the amount of trunk extension induced by downward acceleration of the visceral mass. For AR, T10 and S3 have AMP that are extremely different. At hoof contact, the AR of T10 is counterclockwise until approximately midstance. Therefore, unlike S3, at hoof contact of the right forelimb, the dorsal part of the trunk drops toward the unsupported side, because loading of the forelimb is more progressive as a result of freedom of movement of the scapula. At midstance, the right forelimb starts to push off, the right forelimb is retracting, and the left forelimb is protracting. As a result, T10 rotates clockwise. This facilitates clearance of the protracting forelimb. Immediately after the moment of maximal propulsion, T10 AR reverses again into a counter-
clockwise rotation as the left forelimb is starting to prepare for hoof contact. Excessive AR is limited in T10 by the ribs.1

The clear LB-AR interrelationship found in T10 (Fig 4) is in agreement with in vitro results. Townsend et al4 observed that LB resulted in a concomitant AR in the thoracic portion of the vertebral column that was most easily seen in the joints around T11 and T12. A counterclockwise LB produced a coupled clockwise AR. Except for 2 periods at the beginning of each stance phase for both hind limbs (0 to 15% and 50 to 65% of the SCT), this coupling is evident throughout the stride cycle during trotting.

Trotting and walking differ conspicuously, and the function of the vertebral column should reflect these differences. During trotting, the diagonal stance phase is followed by a suspension phase, whereas during walking, there are alternating periods of 2 and 3 limbs having contact with the ground. Therefore, the demands on equilibrium control differ considerably. As a result of more extensive and greater muscular activity during trotting, compared with walking, the vertebral column is made as rigid as possible to resist wasteful lateral movements10 and limit the amount of lateral excursion for the body’s center of mass. During walking, the body’s center of mass should be as close to the center of rotation as possible to resist wasteful lateral movements10 and limit the amount of lateral excursion for the body’s center of mass. In general, the magnitudes of the rotations during walking are larger, compared with those during trotting. In addition, examination of the literature reveals differences. During trotting, the diagonal stance phase is followed by a suspension phase, whereas during walking, there are alternating periods of 2 and 3 limbs having contact with the ground. Therefore, the demands on equilibrium control differ considerably. As a result of more extensive and greater muscular activity during trotting, compared with walking, the vertebral column is made as rigid as possible to resist wasteful lateral movements10 and limit the amount of lateral excursion for the body’s center of mass. During walking, the body’s center of mass should move to maintain equilibrium during the alternating periods of 2 and 3 limbs having ground contact. Lateral bending and AR are able to initiate this shift of the center of mass. In general, the magnitudes of the rotations during walking are larger, compared with those during trotting. In particular, the amount of AR is almost double during walking, compared with the amount during trotting.1 The AR motion for all vertebrae has high intervertebral synchronization and an increasing ROM toward the caudal part of the vertebral column. This synchronization minimizes the amount of motion per intervertebral joint and provides the ROM in the pelvic region that is needed to allow normal hoof clearance during protraction and retraction.

Analysis of kinematics of the vertebral column of horses trotting on a treadmill described here reveals the complex nature of movements of the vertebral column. Limb movements are closely related to kinematics of the vertebral column, and this probably is a causal correlation in which the vertebral column follows movement of the limbs. In addition, examination of the literature reveals that a close relationship apparently exists between the kinematics and muscular activity of the vertebral column. This muscular activity has a major role in limiting, rather than initiating, movements of the vertebral column. Muscular dysfunction and asymmetric vertebral column.

References

7. Schamhardt HC, Merkens HW. Objective determination of ground contact of equine limbs at the walk and trot: comparison between ground reaction forces, accelerometer data and kinematics. Equine Vet J 1994; suppl 17:75–79.