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REVIEWS OF THE LITERATURE

A Review of Biomechanics of the Central Nervous System—Part II: Spinal Cord Strains from Postural Loads

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ABSTRACT

Objective: To review spinal cord strains arising from postural loads.

Data Collection: A hand search of available reference texts and a computer search of literature from the Indexed Medicus sources were collected, with special emphasis placed on spinal cord strains caused by various postural rotations and translations of the skull, thorax, and pelvis

Results: All spinal postures will deform the neural elements within the spinal canal. Flexion causes the largest canal length changes and, hence, the largest nervous system deformations. Neural tissue strains depend on the spinal level, the spinal movement generated, and the sequence of movements when more than one spinal area is moved.

Conclusions: Rotations of the global postural components (head, thoracic cage, pelvis, and legs) cause stresses and strains in the central nervous system and peripheral nervous system. Translations of the skull, thorax, and pelvis, as well as combined postural loads, need to be studied for their effects on the spinal canal and neural tissue deformations. Flexion of any part of the spinal column may generate axial tension in the entire cord and nerve roots. Slight extension is the preferred position of the spine as far as reducing the magnitude of mechanical stresses and strains in the central nervous system is concerned. (J Manipulative Physiol Ther 1999;22:322-32)

Key Indexing Terms: Posture; Spinal Cord; Biomechanics; Central Nervous System.

INTRODUCTION

In Part I of this review[1] some basic engineering concepts were discussed and applied to deformations of the spinal canal. In Part II, deformations of the central nervous system will be discussed. The stresses and strains discussed in Part I[1] for the four types of loads (axial, torsion, pure bending, and transverse) are critical to this debate. The central nervous system (CNS) deformations are primarily due to changes in posture. It is a basic theorem in physics that any motion (postural position) can be decomposed into a rotation, translation, and deformation.[2] While assuming the head, thoracic cage, and pelvis to be moved as rigid bodies and considering deformations of only the soft tissues, human postures will be described as rotations (Rx, Ry, Rz) and translations (Tx, Ty, Tz). Figs 1 and 2 illustrate this mechanical engineering approach to posture.[3] Before reviewing the stresses and strains in the CNS, some basic properties of the nervous system will be discussed.

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DISCUSSION

Mechanical Properties of Neural Tissue

Spinal cord tissue removed from the dural covering (cord and pia mater only) has its own unique physical characteristics. When all nerves and dentate ligaments are detached, the cord behaves as a homogenous fluid of low viscosity.[4] It is important to note that axoplasm possesses thixotropic properties: viscosity diminishes with repeated strains and if the strain is maintained at a given level, it becomes more viscid.[5] This phenomenon will become pertinent later in the discussion. Spinal cord tissue also displays viscoelastic and plastic properties.

Spinal cord tissue suspended from one end will deform roughly 10% under its own weight. This deformation is likely the result of two factors: the low viscosity of the spinal cord and the unfolding phenomenon of the folded neural tissue. After the initial strain an additional force must be applied to deform the spinal cord further. This part of the load deformation curve may represent the true properties of the cord tissue. Once the added force is removed, there is an initial elastic recovery; however, there is large hysteresis (energy loss) in which some of the deformation remains permanent or plastic. White and Panjabi[6] claim that this is roughly analogous to the rheologic properties of ligamentous tissue. The addition of the dentate ligaments, and their attachment to the dural covering, changes the behavior of the spinal cord tissue because forces generated in the dura are now transmitted to the spinal cord tissue.

A detailed model of the rabbit tibial nerve was presented by Kwan et al.[7] The peripheral nerve of the rabbit, in situ,

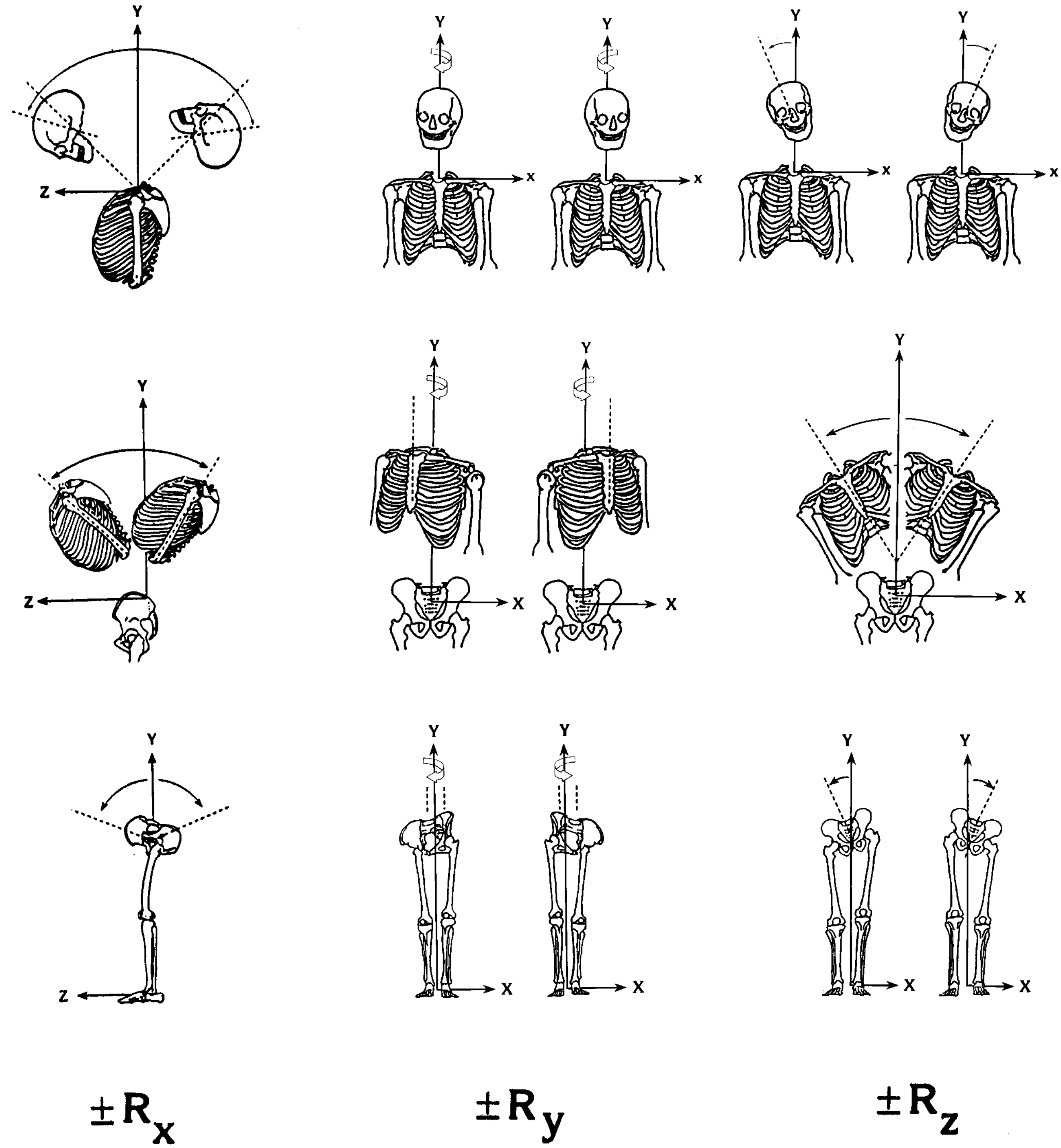

Fig 1. *Global posture in terms of rotations. The head, thoracic cage, and pelvis can rotate and translate in three dimensions with 6 degrees of freedom.[14] The rotation main motions are depicted here. The rotations have been termed the traditional planes of motion and are the main motions used when spinal coupling and tissue deformation are studied.*

was found to be under large strain but minimal stress. However, with further increases in length, the stiffness increases, as shown by their load-deformation curve. They state, "peripheral nerve was found to exhibit highly non-linear stress-strain behavior, contrary to what is often described in the literature—a linearly elastic material."[7] Peripheral nerve was shown to exhibit creep (deformation over time with an applied load) and stress relaxation (reduction in the force per unit area over time for the same load). Significantly, under larger strains the stress relaxation was less. Tencer et al[8] demonstrated similar results in the CNS. These two phenomenon, creep and stress relaxation, are important in minimizing the forces generated internally in the tissue.

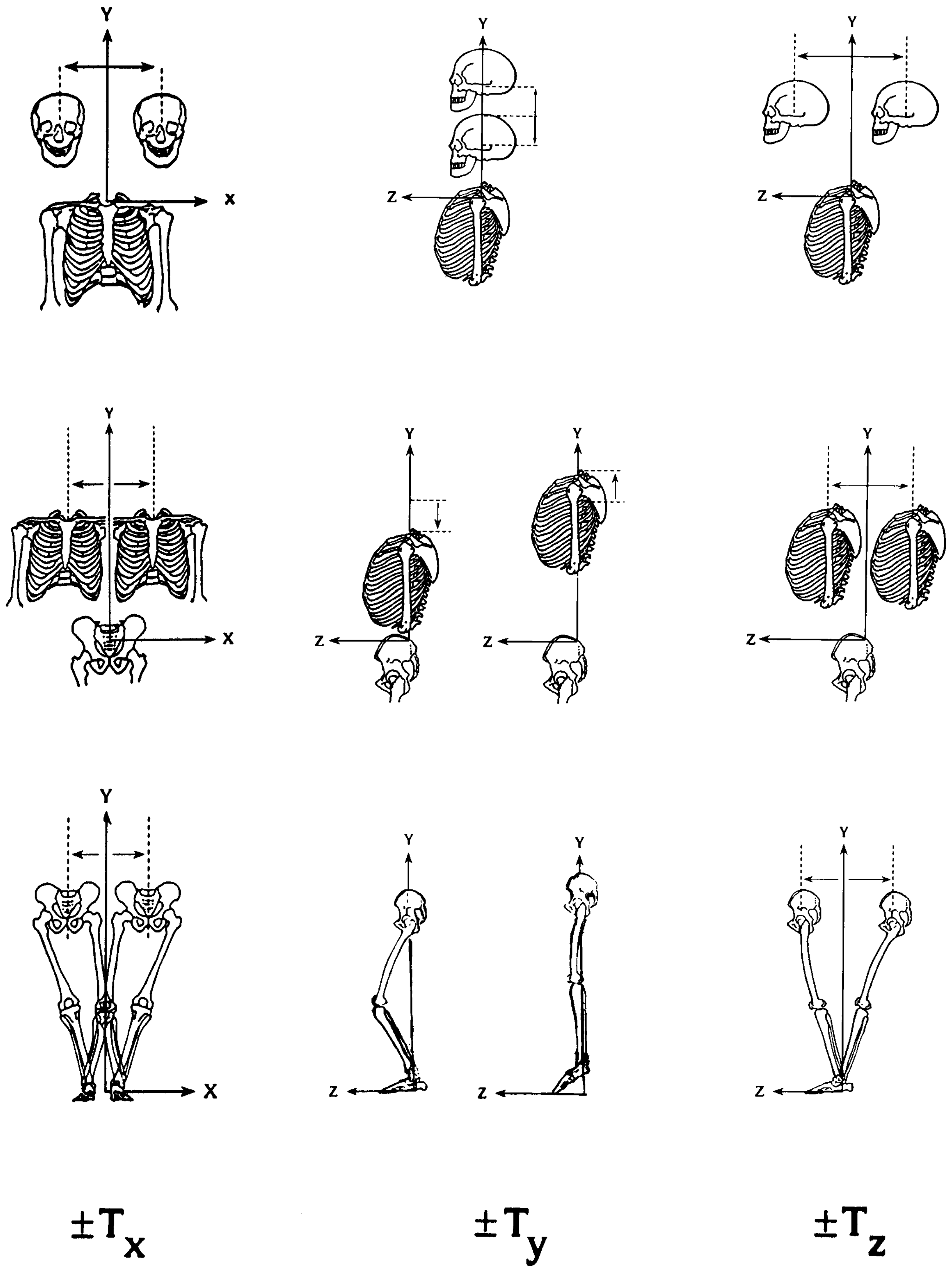

Fig 2. *Global posture in terms of translations. The translations of the head, thoracic cage, and pelvis are illustrated here. Postural permutations are combinations of these rotations and translations. There are very few studies in the literature for spinal coupling and tissue deformations during global translations.*

There is a slight internal displacement of the spinal cord relative to the dura during elongation. Because the displacements are relatively small, 1 to 3 mm, they are generally disregarded.[9,10] When the dura is pulled taut with increasing canal length, tension is transmitted from the dentate ligaments to the cord. Tension in the dentate ligaments stabilizes the cord in the canal, but it can also have a tethering or overstretching effect on the cord. Because of the orientation of the dentate ligaments, inclined inferiorly and directed laterally, the force exerted on the spinal cord has two components: an axial component and a transverse component. The dentate ligaments balance the axial tension of the cord. The transverse forces of the two dentate ligaments balance each other and provide stability and protection.[6] The result is that the cord becomes positioned close to the center of the canal and in the center of the subarachnoid space. This location of the spinal cord, within the canal and within the dural tube, provides protection from external and internal forces that occur during physiological and nonphysiological activities.

The components of the CNS and peripheral nervous system are under resting strain in the neutral position.[4,7,8,11] Therefore any change in position that increases canal length (ventroflexion, lateral flexion, or y-axis distraction) will increase the stress and strain already present in the spinal cord. The increased stress is transmitted to the spinal cord via the dentate ligaments.

The normal configuration of the spinal cord is circular in the upper cervical disks, slightly ellipsoid in the mid-cervical disks to upper thoracic disks, and somewhat more circular in the lower regions.[12] Any change of the normal configuration at a given vertebral level, indicates that the spinal cord is being strained from increased longitudinal or cross-sectional stress.[13] As an example, when the neutral lordotic cervical configuration is altered, for instance in a military/straight cervical spine, the dentate ligaments impart an axial and a transverse stretch to the cord. The anterior-to-posterior dimension of the cord is reduced, but the transverse diameter may slightly increase. This is associated with a reduced cross-sectional area of the spinal cord.[4,6,11,14] This is known as *Poisson's effect:* the decrease in cross-sectional area with an increase in length or an increase in cross-sectional area with a decrease in length, the total volume remaining constant.[6,15]

Because the spinal cord is surrounded by the cerebrospinal fluid system and the internal component of the cord is primarily glial and neuronal cytoplasm, it is essentially noncompressible. Therefore the spinal cord must follow Poisson's law fairly well. All components of the pons-cord system follow this phenomenon, including the neural cells and the extensive vascular system. This is what prompted Breig to term the study of this field *histodynamics*, which he defined as a branch of medicine dealing with the effects produced on cell elements by the action of dynamic forces.[4]

Movement of the Neural Tissue: Unfolding and Sliding

The pons-cord tissue tract consists of the mesencephalon, pons, medulla oblongata, cranial nerves 5-12, spinal cord, nerve roots, and the meningeal coverings. This is considered to be a continuous entity because forces in one component are transmitted to each of the others. The CNS is anchored at the sacrum and coccyx by the filum terminale, at every exiting nerve root level, is secured at the midbrain level, and the pons and medulla are held in place by the exiting cranial nerves 5-12, especially cranial nerve 5.

It is known that the dural sleeves of the nerve roots are attached by collagenous filaments to the bony foramina, the anterior dural covering of the cord is attached to the posterior longitudinal ligament and to the periosteum of the posterior vertebral bodies, and the posterior dura is attached to the posterior bony canal by the posterior epidural ligaments. Furthermore, the rectus capitus posterior minor muscle is attached to the posterior dura in the suboccipital region, and connective tissue bands "tightly attach the cranial end of the dural sac ventrally to the periosteum of the basal part of the occipital bone coursing through the tentorial membrane. The dura is attached to the transverse ligament of the atlas and to the dorsal longitudinal ligament; dorsally to the periosteum of the occipital squama and arches of the atlas and axis; and laterally to the atlanto-occipital and atlanto-axial articulations."[14]

It is apparent that this arrangement of anatomy does not allow the spinal canal to deform without deforming the internal structures. According to McCormick and Stein, "Changes in the canal length (strain), therefore, are transmitted to the dura and spinal cord, resulting in generated stress in both structures."[11]

Alf Breig is considered to be the true pioneer in the field of biomechanics of the pons-cord tract; several other authors have also contributed to the basic knowledge in this field. A few of these works will be presented first in an attempt to provide a historical perspective and to lay to rest any controversy that exists concerning the exact nature of the response in the pons-cord tract to spinal canal deformations.

Smith[9] may actually be the first to perform detailed measurements of the elastic elongation and up and down shifts of the pons-cord tract. His observations were performed on Rhesus monkeys by flexing the skull, trunk, and placing the limbs in various positions to demonstrate the effects of stretching the peripheral nerves on the spinal cord. Smith[9] believed that the cord movements were of two types: a shift of the neural tissue up or down followed by an elastic elongation. On flexion, all segments above the interspace of the fourth and fifth cervical vertebrae, including the hind brain, were displaced caudally. Segments below the C4-C5 disc, down to the sacral plexus, shifted cranially. Accordingly, at the sixth thoracic vertebrae the cord shifted 5.9 mm, and this displacement steadily decreased to the last coccygeal segment where the movement was 4.0 mm. The pons was displaced downward 0.4 mm, the medulla 1.5 mm, the first cervical segment 1.6 mm, and the fourth cervical segment 0.2 mm.

Simultaneously, it was found that flexion stretched each segment of the cord in proportion to the degree of flexion that occurred at the joint at that level.[9] The greatest degree of stretching occurred in the cervical cord. At the atlanto-occipital joint, the cord stretch was 16% (24 degrees of flexion), at C2-C3 it was 9% (10 degrees of flexion), and at

C6-C7 it reached 24% for 18 degrees of flexion. The medulla oblongata was found to stretch 13.5%, the pons 3%, and the midbrain did not show any measurable deformation. Elongation also occurred in the sacral and lumbar segments, with a value of 4% between L3-L4.

In a series of routine necropsy cases, Reid[16] found that the greatest area of cord stretch was in the same general region as that observed by Smith.[9] Flexion of the cervical spine alone caused cord segments C2-T1 to deform an average of 10%, with a peak value of 17.6%. Large cranial and caudal displacements of the cord and dura were found to occur at root levels C8-T5. The greatest shift occurred at T1, being 1.8 cm. Although the greatest flexion angles and, hence, cord stretching occurred in the cervical spine, the stretch produced was transmitted to the thoracic segments and possibly even the lumbar levels.

Adams and Logue[17] believed that stretching only occurred when the dura was fully unfolded near maximum flexion. The greatest amount of movement was believed to be due to up and down shifts. These shifts were claimed to vary from 54% to 93% of the total motion.

When Louis[18] performed measurements on 24 fresh cadavers, the whole spinal column was flexed and extended. The cord was said to shift and stretch simultaneously. Regions of maximum cord displacements were C1 (7 mm caudally), T1 (7 mm cranially), and L1 (10 mm caudally). During spinal flexion a 10% elongation of the spinal cord was found. However, Louis[18] showed that this was not distributed equally. Some areas did not stretch at all, whereas others were strained up to 30%. For example, the L3 nerve root remained relatively static, whereas the L5-S1 root strain was 30%, and the S2 root was strained by 16%. This would theoretically result in stress concentration at four levels, C6, T6, L4 and the roots of the cauda equina distal to the fourth lumbar roots.

Taken as a whole these studies indicate that the spinal cord slides up and down in the spinal column, unfolds, and finally will deform elastically to varying degrees.[9,16-18] The shift up and down of the dura and cord was believed to comprise a significant portion, if not the majority, of the total displacement that occurs in the pons-cord tract. Other authors also contend that neural "sliding" is an important movement parameter of neural tissue.[19]

One possible explanation for the extremely large up-and-down shifts of the cord found by Adams and Logue[17] is the method that was used to measure these displacements. X-ray films were obtained of the intervertebral foramina in flexed and extended positions of the head and neck. The x-ray tube was tilted 10 degrees superiorly and was angled 45 degrees to the sagittal plane. There are large projection/distortion errors concerning the position and shape of objects away from the central ray, especially when considering the view in which these authors chose. This would result in invalid measurements of cord displacement.[18,20]

The above-mentioned errors associated with x-ray procedures prompted Louis[18] to attempt direct measurements: "A metal wire was positioned transversely between two metal markers embedded in the vertebral pedicles. This was repeated for each vertebra in the column. Wire markers were secured to the meninges, nerve roots, and spinal cord in such a way that all metal reference points coincided with the interpedicular wire when the spinal column was erect."[18] Louis[18] then placed the spines of the cadavers into varying degrees of spinal flexion and measured the displacements between the pedicle markers and neural markers.

Louis[18] should be commended for an ingenious attempt at manually measuring the displacements of the canal contents. However, there may be errors associated with this methodology. The pedicle wires were located at the posterior aspect of the bony canal, that is, further from the instantaneous axis of rotation (IAR), and would be expected to show a greater magnitude of change. The spinal cord does not have to adapt to this discrepancy by sliding because it does not undergo the same magnitude of change because it is closer to the IAR.

It has been claimed that the unfolding and elastic deformation of the dural coverings and cord create the illusion of these structures sliding up and down,[21] but the measuring equipment used by Breig and Troup[21] in 1979 and in earlier studies was not as sophisticated as the motion-tracking magnetic resonance imaging (MRI) used in some studies done in the 1990s. Breig and Troup stated, "The situation then obtained was similar to that in which a uniform rubber band, with one end fixed, is stretched; then, although equal sections are elongated by the same amount, points near the fixed point move smaller distances from it than more remote points."[21] Thus because of the stretching, Breig and Troup[21] believed that although it appeared as though the cord was shifting or sliding up and down in the canal, it was not. Others have shown that the displacement of the neural tissue is due to unfolding and stretch of the tissue and "not the to-and-fro movement of an isometric cord."[6,7,11,22]

To help clarify this conflict in 1998, Yuan et al[23] studied five subjects with a motion-tracking MRI technique during different increments of flexion up to 55 degrees. Although they only used flexion, cord measurements were made at various degrees of flexion, whereas previous studies only made cord measurements at full extension and full flexion. They observed that between neutral and full flexion, the entire cord (C2-C7) elongated linearly (mean, 10% posteriorly, 6% anteriorly; maximum strains, 13.6% posteriorly, 8.7% anteriorly), the upper cord showed caudal movement, and the lower cord moved cephalad. Their results were different from those of both Smith[9] and Breig[4,10,21,26-33] but agreed closely with other recent studies by Bilston[24] and Margulies et al.[25]

General Aspects of Neural Tissue Deformations

Breig et al[4,10,26-33] observed that the change in length of the bony canal was always followed by a similar change of the pons-cord tract. These were derived from autopsy specimens, cadavers, and surgical patients. The mechanism by which this change occurs is primarily by unfolding, accounting for approximately 70% of the total change, and, simultaneously, an elastic and plastic deformation accounting for the other 30% (plastic deformation occurs when neural damage resulting from large forces has occurred or when the change in length of the canal remains, and the cord is not allowed to regain its initial shape).

In the cadaver, extension of the spinal column from the neutral position causes the dural coverings, and, hence, the spinal cord tissue to slacken and fold upon itself. These folds are analogous to that of an accordion when compressed. The cross-sectional area of the cord and dura will increase. Breig[4] has collectively designated this phenomenon of folding and axial compression of the cord as a "telescoping" of the tissue. The folds, however, may not be as accentuated in the living subject as in the cadaver because of the internal pressure of the cerebrospinal fluid, but the cord will still be relaxed.

Histologic examination of the neural fibers reveals that they are folded upon one another in irregular spiral patterns. The folding is most marked in the region of the posterior columns because of the distance from the IAR. In the relaxed state, extension, the fibers of the spinal cord show three unique patterns: folds, spirals, and rhomboid networks. The latter of these three occurs primarily in the meningeal coverings and the dentate ligaments, but they are also present in the spinal cord tissue. These rhomboid networks are organized in such a way as to expand, get wider or bulge outward with extension, and to lengthen and become narrow as a result of spinal flexion.

The pattern of deformation allowed by the rhomboid networks leads to significant elongation with minimal amounts of force, which will, in turn, minimize the stress generated in the spinal cord. On flexion of the spinal column, the folds, spirals, and rhomboid networks are drawn out, and once the neutral position is reached (slight lordosis), the cord comes under resting tension; an elastic stretch is generated in the dura and cord. Only on full ventroflexion is the cord fully drawn out and maximally stretched.[4,6,8,18,27]

The stresses acting on the spinal cord with flexion are transmitted to the nerve roots.[4,18,34,35] This fact can be observed where, in extension, the nerve roots form a larger angle with the long axis of the spinal cord than they do in flexion. Actually, the nerve roots can be drawn up and make contact with the superior medial margin of the intervertebral foramina and become stretched and compressed against this bony structure. Breig[4] claimed this nerve root stretch to be fairly uniform, whereas Louis[18] believed that it depended on the spinal nerve root level and the sequence of movements of the global (head, thorax, and pelvis) body masses. Fig 3 illustrates unfolding of the cord and spinal cord and nerve root tension in flexion.

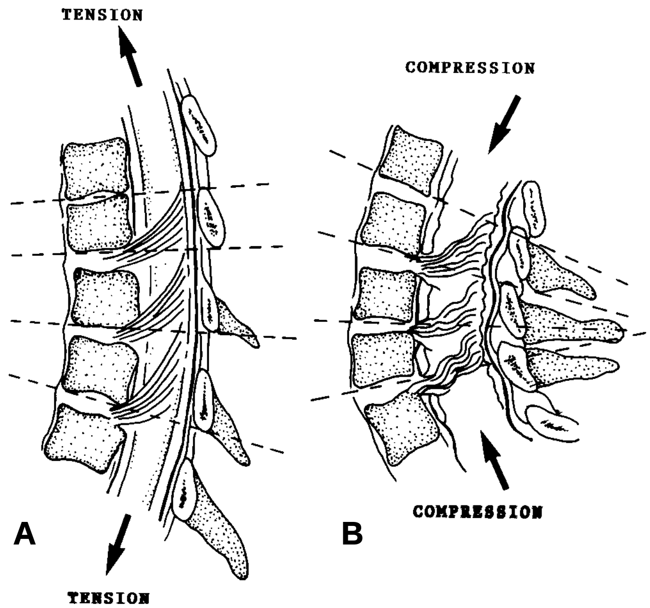

Fig 3. *Unfolding and tension in the CNS caused by flexion. In* ***A,*** *the spinal cord and nerve roots are relaxed and folds are evident in the neutral extended position. In flexion,* ***B,*** *the spinal cord unfolds and then becomes tractioned, as do the nerve roots.*

Flexion and Extension of the Cervical Spine

Flexion and extension of the cervical spine generates tension in the brain stem, medulla, and cranial nerves V-XII. The cervical cord deforms 1.8 to 2.8 cm, whereas the brain stem will change in length from 0.8 to 1.4 cm. In dorsal extension of the cervical spine, the brain stem will shorten, and its cross-sectional area increases significantly. This is best visualized in the medulla oblongata, whose circumference was shown to increase by up to 4 mm in extension. Significantly, during flexion of the cervical spine, the brain stem may actually make contact with the anterior wall of the foramen magnum, the clivus, and the anterior subarachnoid space will either be diminished or completely obliterated.[4,14,22]

Doursounian et al[22] used sagittal plane MRI to study the deformations of the spinal medullary junction in 18 volunteers between the ages of 21 to 40. Although there were errors in the methodology that prevented detailed measurement, there are a couple of important findings. On flexion the brain stem came into contact with the anterior bony canal. They state, "It appeared with great regularity, even in subjects with little mobilization of their cranio-vertebral junction, that the neuraxis was applied to the skeleton anteriorly during flexion."[22] In four cases there was an associated downward traction displacement of the brain stem. This biomechanical deformation of the brain stem and upper spinal cord may be more important than the overall canal size at this level.[36]

As mentioned earlier, tension in the spinal cord is transmitted to the cranial nerves. Specifically, cranial nerves V-XII (cranial nerves I-IV are above the midbrain level and are not directly affected by mechanical tension) will be stretched tight between the brain stem and their bony foramina in the skull. This mechanical/physiological load is borne mostly by cranial nerve V.[4,14]

Postures of the cervical spine will have direct effects on the thoracic cord, lumbar cord and lumbosacral nerve roots. With flexion of the cervical spine, longitudinal stress and strain are generated in the whole pons-cord tract.* Lew et

*References 4,8,13,27,28,30,37,38.

al[37] studied the postures of neck and hip flexion in the baboon for their effects on the lumbar spinal cord. In this study cervical flexion moved the lumbar spinal cord, specifically the conus medullaris, in a superior direction, at least to the level of the third lumbar vertebrae. Tencer et al[8] used neck flexion in cadavers to measure the dural strain from the neutral position. Strains were largest for the cervical spine, reaching 20% at mid levels; however, strains were found at all levels down to the lumbar spine.

Breig and Marions[30] demonstrated the effect of cervical flexion and extension positions on the shape and resting tension in the lumbo-sacral cord and nerve roots in nine cadavers. During cervical flexion a cranial displacement of 1 to 2 mm occurred, and a small but definite reduction in the cross-sectional area of the lumbar dura and the sacral cone was demonstrated. Extension of the cervical spine was found to shorten or axially compress the cervical cord; this resulted in an increased mobility of the entire pons-cord tract.

For example, a loop of fine thread was slipped around all the nerve roots at the level of L4 and was then tied to a spring balance. The bundle of nerves was raised in a posterior direction by a force of 20 g. Their displacement was measured with the cervical spine first in slight extension (a normal lordosis) and then with the cervical spine in marked extension. In the neutral lordotic posture, the nerve root bundle was raised to a lesser extent than they were with the cervical spine in marked extension, indicating that tension in the lumbosacral roots is directly related to the degree of cervical extension. After ventroflexion of the cervical spine, a marked increase in the resting tension of the cauda equina and lumbosacral roots was found.[30] Similar results have been shown by others.[8] This biomechanical information would indicate that patients with lumbar disc herniation may benefit from having a deep, uniform cervical lordosis to relieve the stress and strain on the lumbosacral nerve roots.

To reiterate, the posture of the cervical spine directly influences the stress of the entire pons-cord tract.[4,27,28,37,38] This is shown by the fact that the entire tract adopts a slackened and wavy form on cervical extension (assuming that the rest of the spine is kept neutral). Remarkably, slight but observable movements cranially and caudally of the pons-cord tract are known to occur with respiration. This may be a mechanism for metabolic exchange to and from the neural tissue. These neural movements diminish as the cervical spine is straightened and will then totally cease in ventroflexion.[4,10,39]

The changes of the cervical canal and cord dimensions are greater than that for all the other components, the thoracic and lumbar sections, combined. Cervical extension will reduce the tension in the pons-cord tract in any position of the body. In different positions of the body with cervical extension, the pons-cord tract will come into contact with the canal surface, whichever is inferior and perpendicular to the force of gravity. For example, with the cadaver in the supine position, Breig[4] demonstrated that the cord would actually rest against the posterior elements of the canal in extension of the neck. Placing the cervical spine in flexion, however, raised the cord toward the anterior surface of the canal; this displacement is in opposition to the force of gravity. Similarly, with the cadaver in the lateral position, the pons-cord tract was seen to move to a more central location in the canal with flexion of the cervical spine. These simple demonstrations prove that the spinal cord's resting tension is increased by canal lengthening and that it is the increased tension that forces the cord to oppose gravity.

This obviously has important beneficial implications for patients undergoing surgery on any part of the canal or components of the canal. With the cervical spine in slight extension, the spinal cord and brain stem can actually be displaced to either side or pulled in a posterior direction without adversely affecting the axons or the vascular components. This biomechanical fact would seemingly reduce the neurologic deficits that do occur in surgical procedures.[4,27,28,40] Individuals with bone or soft tissue structures encroaching on the canal would obviously benefit from this fact as well (slight extension or lordosis of the cervical spine); this is discussed in detail later.

Flexion and Extension of the Thoracic Spine

The thoracic region of the spine has a relatively small sagittal plane mobility because of the stiffening effects of the rib cage, and this accounts for the smaller amount of cord deformation in this region of the spine of 0.9 to 1.3 cm. In increased kyphosis of the thorax, however, the length of the spinal canal is increased, and the dural covering and spinal cord tend to be overstretched.[4,13]

The position and biomechanics of the thoracic cord are largely dependent on the movements and postures of the cervical and lumbar spines. For instance, Ishida et al[38] used computed tomography scans to determine what effects cervical flexion had on the thoracic spinal cord. The mid to upper thoracic spinal cord was found to shift toward and make contact with the anterior portion of the spinal canal even though the thoracic region of the spine was in its normal sagittal plane kyphotic configuration. Similar results have been shown by others.[8,13] To the same extent, an increased thoracic kyphosis will force the thoracic spinal cord up against the anterior canal even if there are normal cervical and lumbar sagittal plane curves.[13]

Louis[18] demonstrated that during full spinal flexion, the thoracic nerve roots moved away from the apex of the kyphosis, T6. Thus, above T6 the roots became more vertically orientated whereas nerve roots below T6 were more horizontal. This suggests that the upper levels of the thoracic cord and roots may be under significant stress during full spinal flexion.

Flexion and Extension of the Lumbar Spine

The lumbar spine is normally very flexible; here the cord deformation is between 1.0 to 2.8 cm.[4,18] The dura, cord, and lumbosacral nerve roots will be tensioned with flexion, whereas in extension these structures will be relaxed and slightly folded.[4,13,18,34] In extension of the lumbar spine, Louis[18] describes the nerve roots of the lumbosacral region as "undulatory and loose in the subarachnoid space." This is true in spite of the fact that the intervertebral foramen is narrowed in extension. The observations from Louis[18] indicate that with full spinal flexion, the L3 nerve root remains relatively static whereas the roots above become more horizontal and the roots below become progressively vertical. The nerve roots of L3 and above are relatively neutral in their exiting foramina, whereas the roots of L4 and lower will make contact with and be pressed against the medial surface of the pedicle forming the roof of the IVF. This has important implications to individuals presenting with space occupying lesions around the nerve roots. This will be discussed in detail later.

The magnitude and stress patterns in the lumbar nerve roots will change depending on the configuration of the lumbar spine in the sagittal plane.[13,34] A tensile or traction force applied in the y-direction to the lumbar dura or filum terminale will be transmitted to the cervical dura and cord but not to the same extent that traction to the cervical cord is transmitted to the lumbar area. This phenomenon is intuitively obvious because the spinal cord itself is not directly anchored to the sacrum or the lumbar canal; it is indirectly attached via the filum. In contrast, the cranial portion of the spinal cord is continuous with the midbrain, which is firmly anchored (demonstrated by its lack of displacement or stretch on spinal flexion).

As stated previously, postures of the cervical spine have direct consequences on the state of tension (stress) in the lumbosacral cord and nerve roots. This indicates that the magnitude of cervical lordosis may be related to stresses and symptoms at the lumbar levels. This is especially true if the lumbar spine is altered in shape.[13]

Axial Rotation of the Spinal Column

Breig[4] is the only investigator to document the effects that axial rotation of the spinal column has on the CNS (Fig 3, *B*). Rotation of the upper cervical spine creates a constriction of the canal size at this level proportional to the amount of movement. Because the cord and canal are intimately connected in a circumferential arrangement at this level, the upper cervical cord is strained by axial rotation. Additionally, there is coupled lateral bending associated with the main motion of axial rotation, indicating that the cord will experience strain from this motion as well. In the cadaver subjected to axial rotation of the cervical spine, a deep oblique fissure caused by folding of the dura was found on the ipsilateral side of the upper cervical cord. Again, this folding may not be present in the living because of the hydrostatic pressure of the cerebrospinal fluid exerted against the dura.[4]

The meninges have a constricting effect on the spinal cord similar in function to the "Chinese finger toy." If one places a finger in either end of the finger toy and tries to twist or pull the fingers out, then the meshwork of fibers of the toy is tensed and a force is transmitted that firmly grasps the fingers. Alternately, if the fingers are pushed together, compressing the long axis of the toy, then the fibers become relaxed and the fingers can be removed. Rotation of the skull around the y-axis causes the pons to be displaced in the ipsilateral direction on the same side as head rotation. Consequently, the contralateral side of the pons and cervical cord is stretched. The tensile stress is transmitted to cranial nerves V-XII, especially cranial nerve V.[4,14]

Similarly, the cervical nerve roots are stretched on the contralateral side and are relaxed on the ipsilateral side; however, the stress resulting from axial rotation is not as great at the lower levels because most of the rotation is due to the upper cervical spine.[41,42] Movement of the head or thorax, rotation or translation, on any axis generates complex coupling patterns that accompany the main postural motion. Actually, there are usually 5 coupled motions for every one main motion so that all 6 degrees of freedom occur simultaneously. This is relevant to the discussion of stresses in the pons-cord system because evidence indicates that the strain of the neural tissue at a given level is proportional to the magnitude of displacement of the vertebrae at the same level.[9,11,38] For example, axial rotation of the cervical spine causes coupled extension to occur at the first three cervical vertebrae whereas coupled flexion occurs below C4. In addition, coupled lateral bending is present that also differs in direction at the upper versus lower cervical vertebrae, the magnitude reaching 11 degrees between C1/C2.[42] The above analysis of vertebral motion resulting from axial rotation indicates that the upper cervical cord will be strained because of axial rotation and lateral bending, whereas the lower cervical cord will experience strain resulting from coupled flexion and possibly lateral bending.

The mobility of the thoracic spine is greatest during axial rotation.[6] From Breig,[4] it is apparent that during axial rotation of the thoracic spine, the dentate ligaments become taut, and there is some deformation and decrease in circumference of the cord. Again the nerve roots on the ipsilateral side of rotation will be relaxed, and the contralateral nerve roots will be under tension. The same phenomenon occurs in the lumbar spine and is also dependent on the coupling patterns at the different vertebral levels.[43]

Lateral Bending of the Spinal Column

Although no normative data concerning canal deformations during lateral bending were presented, many authors claim that deformations of the spinal cord do indeed occur.[4,6,14,18,27] Breig[4,27] and Louis[18] are the only authors who have studied this spinal motion in conjunction with neural tissue deformations (Fig 3, *C*). Breig's analysis was quantitative and qualitative whereas only qualitative results were discussed by Louis. Breig[27] showed that, in lateral bending of the cervical spine, the convex or contralateral side will lengthen by 6 mm, whereas the concave or ipsilateral aspect of the pons-cord tract will shorten by a similar amount. Louis[18] offered one photograph of a cadaveric cervical spine and neural tissue in the position of right lateral flexion. Accordingly, he states, "The left roots elongate while the right become loose and thick."[18]

With the cadaver lying on its side, Breig[4] demonstrated that lateral bending of the cervical spine toward the side that was down (cadaver on its right side, cervical spine laterally bent to the right) forces the cord to be raised to the middle of the canal. Conversely, if the head was laterally bent opposite the side lying down, the cord was seen to drop onto the lower side of the canal toward the side that was down. These findings can be attributed to the tensile stress generated in the contralateral side of the cord; the relaxation of the ipsilateral side of the cord creates extra tissue that allows for a displacement of the cord in any direction of force. Thus the neural tissue does not take the shortest route through the vertebral canal; rather the route is dictated by internal and external stresses.

A similar phenomenon occurs in the lumbosacral tract during lateral flexion of the thorax relative to the pelvis. The elongation of the canal on the opposite side of the lateral bend in the thorax will stretch the cord, root sheaths, and nerve roots, including the sacral plexus and sciatic nerve. Breig states, "as long as the thoracolumbar column is kept in this position (a positive rotation around the z-axis of the thorax) the sacral plexus of the left side is stretched and resists attempts to displace it with instruments inserted between the bone and the plexus, which has moved laterally towards the great sacrosciatic foramen."[4]

On lateral flexion of the whole spine in the same direction, the head to the thorax and the thorax to the pelvis, the pons-cord tract will shift a few millimeters cranially in the thoracic canal in relation to the vertebrae.[4] Additionally, a laterally flexed position of any region of the spinal column, such as sectional scoliosis, will increase the risk of neurologic deficits from space occupying lesions (eg, a disc herniation).[44]

Effects of Extremity Positions and Movements on Neural Tissue

Lower extremity flexion/extension. There is a large body of literature concerning the effects of leg movement on the lumbar and sacral nerve roots, as well as the distal effects on the peripheral nerves. Less common are studies demonstrating the consequences of upper extremity positions on the brachial plexus and cervical spinal cord. It is not the intent here to examine all possible aspects but to present a brief overview. The interested reader is encouraged to review the works of Butler.[19,45]

Leg movements are able to generate stress in the lumbosacral nerve roots and thus the lumbar dura and cord via the sciatic nerves.[4,9,21,37] Smith's[9] observations were on the rhesus monkey. Flexion of the hip joint, extension of the knee, and dorsiflexion of the ankle were found to stretch the sciatic and tibial nerves and thus generate tension in the lumbosacral trunk. The lumbosacral trunk was displaced downward a distance of 4.0 mm, of which one half of the displacement was due to the peripheral nerves and their roots and the other half was due to the stretch of the spinal cord. Smith[9] stated, "as a result of this traction, each of the segments of the cord between the lumbar region and the brain is stretched equally." Although his measurements may not have been completely accurate, his observations document that movements of the lower extremities can generate tensile stress in the pons-cord tract as far up as the brain stem, medulla, and midbrain. Smith[9] also extended this experiment to a full-term unembalmed human fetus. The findings were strikingly similar.

Extension of the knee in adult human beings causes an increase in hamstring tension, with the result being lumbar flexion.[4,21] Raising of the leg upward, with cadaver/person in the supine position, causes the nerve roots to be stretched further into the intervertebral foramen. At the S1 root, where the range of movement is greatest, it may approach 1 cm, decreasing cranially to 0 cm at the L3 nerve root. The traction was shown to occur within the first 15 degrees of leg movement, and as tension is increased, a transverse pull from the ipsilateral nerve root is transmitted to the contralateral root. The transverse force caused the contralateral nerve root to be displaced medially into the central canal.

Axial rotation of the leg and hip joint. Breig and Troup[21] were the first, and to our knowledge, the only investigators to demonstrate the effect that medial hip rotation has on the sacral plexus and lumbar cord. Here observations were made on 6 cadavers with the sacral plexus exposed. In all specimens there was a palpable increase in the resting tension of the sacral plexus when the hip was rotated internally. A 4 cm marker was laid obliquely across the sacral plexus with the proximal end tucked into the greater sciatic foramen. The marker was then stitched to the perineurium of S2 and S3 nerve roots. After medial hip rotation, the marker (on the ipsilateral side) was found to be displaced up to 1 cm into the foramen, indicating that the sacral plexus and lumbar cord are tractioned with internal rotation of the hip. It should be noted that several different conditions will result in the above occurrence. The first would be an internal y-axis rotation of one hip with the other fixed. This may also occur bilaterally in children or adults who are "pigeon-toed" or in children with cerebral palsy.[46] One other posture may result in stretch of the sacral plexus; however, this is not commonly discussed.

In the upright static stance, with the feet in the neutral position and fixed if the pelvis is considered as a rigid body or block, then this body can be rotated or translated along three mutually perpendicular axes x, y, and z. When the rigid pelvis is rotated around the y-axis, keep in mind that the feet are still fixed and held in this position; one of the legs/hip joints would be in an internally rotated position whereas the other would be externally rotated. If a positive rotation about the y-axis is imparted, then the left hip joint would be internally rotated and the right would be in external rotation. The converse is true of a negative rotation around the y-axis. Thus a posture of y-axis rotation of the pelvis to the feet will impart an ipsilateral tensile stress to the sacral plexus and lumbar cord, creating a displacement of up to 1 cm.

Upper extremity movements. Reports of traction injuries to the brachial plexus resulting from shoulder impacts, falling on an outstretched arm, or direct traction (yanking, pulling) applied to the arm are common.[45] Less common are studies demonstrating the effect of arm position on peripheral and central nervous tissues.[47] Farmer and Wisneski[47] used eight cadavers to examine the effect of arm abduction on neuroforaminal pressure changes during cervical flexion and extension. The pressure changes were monitored at the C5-C7 levels with a balloon catheter that, in addition to monitoring pressure changes, also simulated foraminal canal stenosis. Neck extension of 20 and 40 degrees increased the neuroforaminal pressures at all levels, whereas neck flexion only increased the pressure at the C5 and C7 nerve root levels. The greatest increase in pressure was seen with neck extension and with the larger angle change (40 degrees). Interestingly, arm abduction always relieved the increased nerve root pressure in the extended neck position, more than likely a result of slackening the nerve root and epidural ligaments. Although this study demonstrates the association between foraminal degenerative changes and nerve root compression in the hyperextended neck position, some clinicians have misunderstood this to indicate that extension of the neck in all subjects is potentially harmful.[48] Clearly, this is not the case and is only applicable to individuals with foraminal canal stenosis from a posterolateral disc, osteophyte, or other space-occupying lesion.

CONCLUSION

A conclusion from this review is that extension of the spine, especially the cervical and lumbar areas, results in relaxed (decreased strain) CNS structures. Postural flexion of any part of the spinal column may generate axial tension and therefore longitudinal strain in the entire cord and nerve roots. Similarly, a flexed vertebral (segmental level) will strain the spinal cord and nerve roots at that level and perhaps adjacent levels. Lateral flexion of the spinal column creates an ipsilateral relaxation of the pons-cord tract and a tensile stress and strain in the contralateral side. Axial rotation of the spine does not result in canal lengthening, but the contralateral side of the nerve roots and cranial nerves are tensed. The cross-sectional area of the cord and canal may be reduced locally in areas of segmental flexions.[22,38] Internal hip rotation and axial rotation of the pelvis relative to a fixed feet stance will cause longitudinal strain in the ipsilateral sacral plexus and lumbar spinal cord. Extension of the pelvis as a unit will traction down the conus medullaris.

It is important to note that x-axis and z-axis translations of the skull, thoracic cage, and pelvis have not been studied for their effects on the pons-cord tract. This indicates an area for future study. Additionally, combinations of postures (eg, lateral flexion combined with axial rotation or flexion) have not been studied for their effects on cord stresses and strains. However, it should be intuitively obvious to the reader that individuals who adopt a combination of two or more of the above-mentioned postures or who have them present in their upright static stance will have larger stresses and strains applied to their spinal cords and nerve roots. These neural deformations may also be larger than expected for the combined effect of the different postures because of the shift of the IAR outside of the vertebra during combined loading.[49] For instance, the combination of a cervical kyphosis, right head tilt, and right head rotation would result in increases in cord stress and strain on the contralateral side. In the lumbar spine, the postures of left rotation of the pelvis on the y-axis, right lateral flexion of the thorax, and right axial rotation of the thorax will stretch the left side of the cord more than just one or two of these postures.

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