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SPINAL BIOMECHANICS AND FUNCTIONAL ANATOMY

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For a long time, back pain in horses has been identified as a cause of poor performance,[15] and with the evolution of diagnostic methods (e.g., radiography, scintigraphy, ultrasonography), knowledge of the responsible lesions is progressing.[10, 23]

To understand the cause of back injuries, the circumstances that induce pain, and the physical management of these lesions, a precise knowledge of the functional anatomy and biomechanics of the vertebral column is required. Moreover, evaluation of mobility in the thoracolumbar and lumbosacral areas is an important part of the routine clinical evaluation of back problems in horses.[6]

Objective data on the movements (kinematics) and forces (kinetics) that take place in the horse's back are difficult to obtain. The mobility of the equine spine is limited, and the thoracolumbar vertebral column is composed of numerous small joints that are covered with thick muscles. These anatomical and functional particularities may account for the paucity of information in the current literature.

The first reports dealing with equine back biomechanics presented the results of in vitro investigations on the dissected vertebral column.[8, 11, 17, 29]

Although some functional aspects of the back in sport horses have been described during jumping and dressage exercises,[9] the first in vivo objective studies of equine back behavior were electromyographic investigations of trunk muscles[25] and kinematic investigations during jumping.[24] In the near future, new in vitro and in vivo complementary studies are likely to improve our knowledge about back biomechanics.

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In our laboratory, analysis of back functional behavior and mechanical properties includes kinematic evaluation of sound and lame horses, surface electromyography of trunk muscles, and functional anatomy of isolated vertebral segments.

IN VIVO STUDIES

Few in vivo studies have been focused on the biomechanics of the equine back. A kinematic analysis of the dorsoventral (flexion and extension) movements of the thoracolumbar and lumbosacral areas was performed in sound horses at a trot on a hard surface using a three-dimensional kinematic analysis system.[1, 2, 18] On each horse, five skin markers were placed in the median plane over the top of the spinous processes. The two most extreme markers were positioned over the top of the withers and at the sacrocaudal junction. Three intermediate markers were used to define three spine angles; they were placed over the top of T12 or T13, over the top of T18 or L1, and over the tuber sacrale (Fig. 1).

The angle-to-time diagrams showed that at a trot, all three dorsal spine angles decrease during the first part of each diagonal stance phase (Fig. 2), indicating a thoracolumbar and lumbosacral extension. All dorsal spine angles increase during the second half of the stance phase, indicating a vertebral column flexion. The maximal thoracolumbar extension occurs at the midstance phase of each diagonal, just after the maximal thoracic extension and before the

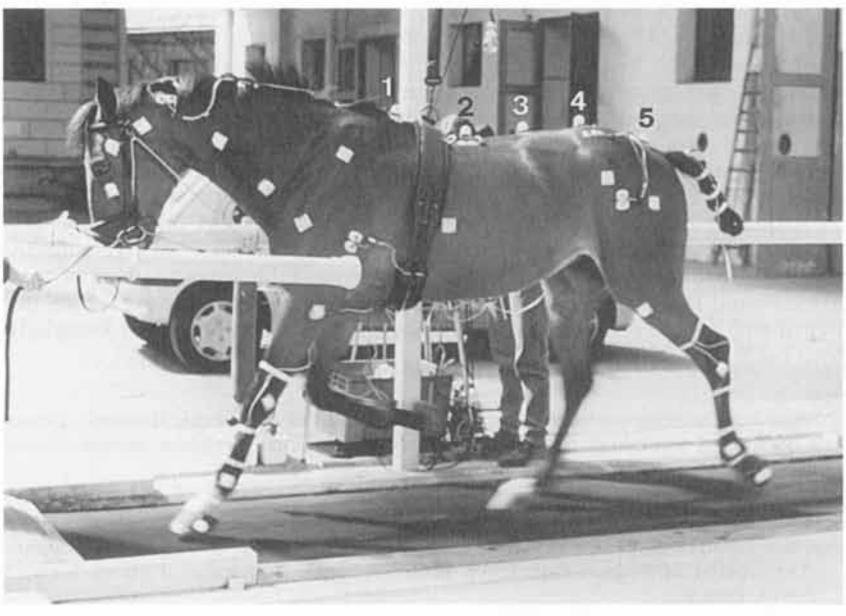

Figure 1. Investigation of spinal biomechanics with simultaneous recording of kinematic data and electromyographic activities at trot on a treadmill. Note the five reflective markers *(1 to 5)* placed on the dorsal midline. (Courtesy of Fabrice Audigié, DVM, MSc, Maisons-Alfort, France.)

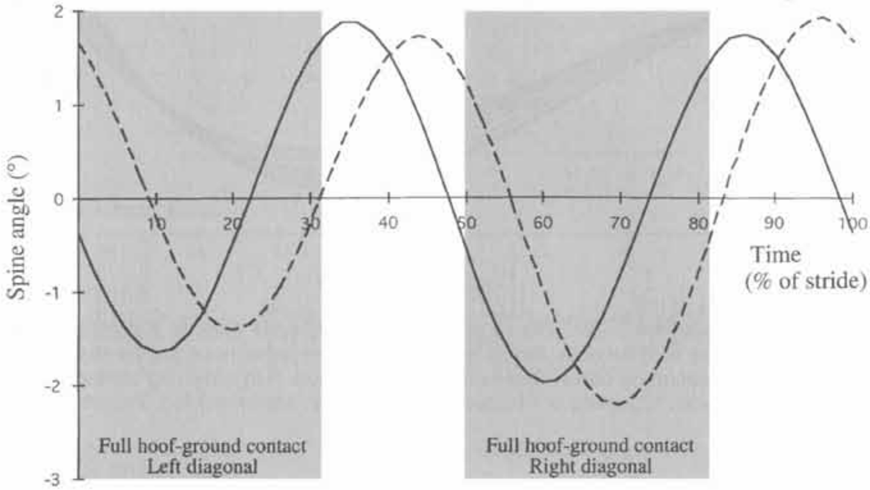

Figure 2. Regional flexion and extension movements of the spine in sound trotting horses (3 m/s). The 0° represents the mean values of the curves; a decrease in the angle value indicates spinal extension and an increase indicates spinal flexion. Solid line = thoracic angle; dashed line = lumbosacral angle. (Thoracic angle = T6–T12/13–T18/L1; lumbosacral angle = T18/L1–tubersacrale–sacrocaudal junction.) (Courtesy of Fabrice Audigié, DVM, MSc, Maisons-Alfort, France.)

maximal lumbosacral extension (see Fig. 2). Maximal thoracolumbar flexion occurs during the suspension phase, after maximal thoracic flexion and before maximal lumbosacral flexion (see Fig. 2), which is synchronous to the maximal protraction of the hind limb.[1] For each of these three spine angles, the range of motion was about 3° to 4°. The maximal range of vertical displacement of the thoracic spine occurred near T15 (Fig. 3) and was about 1.5 cm.[1]

Electromyographic activity of trunk muscles has been investigated in horses moving at different gaits (walk, trot, canter) on a treadmill (see Fig. 1), in hand, and under saddle.[20, 25, 26] These studies demonstrated that electromyographic patterns of the longissimus dorsi, rectus abdominis, and obliquus internus abdominis muscles vary considerably from one gait to another.[20] The rectus abdominis muscle is inactive during walking and like the longissimus dorsi muscle, for each stride, it shows two bursts of activity at the trot (Fig. 4) and only one at the canter (Fig. 5).

On both the left and right sides, at the trot and at the canter, the homologous left and right muscles act simultaneously. The asynchronism of the activity patterns clearly confirms that the longissimus dorsi and rectus abdominis muscles are antagonist.

A comparison of kinematic data of the spine (see Fig. 2) with the electromyographic pattern of trunk muscles (see Fig. 4) reveals interesting functional features of equine spinal biomechanics.[20, 25, 26] The activity of the rectus abdominis muscles during the last part of the swing phase and the first part of the stance phase of each diagonal at the trot limits passive vertebral column extension (and supports visceral mass acceleration).

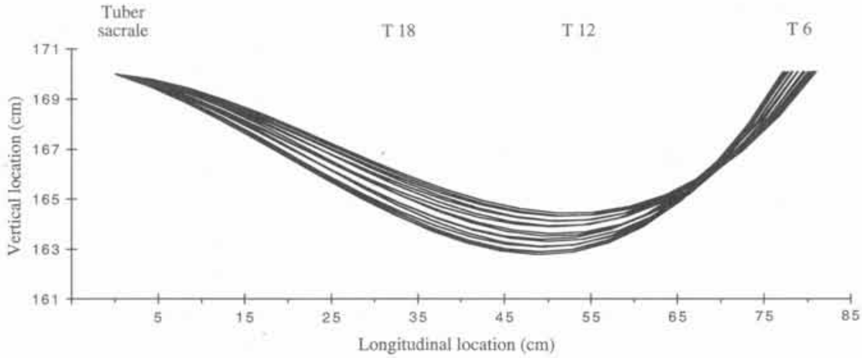

Figure 3. Oscillating displacements of the dorsal profile of the back in a sound trotting horse (3 m/s) due to alternative flexion and extension movements of the thoracolumbar spine. The tuber sacrale is considered fixed; thus, the withers (T6) is moving craniocaudally during the gait cycle. (Courtesy of Philippe Pourcelot, MSc, Maisons-Alfort, France.)

During the second part of each diagonal stance phase and the first part of the swing phase, the longissimus dorsi muscle acts both to contribute to propulsion and to stabilize the vertebral column (undergoing an ascending displacement).

Active displacements of the vertebral column are induced by these trunk muscles at the canter.[9, 12] Activity of the rectus abdominis and obliquus internus abdominis muscles has been recorded during the diagonal stance phase (see Fig. 5). The role of this contraction is to act against the ventral visceral mass acceleration and to prepare for the spinal flexion that occurs during the last part of the stance phase (leading forelimb weight-bearing phase).

Conversely, bursts of activity of the longissimus dorsi muscle occur from the last part of one stance phase to the beginning of the following one (see Fig. 5). The role of this muscle is to elevate the cranial part of the body (suspension phase) and to induce spinal extension (first part of the following stance phase).[9]

IN VITRO STUDIES

Regional (General) Kinematics

Few in vitro kinematic studies of the thoracolumbar spine of the horse have been performed during the last two decades.

Dorsoventral Movements

Jeffcott and Dalin[17] examined the dorsoventral movements of the isolated thoracolumbar spine and concluded that the range of possible movements gradually decreases craniocaudally from T10 to L2. In this study, flexion was pro-

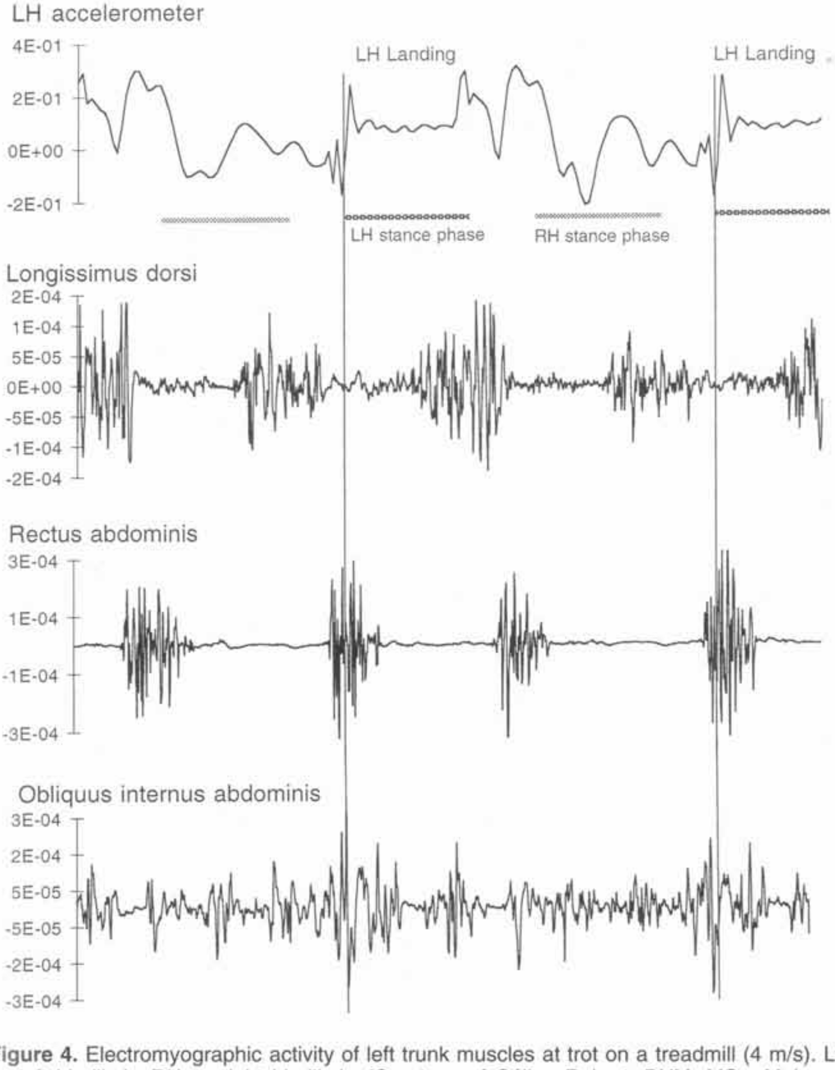

Figure 4. Electromyographic activity of left trunk muscles at trot on a treadmill (4 m/s). LH = left hindlimb; RH = right hindlimb. (Courtesy of Céline Robert, DVM, MSc, Maisons-Alfort, France.)

duced by suspending the isolated thoracolumbar spine from beneath at T13. Extension was induced by supporting the thoracolumbar spine at its cranial and caudal extremities and by suspending a 10-kg weight from the midpoint of the back. Intervertebral joint movement was estimated by measuring the change in distance between the dorsal spinous processes.

Townsend et al[29] performed a precise kinematic study in the isolated equine thoracolumbar spine. Photographs were used to measure the total change in the angle of pins inserted into the vertebral bodies when the rib cage was removed

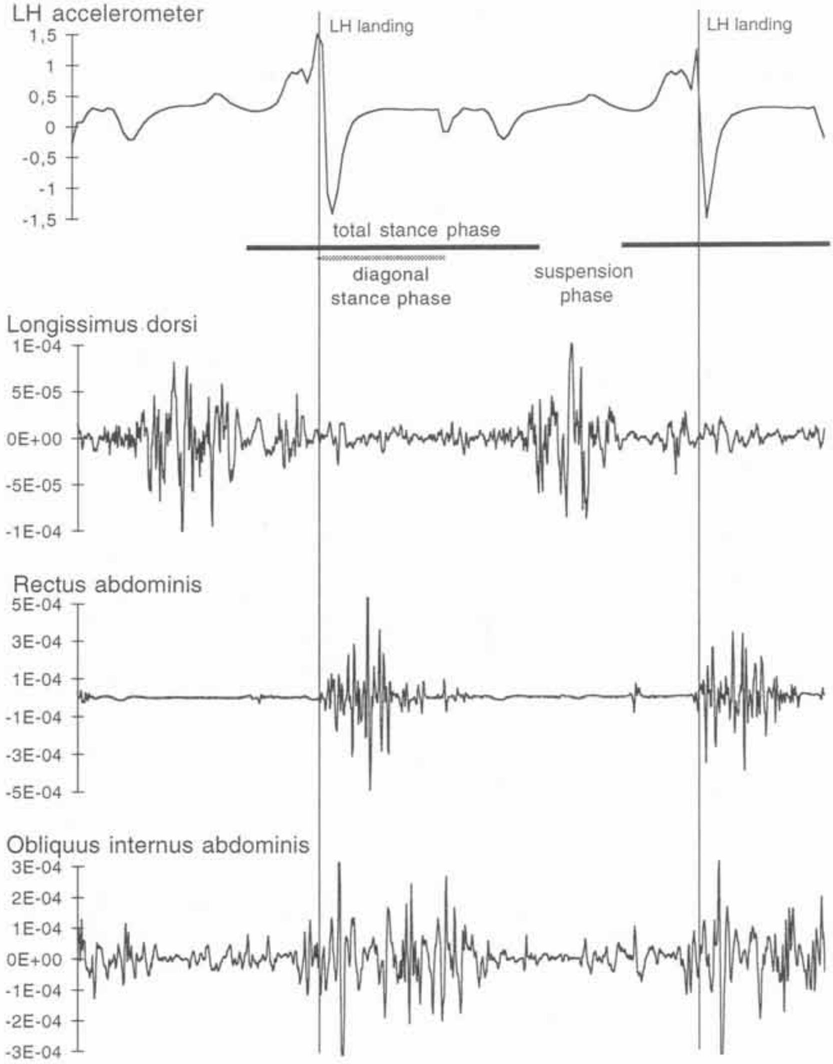

Figure 5. Electromyographic activity of left trunk muscles in a ridden horse at left lead canter (5.8 m/s). LH = left hindlimb; RH = right hindlimb. (Courtesy of Céline Robert, DVM, MSc, Maisons-Alfort, France.)

and into the dorsal spinous processes when it was left intact. Flexion and extension were alternately produced by an operator who applied as much manual pressure as he could on the first thoracic vertebra. With this procedure, dorsoventral movements were induced by force orientated perpendicular to the vertebral axis. This study demonstrated that without any force applied on the rib cage (by the abdominal muscles), no significant difference in the maximum range of dorsoventral movements occurred in the intervertebral joints between

T2 and L6. In further surveys, Townsend and his colleagues established relationships between spinal biomechanics and both intervertebral joint morphology[28] and pathological changes in the equine thoracolumbar spine.[27, 30]

In these studies, vertebral movements were induced by forces acting perpendicular to the axis of the spine, whereas most of the physiological muscular forces inducing movements of the vertebral column are parallel to it. None of these investigations considered the whole vertebral column to determine the effect of one region's position on the mobility of other areas.

In another study,[11] the purpose was to determine the kind, sites, and amount of vertebral thoracolumbar flexion and extension movements as well as to evaluate the effect of neck position on thoracolumbar mobility in the horse.

Materials and Methods. The axial skeleton and its associated ligaments were dissected from five fresh carcasses of adult horses that were between 3 and 21 years old. The limbs as well as the trunk muscles were removed so as to conserve only the head, vertebral column, ribs, sternum, and pelvis as well as their associated ligaments. Glycerin was applied on the nuchal and supraspinous ligaments in order to prevent desiccation.

On each specimen placed horizontally, dorsoventral (flexion and extension) movements of the thoracolumbar spine were performed by means of elastic straps attached so as to respect the anatomical insertions of trunk muscles.[11] These straps were stretched between the sternum and pubis in order to reproduce the flexing action of the rectus abdominis muscle. Other straps were then stretched between the tuber sacrale and the first three thoracic spinous processes to reproduce the extending action of the erector spinae muscle. Several forces varying from 50 to 400 N were applied to induce these movements.

In this study,[11] vertebral movements were measured using two different methods. Pins that were 50 cm in length were drilled into the spinous processes of the following vertebrae: T5, T9, T14, T18, L5, and S1. For each flexed or extended position of the specimens, photographs were taken from a height of 300 cm. Measurements of the pins' angular displacements were made on the projected images of the slides. In addition, little nails were stuck into the spinous and articular processes (APs) as well as into the vertebral body of each vertebra from T1 to S1. From radiographs taken all along the vertebral column in each position from a distance of 150 cm (with the same incidence and beam center), these radioopaque markers allowed the measurement of intervertebral joint movements as well as the determination of their center of rotation (CR).

The site and amount of thoracolumbar movement were assessed under different circumstances: (1) when the neck was raised (held up), that is, extended (relaxation of the nuchal ligament), and the thoracolumbar spine was flexed; (2) when the whole vertebral column was extended; (3) when the neck was lowered, that is, flexed (tension of the nuchal ligament); and (4) when both cervical and thoracolumbar regions of the spine were flexed (Fig. 6).

Amount of Regional Mobility

Natural Orientation of the Neck or Thoracolumbar Mobility

Thoracolumbar regional mobility was first assessed with the neck orientated in a craniodorsal neutral position (Fig. 7). The greatest range of dorsoventral movements appeared at the lumbosacral junction (L5–S1). Moreover, differences in regional mobility were recorded between T5 and L5.

Flexion. During flexion, the average amount of displacement in the lumbo-

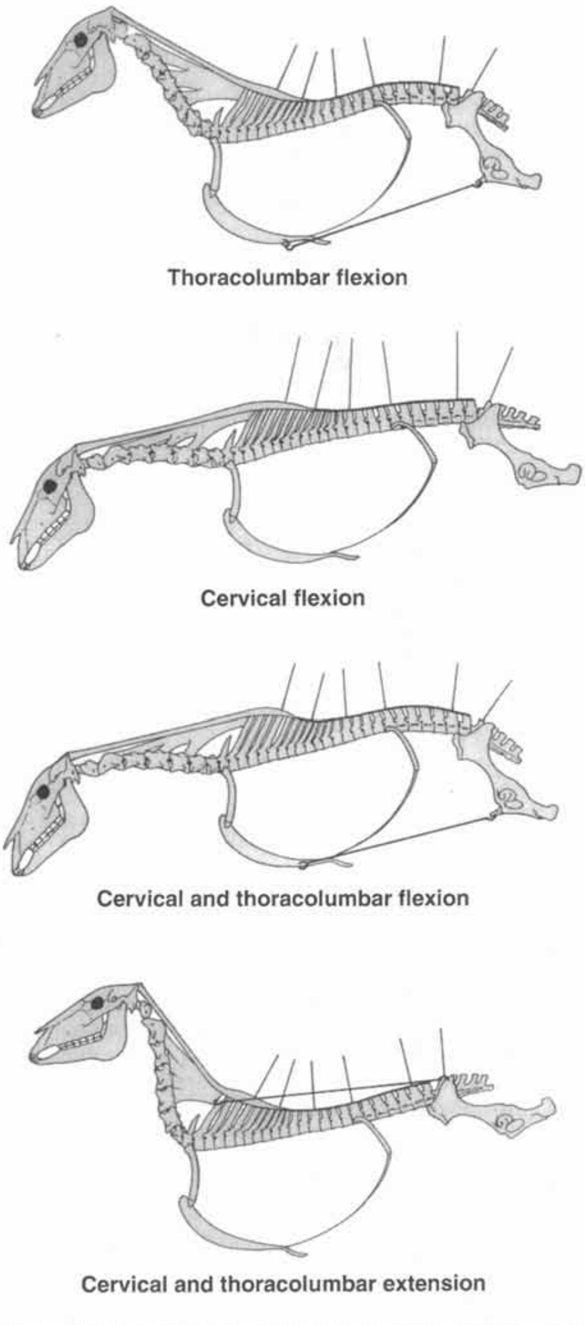

Figure 6. Neck and back positions investigated to study dorsoventral mobility of the thoracolumbar and lumbosacral vertebral column. *(From* Denoix JM: Kinematics of the thoracolumbar spine in the horse during dorsoventral movements: A preliminary report. *In* Proceedings of the 2nd International Conference on Equine Exercise Physiology. San Diego, CA, 1987, p 607; with permission.)

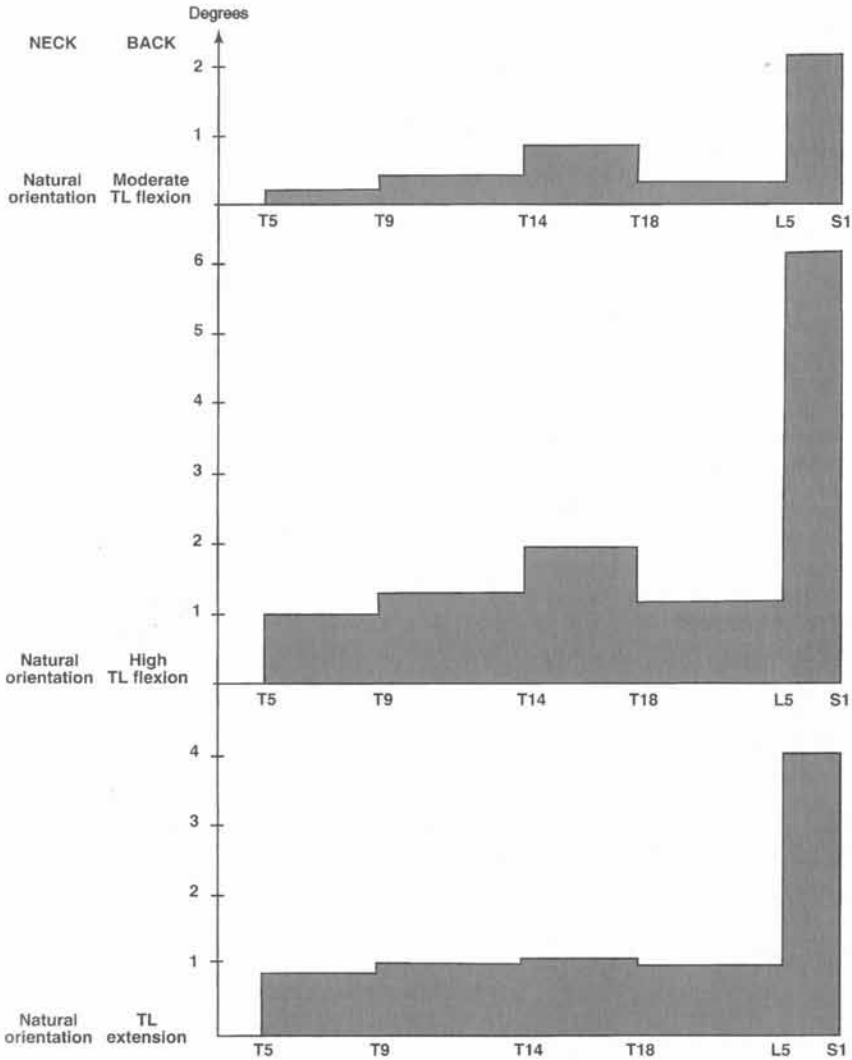

Figure 7. Regional mobility in the thoracolumbar spine. Average amount of dorsoventral movements (in degrees) in each intervertebral joint of the different regions during thoracolumbar flexion and extension, with the neck in a neutral position. *(From* Denoix JM: Kinematics of the thoracolumbar spine in the horse during dorsoventral movements: A preliminary report. *In* Proceedings of the 2nd International Conference on Equine Exercise Physiology. San Diego, CA, 1987, p 607; with permission.)

sacral joint was 12.3°, but it could reach 20° in a single specimen. The subset between T14 and T18 seemed to be more flexible than the rest of the thoracolumbar spine (see Fig. 7).[11] Measurements of intervertebral mobility revealed that the amount of flexion was higher in the thoracolumbar junction, particularly between T17 and T18 and between T18 and L1, where the angular displacement could reach 3.6° (for a 400-N force of flexion). When the flexion forces were applied on the rib cage between the sternum and pubis, the most flexible area appeared to be the thoracolumbar junction. The least movement took place in both extremes of the thoracolumbar spine: in the joint complexes between T3 and T9, where the displacement gradually increased in a caudal direction, and between L2 and L5, where the average amount of intervertebral flexion never exceeded 2°. The values of intervertebral mobility were consistent with those of a previous report.[29]

Extension. The lumbosacral junction underwent the greatest range of extension (see Fig. 7), where the amount of movement varied from 4° to 14°. This region was followed by the caudal part of the thoracic spine (T14–T18), where the average amount of intervertebral displacement varied from 0.3° to 1.8°. The least extension movement took place in two subsets: the cranial thoracic region (T2–T9) and the lumbar region (L2–L5).

Displacements Due to Cervical Flexion

The lowering of the neck provoked flexion all along the thoracic spine (Fig. 8). Intervertebral movements were greater between T6 and T10, where the average amount of flexion was 1.7°.

Modifications of Thoracolumbar Mobility When the Neck Is Lowered

In the lumbar spine, the modifications differed from those in the thoracic spine. For an equal force of flexion, a decrease in the possibilities of bending was recorded between T18 and L5 in all five specimens examined when the cervical spine was flexed (see Fig. 8). This diminution ranged from 0.1° to 0.9° in each intervertebral joint.

In two specimens, a diminution of regional mobility was recorded in the thoracic spine. It occurred between T14 and T18 for one horse and between T9 and T14 for the other one.

In all of the other regions, there was no addition of the displacement provoked by cervical flexion or thoracolumbar flexion. When the flexion force increased, the proportion of displacement due to cervical flexion decreased, especially caudal to T9 (see Fig. 8).

The measurements of intervertebral joint mobility showed that the thoracolumbar junction (T17–L1) remained the most mobile. The average amount of flexion in the lumbosacral area (L5–S1) was greater under these conditions than during flexion of the thoracolumbar spine only. In spite of large individual variations, lumbosacral flexion could reach 23°.

Functional Anatomy

Relationship Between Dorsoventral Mobility and Morphology

In each region of the vertebral column, mobility seems to be related to local variations in osteoarticular component morphology.[2, 3, 28] During dorsoventral movements, the size, shape, and orientation of the spinous processes are essential as well as the structure and elasticity of the supraspinous ligament.

The high dorsoventral mobility of the caudal thoracic spine (T14–T18), especially the thoracolumbar junction, can be related to the shortness of the

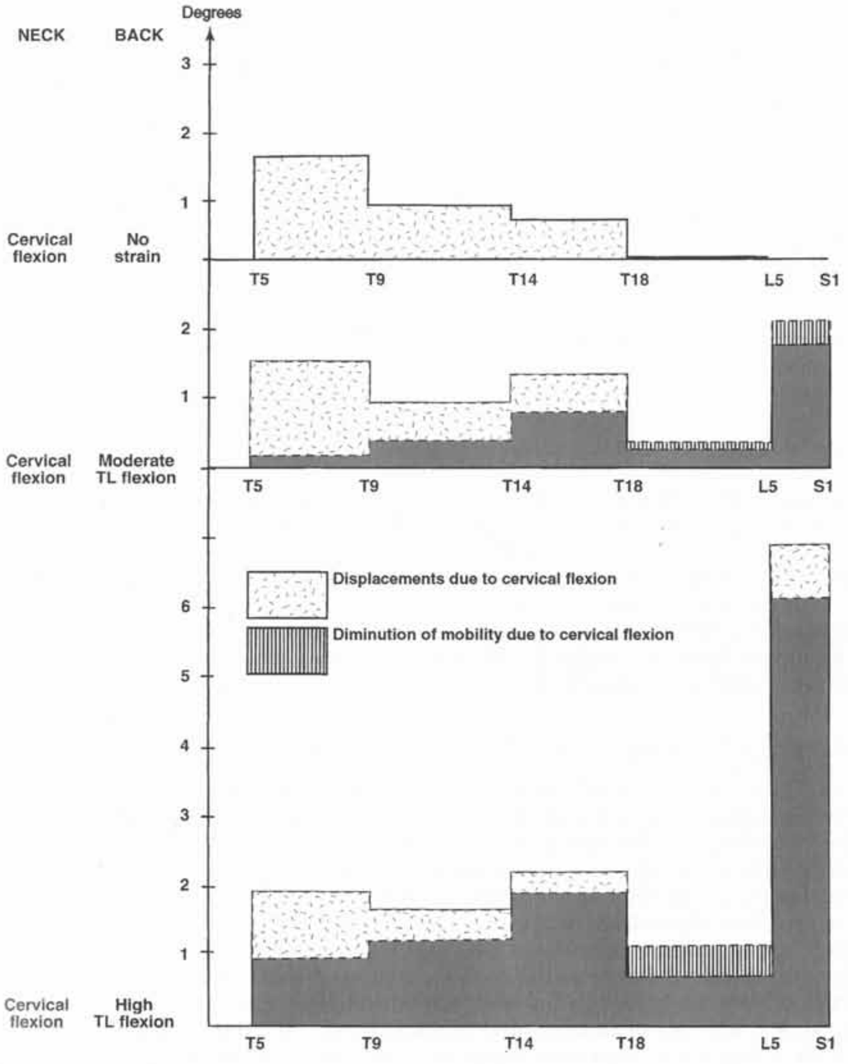

Figure 8. Regional mobility in the thoracolumbar spine. Average amount of dorsoventral movements (in degrees) in each intervertebral joint of the different regions during isolated cervical flexion and during combined cervical and thoracolumbar flexion. *(From* Denoix JM: Kinematics of the thoracolumbar spine in the horse during dorsoventral movements: A preliminary report. *In* Proceedings of the 2nd International Conference on Equine Exercise Physiology. San Diego, CA, 1987, p 607; with permission.)

spinous processes, the relative thickness of the last thoracic intervertebral discs,[28] and the small size of the vertebral bodies and their articulations with asternal ribs, which do not limit vertebral displacement (Table 1).

Many anatomical features can account for the relative stiffness of the lumbar region during dorsoventral movements, including the width and height of the

Table 1. STRUCTURES UNDERGOING PRESSURE OR TENSION AND LIMITING THE MOBILITY OF THE VERTEBRAL COLUMN

Limiting Structures	Flexion	Extension	Lateroflexion	Rotation
Supraspinous ligament	+ + +	0	0 or ±	+
Spinous processes	+ + (height)	+ (width)	0 or ±	+
Articular processes	0	+ +	+ +	+ + +
Last lumbar transverse processes	0	0	+ + +	+ +
Sternal ribs	+	0	+	+
Discs	0	±	+	+
Dorsal longitudinal ligament	±	0	±	±
Ventral longitudinal ligament	±	+ +	0	+ +

+ = mild effect; + + = moderate effect; + + + = marked effect; 0 = no effect; ± = ambiguous.

spinous processes, which are related to the narrowness of the interspinous ligaments, and the low extensibility of the supraspinous ligament. The presence and frequent fusion of lateral joints,[22, 28] the size of the vertebral bodies, and the presence of a high crista ventralis[3] covered with a strong ventral longitudinal ligament[2] may also be of importance (see Table 1).

In the cranial thoracic region, flexion and extension movements are limited by the height of the spinous processes. The articulation of the first ribs with the sternum is likely to restrict flexion when forces are applied on the rib cage as occurs under physiological circumstances.

Thoracolumbar Displacements Caused by Cervical Flexion

The lowering of the neck provokes thoracic flexion. The associated displacement is related to the cranial traction of the strong nuchal ligament applied on the dorsal tips of the thoracic spinous processes. The first of these processes from T2 to T6 are high, closely linked, and cannot diverge widely. The greater displacement recorded from T6 to T10 is related to two anatomical functional features: the elasticity of the supraspinous ligament, which is still effective in this region,[2] and the decrease in length of the spinous processes. Caudal to T10, the gradual diminution of the nuchal traction in each intervertebral complex and the lesser elasticity of the supraspinous ligament may account for the decreased amount of dorsoventral bending observed caudally from this point. In the living horse, as is also the case in anatomical specimens, the lowering of the neck produces a verticalization of the spinous processes in the withers and therefore the stretching of the erector spinae muscle. In this position, there is a relative elevation and bending of the thoracic part of the equine back just beneath the point where the rider sits that assists in supporting the rider's weight. By separating the thoracic spinous processes, the lowering of the neck can be considered an analgesic effect in horses that suffer from impingement or overriding of these processes.

Study Analysis

Townsend et al,[29] indicated that the presence or absence of the ribs and sternum did not significantly change the average amount of dorsoventral movement in the intervertebral joints of the thoracolumbar spine. This conclusion was based on a protocol in which no strain was applied on the ribs or sternum. According to the present study, it seems that traction on the ribs locks intervertebral joints in the cranial thoracic spine. Moreover, when forces reproduce muscle actions, regional mobility seems to differ from one area to another, particularly during flexion. This movement can be reproduced, as it was in our protocol, by two different procedures: (1) contraction of the abdominal muscles, which act between the sternum and ribs cranially and the pubis caudally (in our protocol, the action of the iliopsoas muscle was not reproduced because it has no effect cranial to T16), or (2) tension of the nuchal ligament, which pulls the first thoracic processes cranially.

Clinical Correlations

The greater range of thoracolumbar mobility observed between T14 and T18 can account for the frequency of impingement of the spinous processes from T10 to T18.

Osteoarthrosis of the dorsal synovial intervertebral joints between the APs is also a significant pathological entity inducing back pain.[10] In our clinical experience, these lesions mainly involve the segment between T16 and L2, and this could also be in relation to the higher mobility of the thoracolumbar junction during flexion and extension movements.

Lateroflexion and Rotation

A left lateroflexion is defined as a bending of the vertebral column, presenting a left concavity and a right convexity. A left rotation is defined as a left shifting of the ventral aspect of the vertebral body (or a right bending of the spinous process) of one vertebra with reference to the following vertebra.

In 1983, Townsend et al[29] quantified lateroflexion and rotation in the equine thoracolumbar spine. According to this study, the amount of these movements is greatest in the second half of the thoracic spine in the segment extending from T9 to T14. Anatomical functional studies performed on isolated segments of the vertebral column have confirmed these results, which are useful for the clinical evaluation of back mobility (Figs. 9, 10, and 11).

In the lumbar spine and thoracolumbar junction, rotation is limited and lateroflexion is only present cranial to the last lumbar vertebra (usually L4 or L5), presenting articular facets on its transverse processes. Between L4 (or L5) and S1, because of the presence of intertransverse joints, lateroflexion is virtually nonexistent. From L4 to T18, lateroflexion increases progressively in each intervertebral joint. It must be noted that overriding of the transverse processes is not a limitation to lateroflexion.

In the thoracic spine, lateroflexion induces a locking of the ipsilateral ribs (in the concavity) and an increased mobility of the opposite ribs (in the convexity).

In the cranial thoracic region (T2–T9), rotation and lateroflexion are limited by the sternal ribs attached to the sternum, and rotation is also limited by the height of the spinous processes attached by a strong supraspinous ligament.

In the second half of the thoracic spine, the shortness of the spinous processes, the presence of asternal ribs, the shape of the APs, and the presence of a thin ventral longitudinal ligament are anatomical factors permitting greater lateroflexion and rotation.

According to Townsend and Leach,[28] the shape, size, and orientation of the APs[19] as well as the presence and frequent fusion of the lateral joints in the lumbar spine[22] are important structures limiting mobility, particularly during

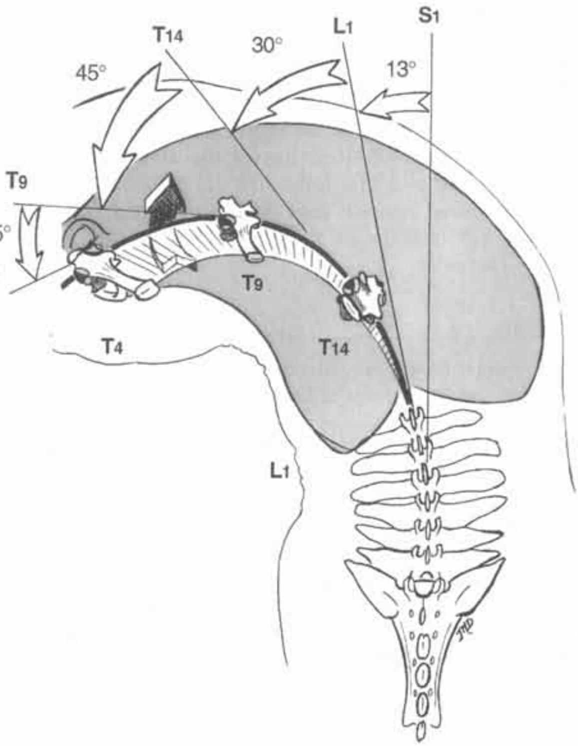

Figure 9. Mobility in the thoracolumbar spine during left lateroflexion. Submaximal amounts of regional spinal mobility referenced from labeled vertebral segments. Note the coupled right rotation *(three-dimensional arrow)*.

rotation and lateral bending. The presence of a fibrous supraspinous ligament and a strong ventral longitudinal ligament also limits rotation (see Table 1).

In the cervical and thoracic vertebral column, rotation is always coupled with lateroflexion and vice versa (see Figs. 9 and 11). In the thoracic spine, as is the case during lateroflexion, the spinous processes bend in the concavity and left lateroflexion is spontaneously associated with right rotation (see Fig. 9).

As rotation is a limited movement in the lumbar spine, there is no substantial rotation associated with lateroflexion (and no real lateroflexion associated with rotation). Although this mobility is limited, it is likely that because of the regional stiffness, rotation and lateroflexion (and even flexion and extension) induce higher stress (especially compression on bone structures) in the anatomical structures of the lumbar spine than in other more deformable areas. Conversely, soft tissue strains on ligaments and capsules are greater in the thoracic spine than in the lumbar segment.

Ventrolateral spondylosis deformans is believed to occur mainly in the mid to caudal thoracic region, being found with greatest frequency between T11 and T13.[16, 30] Townsend and his colleagues[28, 30] noted that this location corresponds to the region of the spine where the greatest amount of lateral bending and axial rotation occurs.

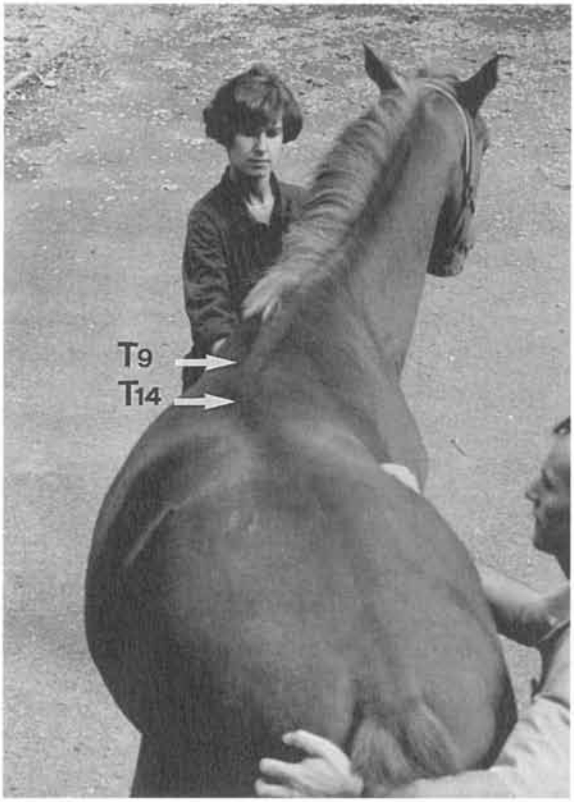

Figure 10. Induced lateroflexion of the thoracolumbar spine. Note the greater range of motion between T9 and T14.

Segmental Thoracolumbar Intervertebral Biomechanics

The functional unit in spinal kinematics is the "intervertebral joint complex" or "motion segment", which is composed of two contiguous vertebrae and their associated soft tissues.[31, 32] Conventionally, each intervertebral joint complex is numbered according to the more cranial of the two adjacent vertebrae of which it is composed (e.g., the first intervertebral joint of the lumbar spine is referred to as either L1–2 or simply the L1 intervertebral joint complex). For two contiguous vertebrae, the displacement of the cranial one is considered in relation to that of the adjacent caudal one, which remains fixed.

The CR of a moving body is defined as the fixed point around which the movement occurs. As biological displacements are complex, each elementary movement can be defined with an instant center of rotation (ICR).

The determination of the ICR is essential to appreciate the precise nature of the biomechanical events occurring in several associated structures of an intervertebral joint, especially in the articular facets and within the intervertebral disc.

It must be mentioned that as a result of the slight amount of movement

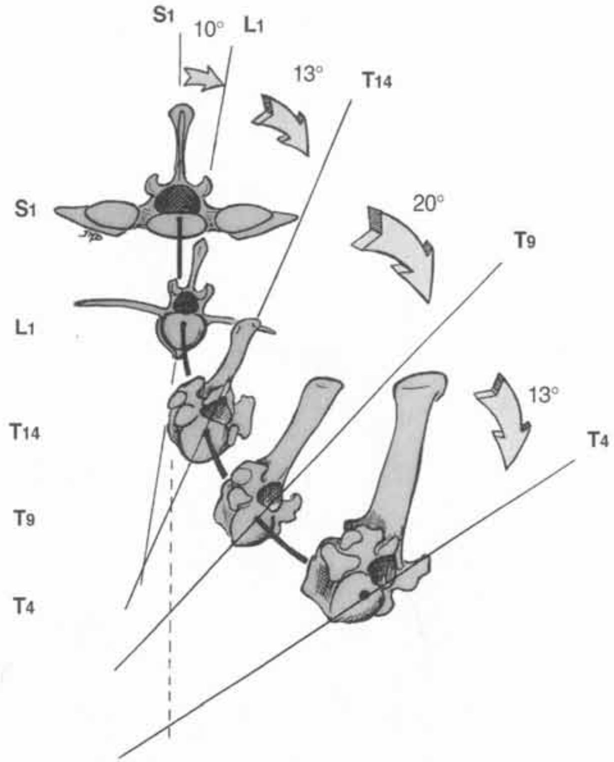

Figure 11. Mobility in the thoracolumbar spine during right rotation. Submaximal amounts of regional spinal mobility referenced from labelled vertebral segments. Note the coupled left lateroflexion *(heavy curved line)*.

occurring in the intervertebral joint complexes of the horse, the ICR can be assimilated to the CR.

Dorsoventral Movements

Intervertebral mobility in the median plane has been investigated on anatomical specimens composed of the whole axial skeleton.[11] The objective was to assess the kind and magnitude of the associated displacement undergone by related structures such as spinous processes, articular facets, intervertebral foramens, vertebral bodies, and intervertebral discs.

Kinematic Analysis. On five isolated axial skeletons, radioopaque markers were used to determine the intervertebral ICR during dorsoventral movements.[7] Although only 2 reference points would have been enough, 3 to 10 of them were finally used to determine the CR, which proved to be the barycenter of the intersections of the medians drawn from two positions of the same point (Fig. 12).

During thoracolumbar and lumbosacral flexion (with and without neck flexion) and extension, the ICR of any equine thoracolumbar intervertebral joint was generally situated in the body of the caudal fixed vertebra (Fig. 13), thus

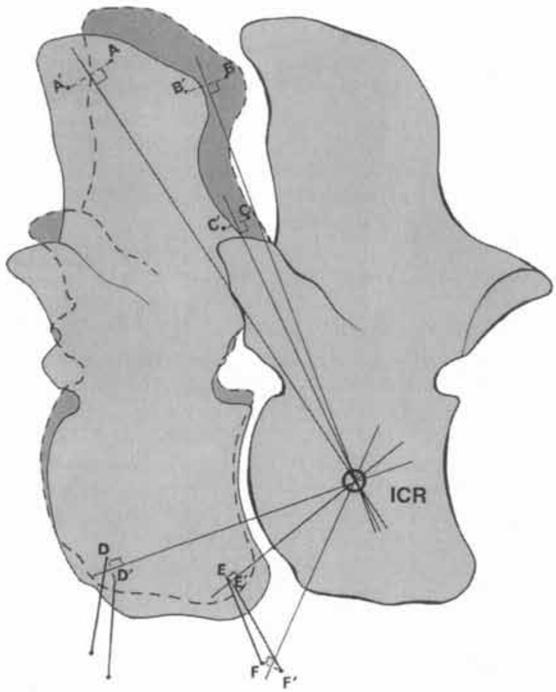

Figure 12. Geometric method used to determine the instantaneous center of rotation of thoracolumbar joints. (*From* Denoix JM: Kinematics of the thoracolumbar spine in the horse during dorsoventral movements: A preliminary report. *In* Proceedings of the 2nd International Conference on Equine Exercise Physiology. San Diego, CA, 1987, p 607; with permission.)

determining the displacement of the different parts of the vertebra and that of associated articular structures. As is suggested by the positions of the ICR, dorsoventral movements of a vertebra can be considered either as a rotation about a transversal axis which passes through the following vertebral body center or as a translation along a vertical axis coupled with a rotation about a transversal axis which passes through its own body center.

A kinematic analysis performed in the human lumbar spine by Gonon et al[13] revealed that the ICR of each intervertebral joint is situated on and around the intervertebral disc. During flexion, the ICR appeared in a ventral position, whereas during extension, it appeared to be situated in a dorsal position. It is of interest to note that in our study on equine cadavers, this distribution occurred in the lumbosacral joint.

Anatomical Functional Analysis of Dorsoventral Movements. During extension, because of the position of the ICR (see Fig. 13), the spinous process moves caudally and the supraspinous ligament relaxes (Fig. 14). The caudal articular facets slide in a dorsocaudal direction on the cranial facets of the following vertebra, and the intervertebral foramen narrows. The vertebral body moves dorsally and caudally, and this displacement is accompanied by tangential and shearing movements within the intervertebral disc. During extension, the ventral longitudinal ligament is stretched.

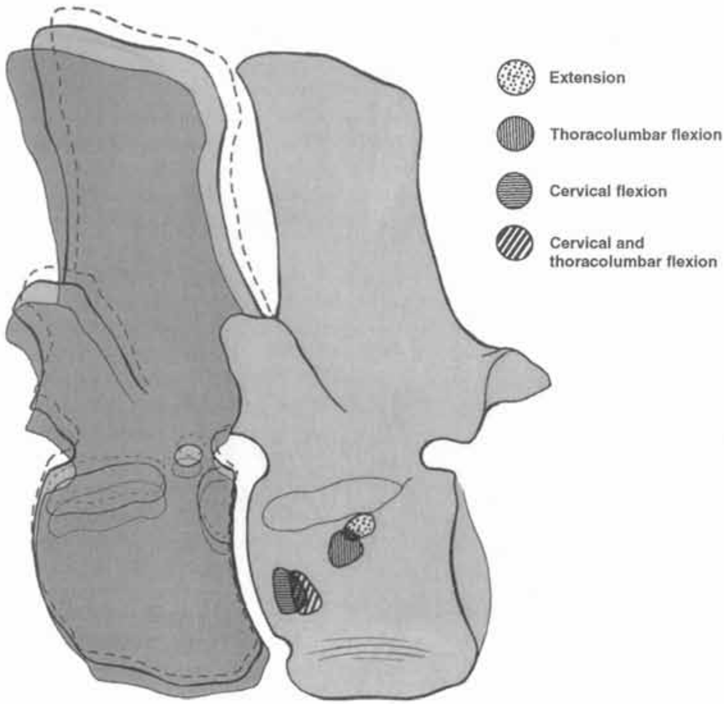

Figure 13. Positions of the ICR of the thoracic intervertebral joint (T17–T18) during different dorsoventral movements. *(From* Denoix JM: Kinematics of the thoracolumbar spine in the horse during dorsoventral movements: A preliminary report. *In* Proceedings of the 2nd International Conference on Equine Exercise Physiology. San Diego, CA, 1987, p 607; with permission.)

During thoracolumbar flexion, the ICRs were especially concentrated in the center of the vertebral bodies of the thoracolumbar region (T17–L2) (see Fig. 13). This location of the ICR suggests that in flexion, the spinous process of a vertebra moves cranially and the vertebral body moves ventrally as compared to the following one (see Fig. 14).

When the cervical spine was flexed and during both cervical and thoracolumbar flexion, the ICR of every thoracolumbar intervertebral joint tended to move cranially and ventrally in the caudal adjacent vertebral body in order to be closer to the ventral part of the disc (see Fig. 13). Because of this position, these movements induce more tension in the supraspinous and interspinous ligaments. The caudal and cranial APs separate, and the intervertebral disc undergoes less tangential displacement (shearing) than during thoracolumbar flexion alone.

In the lumbosacral joint, the ICR was situated in the cranial part of the vertebral body of S1, close to the intervertebral disc (Fig. 15). During flexion, the ICR appeared in a more ventral position than during extension. Consequently, shearing strains are limited, whereas compression and stretching (elongation) seem to be absorbed by the thickness of the disc (see below).

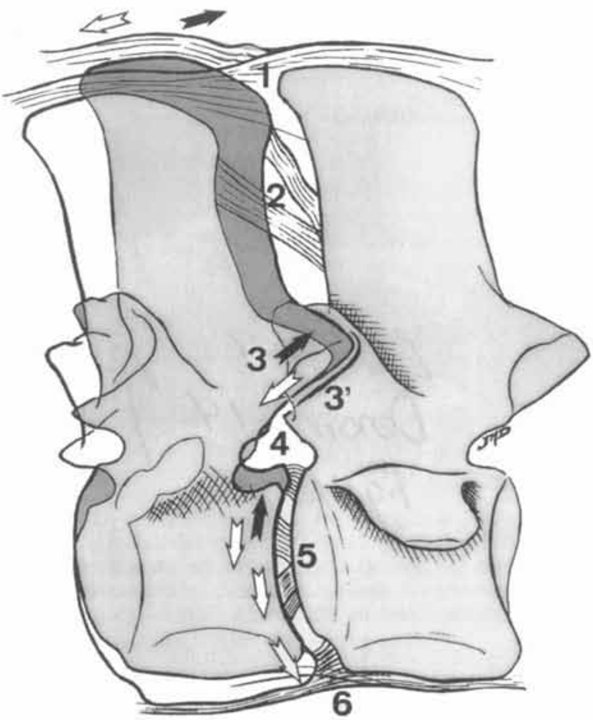

Figure 14. Intervertebral structure displacements within T18–L1 intervertebral joint. 1 = supraspinous ligament; 2 = interspinous ligament; 3 = articular processes; 3' = articular facet; 4 = intervertebral foramen; 5 = intervertebral disc; 6 = ventral longitudinal ligament. Open arrow = Flexion; solid arrow = extension.

Anatomical Functional Behavior of Thoracolumbar Vertebral Structures during Dorsoventral Movements. Establishment of the ICR positions reveals several functional aspects of the vertebral structures and associated ligaments during dorsoventral movements (Table 2).

During flexion, the spinous processes diverged. As compared to the following vertebra, each of them moved cranially and ventrally. The horizontal component of this movement was prominent when the ICR was cranial and ventral (i.e., during cervical flexion). On the contrary, during extension, the spinous processes moved caudally and dorsally.

During dorsoventral movements, the dorsal articular facets of the AP–synovial intervertebral articulation (SIVA) complexes slide along a dorsocaudal-to-ventrocranial axis. The amount of sliding could reach 5.0 to 8.5 mm at the thoracolumbar junction. During flexion of the cervical column, the more ventral and cranial position of the ICR suggests that in this precise location, with or without any thoracolumbar flexion, the two facets move away from each other.

Each vertebral body is prone to two different displacements. When the ICR is situated dorsally (i.e., during thoracolumbar flexion), the body of the moving vertebra is displaced ventrally and caudally. When the ICR is situated more ventrally as is the case during cervical flexion, the dorsal part of the moving body is displaced ventrally and cranially, and the dorsal longitudinal ligament

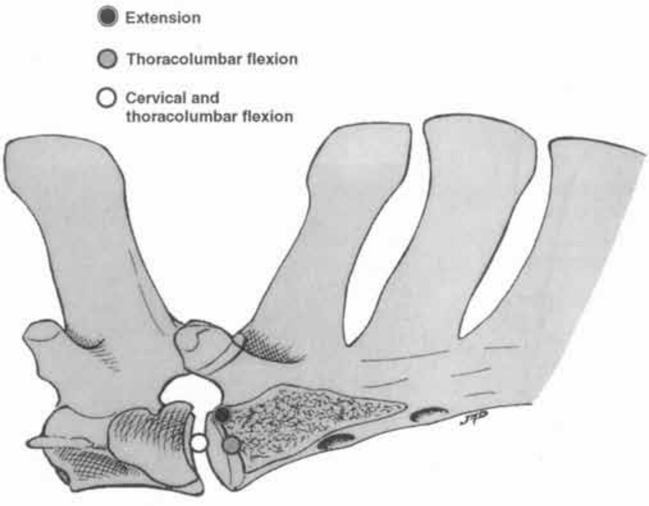

Figure 15. Position of the ICR of the lumbosacral joint during different dorsoventral movements. *(Adapted from* Denoix JM: Kinematics of the thoracolumbar spine in the horse during dorsoventral movements: A preliminary report. *In* Proceedings of the 2nd International Conference on Equine Exercise Physiology. San Diego, CA, 1987, p 607; with permission.)

is stretched. In extension, the body moves caudally and dorsally so that it tends to narrow the intervertebral foramen and induces tension on the ventral longitudinal ligament.

Whatever the position of the ICR, the equine thoracolumbar intervertebral disc sustains shearing strains. This tangential displacement within the disc could reach 5 to 6 mm. It occurs in combination with compressive strains when the ICR is dorsal during flexion and ventral during extension. For example, near the thoracolumbar junction, the measured thickness of the ventral part of the disc could range from 5.0 to 2.7 mm during flexion. When the ICR is ventral during flexion as it is when the neck is lowered, the shearing movement in the disc is less important, but this structure seems to undergo pulling, particularly in its dorsal part.

For all of the dorsoventral movements performed, the average position of the ICR in the equine thoracolumbar intervertebral joints is the center of the caudal adjacent vertebral body, which is near the center of the sphere segment represented by the intervertebral disc.

These data demonstrate that in the equine spine, sliding and shearing movements are the most functional features of the intervertebral discs, which are lacking in nucleus pulposus. On the other hand, the ICR position is closely related to the orientation of the articular facets.

Applied Features. It appears that when the neck is lowered, the ICR of the intervertebral joints moves cranially and ventrally. In this attitude, the spinous processes diverge, the articular facets move away, and shearing strains in the disc decrease. All of these consequences could be beneficial to back problems.

Knowledge of intervertebral kinematics allows one to propose an additional feature in the pathogenesis of ventrolateral spondylosis. Indeed, during dorsoventral movements, the position of the ICR is correlated to tearing of the ventral

Table 2. ANATOMICAL FUNCTIONAL BEHAVIOR OF VERTEBRAL STRUCTURES DURING DORSOVENTRAL MOVEMENTS (FLEXION AND EXTENSION)

Regional Movements	Behavior
Supraspinous and interspinous ligaments	
Flexion	Cranioventral sliding of the cranial spinous process Tension of the supraspinous ligament Shearing and tension of the interspinous ligament Tension of the flavum (interarcual) ligament
Extension	Caudodorsal sliding of the cranial spinous process (contact or narrowing of the interspinous space) Relaxation of the supraspinous ligament Relaxation of the interspinous ligament Relaxation of the flavum (interarcual) ligament
Articular processes and synovial intervertebral articulation	
Flexion	Cranial sliding of the caudal articular processes (separation of articular processes) Tension of the articular capsules Decreased pressure on the articular surfaces
Extension	Caudal sliding of the caudal articular processes (locking of the intervertebral (IV) joint) Relaxation of the articular capsules Increased pressure on the articular surfaces
Disc and longitudinal ligaments	
Flexion	Tension and shearing of the dorsal longitudinal ligament Shearing of the disc Shearing of the ventral longitudinal ligament
Extension	Relaxation of the dorsal longitudinal ligament Shearing of the disc Tension of the ventral longitudinal ligament

longitudinal ligament and shearing in the ventral part of the disc, stresses that could generate bony proliferation.

Rotation and Lateroflexion

These segmental intervertebral movements were studied on isolated vertebral segments (Figs. 16–20).

Thoracic Spine. In each thoracic intervertebral joint, lateroflexion movement is accompanied by a bending of the spinous processes and sliding of the caudal APs of the cranial vertebra in the concavity (see Fig. 16). This anatomical functional feature is correlated to a spontaneous association between lateroflexion and rotation (Table 3) as they occur in the cervical spine, and left lateroflexion is spontaneously coupled to right rotation (see Figs. 16–18). Conversely, in each thoracic intervertebral joint, rotation on one side is associated with lateroflexion on the opposite side (see Table 3 and Fig. 19).

The anatomical functional behavior of intervertebral structures (AP-SIVA complexes and discs) during lateroflexion and rotation is indicated in Tables 4 and 5.

In horses presented with impinged spinous processes or "kissing spines" due to the transverse displacement of the spinous processes, lateroflexion may

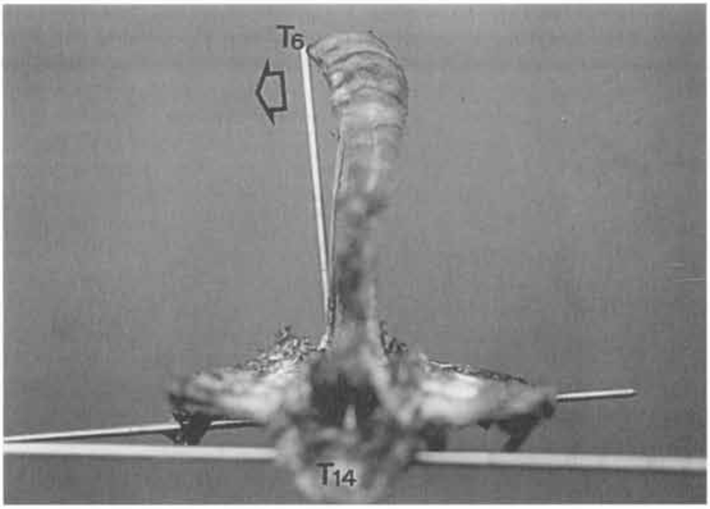

Figure 16. Caudal view of an isolated thoracic region from T6–T14. A moderate left lateroflexion induces a coupled right rotation. *Arrow* indicates the rotation (counter-clockwise) of a pin drilled in the T6 vertebral body. The caudal angulation of the spinal processes minimizes the apparent rotation based on orientation of these processes.

be a movement contributing to the generation of pain, especially when the vertebral column is extended. These combined movements may induce shearing under compression of the interspinous ligament and spinous process margins.

Stresses and strains within the vertebral structures may vary according to the initial positioning of the spine. If the thoracic spine is positioned in left rotation, right lateroflexion is easier because of the increased space between the right APs. These amplified spontaneous associated movements induce the maximal rotation of the intervertebral joint with an increased displacement of the spinous processes and caudal APs on the right side. If the initial positioning of the thoracic spine is in left rotation, an added left lateroflexion induces an inversed rotation (contrary movement) with a contrary realignment of the APs and increased stress and strain on intervertebral structures.

Thoracolumbar Junction and Lumbar Spine. The same kind of movements and associated displacement can be described in these parts of the horse's back, but because of the anatomical functional particularities of these areas, the

Table 3. SPONTANEOUS ASSOCIATIONS BETWEEN LATEROFLEXION AND ROTATION IN THE THORACIC SPINE

Provoked Movement	Spontaneous Associated Movements
Left lateroflexion (bending of spinous processes in the concavity)	Right rotation
Right lateroflexion	Left rotation
Right rotation	Left lateroflexion
Left rotation	Right lateroflexion

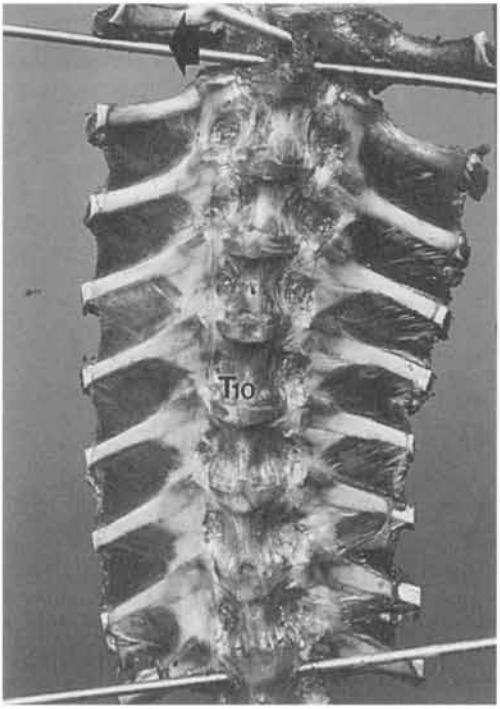

Figure 17. Ventral view of an isolated thoracic region from T6–T14. A moderate left lateroflexion induces a coupled right rotation. The *heavy arrow* indicates the right rotation of the ventral extremity of a pin drilled in the T6 vertebral body. T10 = tenth thoracic vertebra.

amount of motion is limited (see Fig. 20) and can be considered as virtually nonexistent between L4 and L6.

The most limiting factors are (see Table 1):

- Height of the spinous processes and inextensibility of the supraspinous ligament
- Congruence of the APs
- Size of the vertebral bodies
- Strength of the ventral longitudinal ligament

Despite the limited motion, interesting anatomical functional features can be noted in the lumbar AP-SIVA complexes (Table 6). As described in human specimens,[19] the lumbar APs undergo stresses during lateroflexion and rotation.

Lumbosacral Joint

Dorsoventral Movements

Amount of Motion. The great amount of dorsoventral flexion and extension in the lumbosacral joint (Fig. 21) is due to several anatomical features: the thickness and decreased height of the intervertebral disc[28]; the wide divergence

Figure 18. Demonstration of coupled left lateroflexion and right rotation in the thoracolumbar spine in a free-moving horse.

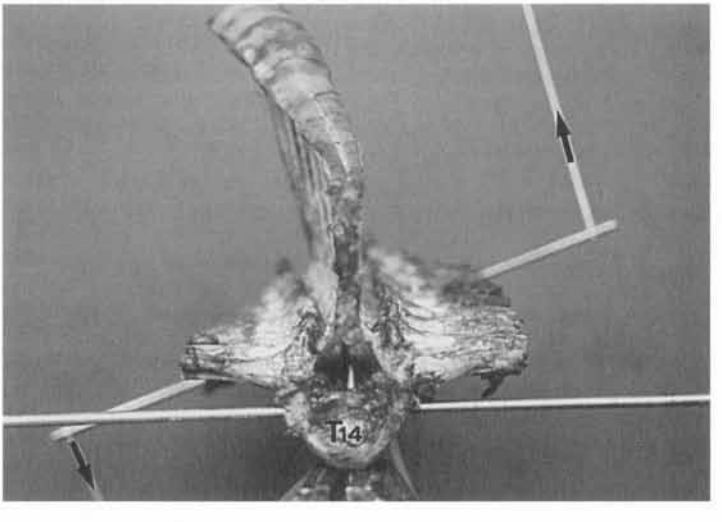

Figure 19. Caudal view of an isolated thoracic region from T6–T14. Right rotation *(arrows)* induces a coupled left lateroflexion.

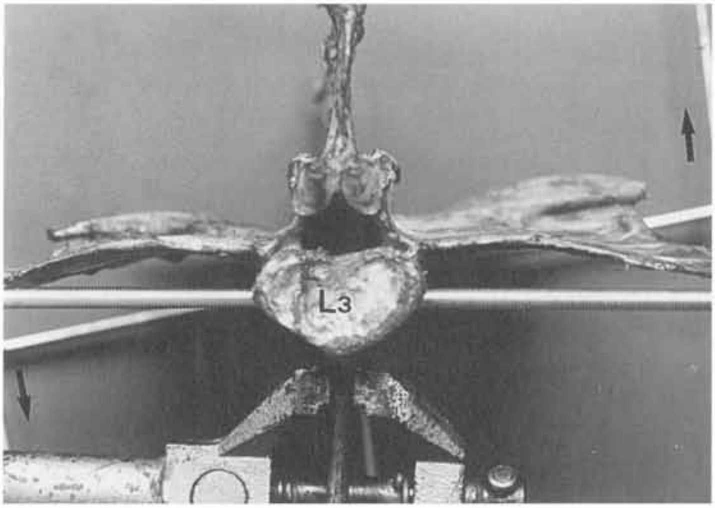

Figure 20. Caudal view of an isolated thoracolumbar region from T15–L3. A small amount of right rotation *(arrows)* induces minimal lateroflexion.

of the dorsal spinous processes, which is favorable to extension; the poorly developed interspinous ligamentous tissue[17]; and the absence of real supraspinous ligament, which makes flexion easier. The vertical orientation of the articular facets in this joint[28] does not limit dorsoventral movements.

It is of interest to note that divergence of the spinous processes generally takes place between L6 and S1. In some horses, however, it occurs between L5

Table 4. ANATOMICAL FUNCTIONAL BEHAVIOR OF THE ARTICULAR PROCESSES AND SYNOVIAL INTERVERTEBRAL ARTICULATION COMPLEXES OF THE THORACIC SPINE (PRE-T17) DURING LATEROFLEXION AND ROTATION

	Joint Movements	
Regional Movements	**Left Side**	**Right Side**
Left lateroflexion (articular processes slide on the left side [cf spinous processes])	Left (caudolateral) sliding of the caudal left articular processes	Separation of the articular processes Craniomedial sliding of the caudal articular processes
	Moderate tension (shearing, lateral distraction) of the articular capsule	Tension (shearing, medial distraction) of the articular capsule
	Locking of the ribs	Increased mobility of ribs
Left rotation	Right (medial) sliding of the caudal left articular processes (compression between left articular processes)	Separation of the articular processes Lateral sliding of the caudal right articular processes
	Tension (shearing, medial distraction) of the articular capsule	Tension (lateral distraction) of the articular capsule

Table 5. DISC DEFORMATIONS AND STRAINS DURING INTERVERTEBRAL LATEROFLEXION AND ROTATION

	Disc Deformations, Strains	
Regional Movements	**Left Side**	**Right Side**
Left lateroflexion	Relaxation of the superficial fibers (prolapse, herniation)	Tension of the superficial fibers
Left rotation	Relaxation of the superficial fibers	Tension of the superficial fibers

and L6, with the spinous process of L6 undergoing caudal bending[7, 14]; in this case, great mobility appears in the last lumbar intervertebral joint. This is the reason why the last two pins were drilled into L5 and S1 rather than into L6 and S1 in our experiments on the complete vertebral column, in order to record the mobility of the entire lumbosacral area. In our study, these last two intervertebral joints had a mean combined dorsoventral movement of 20°, with variations ranging from 9° to 32°.

Lumbosacral Kinematics. It is of interest to note that in the lumbosacral joint, the ICR was closer to the disc. Consequently, shearing strain is less in this disc, whereas tensive and compressive strain is greater (Fig. 22). These mechanical concerns are related to the thickness of the disc in this joint.

Because of the cranial orientation of the L6 and S1 transverse processes, during flexion and extension movements, there is greater sliding in the lateral part of the intertransverse joint than in the medial part (Fig. 23). The movement close to the vertebral axis can be assimilated to a rotation (with a center close to the intervertebral disc), but it is a translation in the left and right intertransverse joints. In both flexed and extended positions of the joint, the ventral intertransverse lumbosacral ligaments are stretched.

Table 6. ANATOMICAL FUNCTIONAL BEHAVIOR OF THE LUMBAR ARTICULAR PROCESSES AND SYNOVIAL INTERVERTEBRAL ARTICULATION COMPLEXES (CAUDAL TO T17) DURING LATEROFLEXION AND ROTATION

	Joint Movements	
Regional Movements	**Left Side**	**Right Side**
Left lateroflexion (articular processes slide on the left side [cf spinous processes])	Covering and compression of the lateral part of the left articular processes Caudal sliding of caudal left articular processes Relaxation of the articular capsule	Separation of the lateral part of the articular processes Craniomedial sliding of the caudal right articular processes Tension of the articular capsule
Left rotation	Separation of the lateral part of the articular processes Medial sliding of the caudal left articular processes Tension of the articular capsule	Lateral compression of the lateral part of the right articular processes Craniolateral sliding of the caudal right articular processes Relaxation of the articular capsule

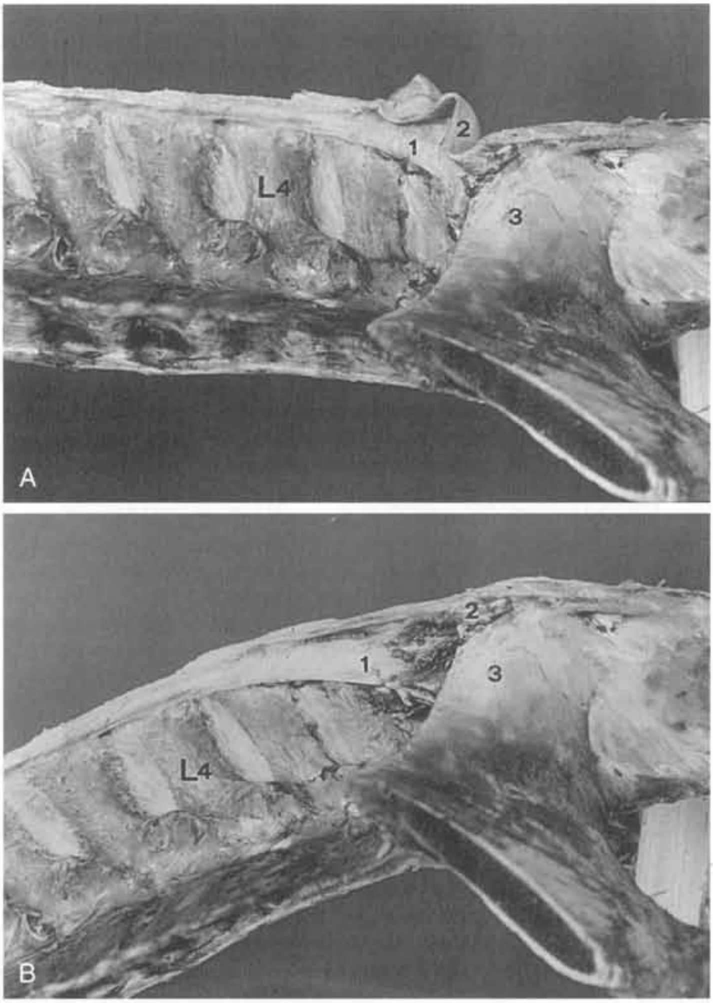

Figure 21. *A* and *B*. Lumbosacral junction during dorsoventral movements. Left view. The total amount of motion is close to 25°. During extension *(A)* the interspinous tissues (1) tissues and erector spinae aponevrosis (2) are relaxed; they become taut and limit the amount of flexion *(B)*. 3 = ilium wing; L4 = fourth lumbar vertebra.

Anatomical Functional Behavior. The anatomical functional behavior of the lumbosacral structures is detailed in Table 7 and Figures 22 through 24. Flexion of the lumbosacral joint is limited by the tension of the interspinous ligament, erector spinae muscle aponeurosis, interosseous sacroiliac ligament (iliolumbar part), intervertebral disc (dorsal part), and ventral intertransverse lumbosacral ligament (see Figs. 22*A* and 24*A*). Extension of the lumbosacral joint is limited by the tension of the ventral intertransverse lumbosacral ligament, ventral part of the intervertebral disc (see Figs. 22*B* and 24*B*), and locking of the APs.

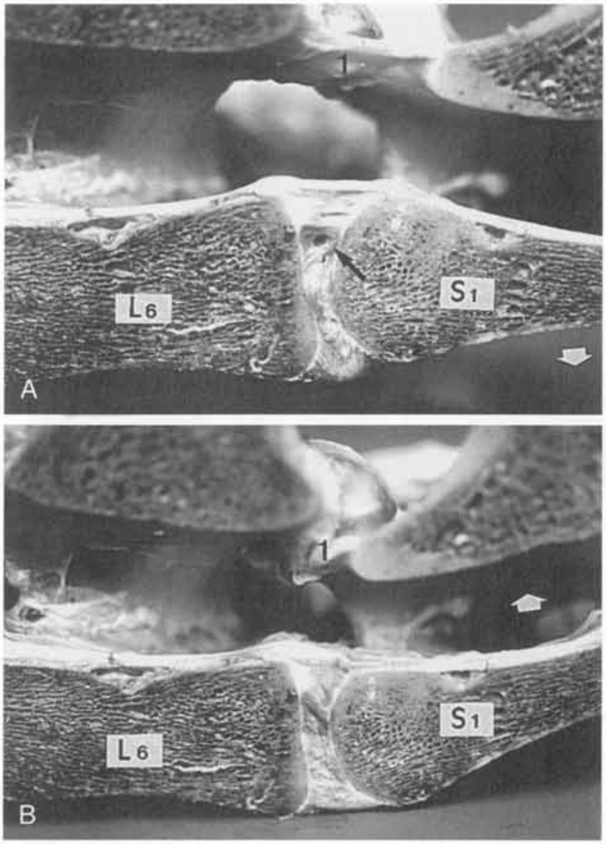

Figure 22. Median section showing disc deformations during dorsoventral movements of the lumbosacral joint. *A*, Flexion: relaxation, and bulging of the ventral portion of the intervertebral disc and tension of the dorsal portion of the disc. There is evidence of disc cavitation in this specimen *(arrow)*. *B*, Extension: relaxation of the dorsal portion of the disc and tension of the ventral disc fibers. The ligamenta flavum (interarcual ligament) (1) is relaxed and bulges during extension and stretched in flexion. White arrow = flexion, A or extension, B movement.

Lateroflexion and Rotation

Because of the presence of intertransverse joints and the strength of the ventral intertransverse lumbosacral ligaments (and interosseous lumboiliac ligament), lateroflexion and rotation of the lumbosacral joint are limited and only possible when the initial angulation of the joint is in an intermediate semiflexed position. This angulation is accompanied by a relaxation of the ventral intertransverse ligament, allowing small movements of rotation and virtually nonexistent lateroflexion (Table 8). When the initial positioning of the joint is placed in full extension or full flexion, rotation and lateroflexion of the lumbosacral joint are virtual, and these movements become more extensive in the sacroiliac joint, although this joint has low mobility (Table 9).[4, 5]

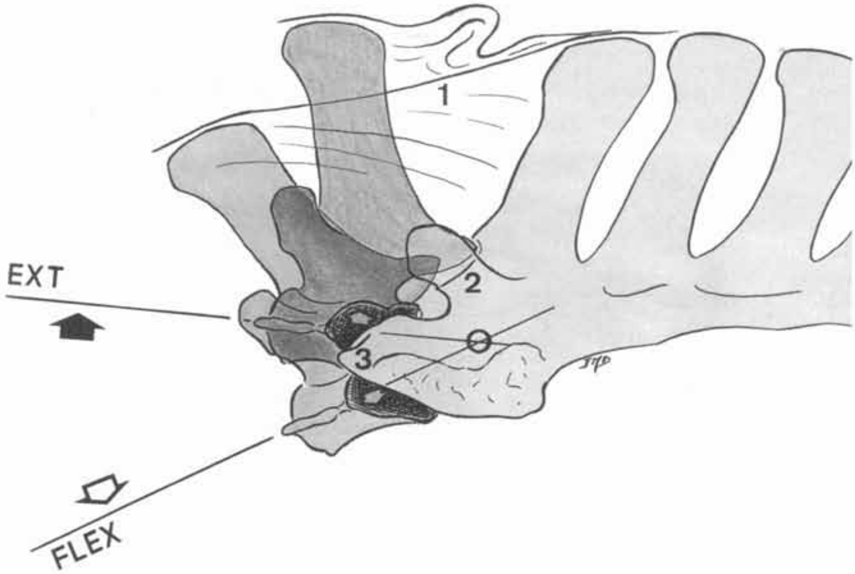

Figure 23. Vertebral displacements during dorsoventral movements of the lumbosacral joint. Notice that because of their craniolateral orientation, the intertransverse joints undergo tangential dorsoventral displacement; tension of the ventral intertransverse lumbosacral ligament occurs during both extension and flexion. 1 = interspinous ligament; 2 = articular processes; (S1) 3 = lumbosacral intertransverse joint.

SUMMARY

Knowledge of the normal functional behavior and mechanical properties of the vertebral column is important to understand the pathogenesis of back lesions, to identify the clinical manifestations of back pain, and to ensure a rational approach to physical therapy. The purpose of this article is to present a synthesis of in vivo and in vitro data obtained from different but complementary investigations.

Presently, in vivo studies are limited; few gait-specific kinematic and electromyographic investigations are in process.

Higher stresses to reach the maximal range of intervertebral motion can be applied on the spine on anatomical specimens than in living horses, and anatomical functional data can be obtained at the level of intervertebral structures. For each movement of flexion, extension, lateroflexion, and rotation, regional and intervertebral mobility is presented with an emphasis on craniocaudal variations and their anatomical causes.

Because of the location of their ICR, the dorsoventral movements of a thoracolumbar intervertebral joint can be defined as a rotation around the center of the more caudal vertebral body. This information supports the new concept of intervertebral mobility in the horse and provides additional elements to facilitate understanding of the pathogenesis of back problems in the horse.

Table 7. ANATOMICAL FUNCTIONAL BEHAVIOR OF THE LUMBOSACRAL JOINT DURING FLEXION AND EXTENSION MOVEMENTS

	Flexion	Extension
Ventral structures		
Disc (shearing movement at center)	Ventral compression thickness of 10 mm Ventral herniation Dorsal tension	Ventral tension thickness of 18 mm (flattening) Dorsal relaxation Dorsal compression (?)
Intertransverse joints (total amount of sliding = 1 cm)	Ventral sliding of the transverse process of L6/S1	Dorsal sliding of the transverse process of L6/S1
Ventral intertransverse lumbosacral ligament	Tension	Tension
Ventral intervertebral foramen L6	Narrowing	Opening
Dorsal longitudinal ligament	Tension	Relaxation
Extrinsic structures		
Interosseous sacroiliac ligament (iliolumbar part)	Tension	Relaxation
Iliolumbar ligament (membrane)	Tension	Relaxation
Dorsal structures		
Flavum (interarcual) ligament	Tension	Relaxation
Dorsal synovial joint (between articular processes)	Separation (cranial sliding of caudal articular processes)	Covering, locking (caudal sliding of caudal articular processes of L6)
Interspinous (supraspinous) ligament	Tension	Relaxation

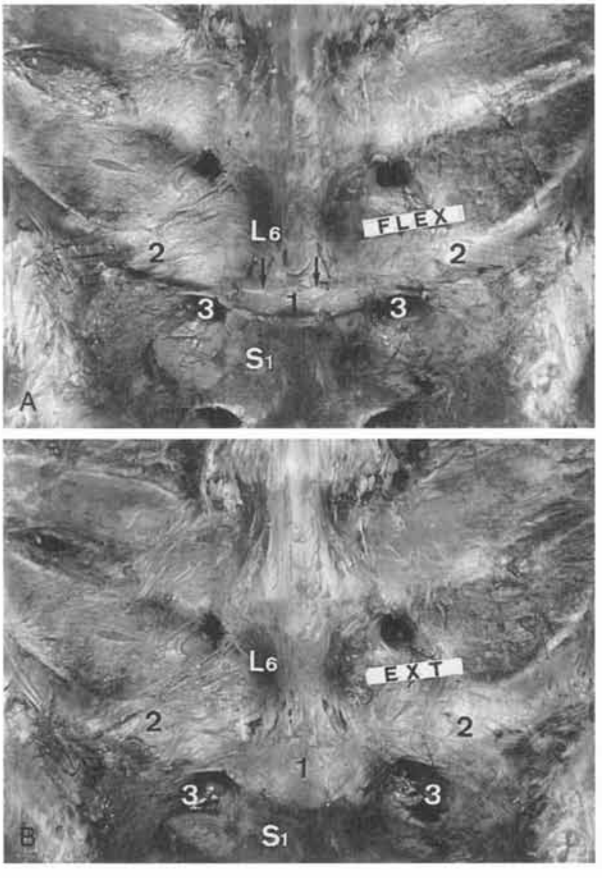

Figure 24. Lumbosacral junction undergoing dorsoventral movements. Ventral view. *A*, Flexion: relaxation and bulging of the ventral portion of the intervertebral disc *(1) (arrows)*, tension of the ventral intertransverse lumbosacral ligaments *(2)*, and narrowing of the ventral intervertebral foramen *(3)*. *B*, Extension: tension of the ventral portion of the intervertebral disc *(1)* and ventral intertransverse lumbosacral ligaments *(2)*. Opening of the ventral intervertebral foramen *(3)*. In both situations, the ventral intertransverse lumbosacral ligament is stretched and restricts any lateroflexion or rotation.

Table 8. ANATOMICAL FUNCTIONAL BEHAVIOR OF THE LUMBOSACRAL JOINT DURING ROTATION AND LATEROFLEXION

Initial Positioning	Amount of Movement	Limiting Factors
Extension	Rotation and lateroflexion minimal (nearly impossible)	Locking of the articular processes Contact between transverse processes Tension of the ventral intertransverse ligament
Flexion	Rotation and lateroflexion minimal but present	Tension of the ventral intertransverse ligament and interosseous sacroiliac ligament (iliolumbar part)
Intermediate (semiflexion): relaxation of the ventral intertransverse ligament	Limited movements: Rotation: 3°–5° (no associated lateroflexion) Lateroflexion: 1°–2°	Lumbosacral disc Contact between articular processes Tension of the ventral intertransverse ligament
Lumbosacral joint	Flexion/extension Variation of position > variation of pressure Rotation Tension of ligament > pressure on intertransverse joints Lateroflexion Tension of ligaments Pressure on articular surfaces	

> = superior to.

Table 9. COMPARISON OF LUMBOSACRAL AND SACROILIAC MOBILITY DURING MOVEMENTS PROVOKED BY MOBILIZATION OF THE LUMBAR SPINE (WITH THE PELVIS BEING FIXED)

Lumbosacral Movements	Sacroiliac Mobility
Flexion and extension	Lumbosacral >> sacroiliac mobility #0
Lateroflexion	Lumbosacral mobility << sacroiliac mobility
Rotation	
Semiflexed position	Lumbosacral mobility > sacroiliac mobility
Flexion	Lumbosacral mobility < sacroiliac mobility
Extension	Lumbosacral mobility < sacroiliac mobility

> = superior to; >> = more superior to ; # = close to; < = inferior to; << = more inferior to.

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