Joints of the Cervical Vertebral Column

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The developing understanding of the morphology of the cervical spine has revealed the complexity of the system. A review of selected literature reported that a number of the joints have an unusual nature and exhibit complicated and even paradoxical motions. For the practicing therapist, the significance of these observations is that assessment and treatment procedures of the cervical spine must be very carefully analyzed. There are significant differing behaviors of some of the cervical joints in response to small changes in movement patterns or initial positioning. Therefore it is not possible to broadly classify results of assessment procedures as normal or pathological without a clear and detailed understanding of the underlying morphology. J Orthop Sports Phys Ther 2001;31:174–182.

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In many circles of clinical practice it is conventional to treat the cervical spine as a single organ (ie, as if it is a single joint between the head and thorax). Indeed, the AMA Guides for the Assessment of Impairment stipulate that range of motion of the head be used for the determination of impairment of the neck. 2 This approach belies the subtleties and complexities of cervical spine structure and function. The cervical spine consists of 7 segments, each bearing at least 3 joints. The segments are not isomorphic, and they contribute to total spinal function neither equally nor regularly.

For example, the total range of motion of the neck is not the arithmetic sum of segmental ranges of motion. 3 Indeed, total range of motion can be as much as 10 or 30 degrees less than the sum of the maximum segmental ranges of motion. 3 In people with nonimpaired necks, the apparent range of motion on one day may be considerably different from that on another day. Measuring range of motion from flexion to extension may yield a different value than when measured from extension to flexion. 3 In patients with neck pain, dysfunctional segments can occur at levels other than those responsible for the pain. 3 These idiosyncrasies indicate that clinicians should appreciate and assess the cervical spine not as a single or homogeneous unit, but as a series of separate, yet linked individual segments that may contribute to symptoms and signs in a variety of complex ways.

Fundamental to understanding the behavior of the cervical spine is an appreciation of how each segment of the neck contributes to the total function of the cervical spine and how each segment is designed anatomically to subserve these functions. This commentary outlines an introduction to biomechanics of the cervical spine from an anatomical perspective. Our commentary includes observations that explain why the cervical spine operates the way it does; these observations have not been formally tested and cannot be supported by citations of the literature. They are offered, nonetheless, in an effort to explain cervical biomechanics with a sensible anatomical basis, and to serve as conjectures worthy of future investigation.

Atlanto-occipital Joint

The first cervical vertebra, the atlas, arguably does not belong to the cervical spine. It has more in common with the occiput than with the rest of the neck. It is designed to cradle the occiput and to transmit forces from the head to the cervical spine. Quintessential features are its 2 lateral masses; each is a stout pillar of bone whose long axis is aligned vertically below the corresponding occipital condyle. The lateral masses are united by anterior and posterior arches of bone that function as outriggers to maintain the relative positions of the lateral masses and allow them to act in parallel and give the atlas its characteristic ring shape.

The superior surface of each lateral mass bears a concave socket...
that receives the ipsilateral occipital condyle. The deep walls of this socket preclude translation of the condyle laterally, anteriorly, or posteriorly, but the concave shape permits nodding movements of the head.

Nodding is achieved by a combination of rolling and contrary sliding, as occurs in any condylar joint (Figure 1). As the head nods forward, the occipital condyles roll forward in the sockets of the atlas, but as they do so they tend to roll up the concave anterior wall of each socket. Concomitant compression loads, exerted by the mass of the head, the flexor muscles, or by tension in capsules of the atlanto-occipital joints, cause the condyles to slide downward and backward along the anterior wall. As a result, anterior rotation is coupled with downward and posterior sliding, and the condyles effectively remain nestled on the floor of the atlantal sockets. This combination of movements results in an axis of movement passing transversely through the bodies of the occipital condyles, around which the head essentially spins tangentially to the curvature of the atlantal sockets.

A converse combination of movements occurs when the head is extended on the atlas (Figure 1). The absolute limit to flexion and extension of the atlanto-occipital joints would be impaction of the occiput against the rim of the atlantal sockets, but under physiological conditions, other factors limit the motion before such impaction occurs. Flexion is limited by tension of the posterior neck muscles and by impaction of the submandibular tissues against the throat. Extension is limited by compression of the suboccipital muscles against the occiput.

The total normal range of flexion and extension at the atlanto-occipital joint has been described as having a mean value between 14 and 35 degrees,7,15,19,20,21,23 a range from 0 to 25 degrees,7 or a mean value of 14 degrees with a standard deviation of 15 degrees.21 With such large variations in what constitutes the normal range of motion for this joint, clinicians need to take care with what they consider normal and abnormal when assessing the movement of occiput on the atlas.

Axial rotation about a vertical axis is not a true physiological movement of the atlanto-occipital joint. Axial rotation requires anterior translation of the contralateral occipital condyle and posterior translation of the ipsilateral condyle. These movements are essentially prevented by the respective anterior and posterior walls of the atlantal sockets. Nevertheless, axial rotation can be induced. The atlantal sockets are cup-shaped and wider at their mouth than at their depths. Consequently, if sufficient axial torque is applied to the head, the occipital condyles will be forced up the walls of the sockets, and axial rotation is achieved at the cost of vertical displacement of the occiput. Ultimately this movement will be limited by tension developed in the capsules of the atlanto-occipital joints and in the alar ligaments. The range of movement possible is therefore limited. Axial rotation has been documented only in cadavers, in which observed range of motion is only seven degrees.28 Other studies stipulate a value of 0 degrees.30,33 In the light of such small values, clinicians should take care if seeking to comment on restrictions of axial rotation of the atlanto-occipital joints.

Lateral flexion of the atlanto-occipital junction is limited by a similar mechanism. For lateral flexion to occur, either the contralateral occipital condyle must rise out of its socket while pivoting on the ipsilateral condyle, or both condyles must slide in parallel up the contralateral walls of their respective sockets in order to tilt the atlas. Such movements are not physiological, but may be induced. In cadavers the total range of motion has been measured as 3.9 ± 1.6 degrees28 and 11.0 degrees.28 When induced, lateral flexion may be coupled with flexion, extension, or axial rotation. The pattern of coupling depends on the exact shape of the atlantal sockets, and any combination of coupling is possible in the face of variations in the geometry of the sockets.35 These variations preclude defining any single rule as to the patterns of coupled motion of this joint. Lateral flexion under physiological conditions has not been systematically demonstrated and studied.

Atlanto-axial Joints

1. The foremost role of the second cervical vertebra, the axis, is to bear the axial load of the head and atlas and to transmit that load into the remainder of the cervical spine. For this function, the axis presents broad, laterally placed superior articular facets that support the lateral masses of the atlas and form the lateral atlanto-axial joints. From these facets, the load of the atlas and the head are transmitted both inferiorly and anteriorly to the C2–3 intervertebral disc and inferiorly and posteriorly to the C2–3 zygapophysial joints.

2. Otherwise, the axis is designed to allow the axial rotation of the head and atlas. The axis presents a centrally-placed odontoid process that acts as the piv-
of which the anterior arch of the atlas spins and glides around in order to achieve axial rotation. Anteriorly, this movement is accommodated by a synovial joint between the odontoid process and the anterior arch of the atlas, known as the median atlantoaxial joint, at which the anterior arch can pivot or slide across the surface of the odontoid process. Inferiorly, the movement is accommodated by the lateral atlantoaxial joints.

Radiographs and skeletal material belie the structure of the lateral atlantoaxial joints. Although the osseous articular facets of this joint are flat, they are covered by articular cartilages that are convex in the sagittal plane. Each joint is, therefore, biconvex in structure. At rest, the apex of the cartilage of the inferior facet of the atlas balances on the apex of the superior articular cartilage of the axis. Anteriorly and posteriorly, where the surfaces of the articular cartilage diverge, the spaces between the cartilages are filled with large intra-articular meniscoids. Not simply space-fillers, these meniscoids serve to keep a film of synovial fluid applied to those surfaces of the articular cartilages that are not in contact with one another.

Axial rotation of the atlas requires anterior displacement of one lateral mass and a reciprocal posterior displacement of the opposite lateral mass. As this occurs, the inferior articular cartilages of the atlas must slide down the respective slopes of the convex superior articular cartilages of the axis. As a result, the atlas screws down onto the axis as it rotates (Figure 2A–C). As the atlas moves, its articular facets assume the space previously occupied by the intra-articular meniscoids. Meanwhile the meniscoids are withdrawn from the space as the lateral mass draws the capsule of the joint anteriorly or posteriorly on each side. Upon reversal of the movement, the meniscoids return passively to resume the space. If the articular cartilages are asymmetrical, a small amplitude of sidebending may accompany axial rotation of the atlas, and the coupling may be ipsilateral or contralateral depending on the bias of the asymmetry. The alar ligaments are the principal structures that restrain axial rotation, with the lateral atlantoaxial joint capsules playing a minor role. The normal range of movement is 43 ± 5.5 degrees in each direction. At the limits of rotation, the lateral atlantoaxial joints are almost subluxated. Axial rotation at the atlantoaxial level is extremely important functionally for movement at this level accounts for 50% of the total range of rotation of the neck. Indeed, the first 45 degrees of rotation of the head to either side occurs at the C1–C2 level before any lower cervical segments move in this plane.

The odontoid process is curved slightly posteriorly. This shape allows the anterior arch of the atlas to slide upwards and slightly backwards, thereby allowing the atlas to extend. Flexion occurs by reciprocal motion but also involves anterior translation of the atlas during which the anterior arch separates from the odontoid process. The total range of flexion-extension is about 10 degrees.

Although not a physiological movement, lateral translation at the atlantoaxial joint is assessed in some schools of manual therapy. Because the superior articular facets of the axis slope inferiorly and laterally, lateral translation of the atlas must be accompanied by ipsilateral sidebending (Figure 3). Reciprocally, lateral translation occurs passively during sidebending of the cervical spine. This movement is primarily resisted by the contralateral alar ligament and ultimately by bony impaction of the contralateral lateral mass onto the lateral aspect of the odontoid process.

Posterior translation of the atlas is limited by impaction of the anterior arch of the atlas against the odontoid process, which blocks this movement. In anterior translation, there is no bony block. This movement is limited by the transverse and alar ligaments. Either ligament alone is enough to ensure integrity of the atlantoaxial joint. Subluxation or dislocation implies destruction of both ligaments.

**Cranio-cervical Motion**

Although certain characteristic movements occur selectively at the atlanto-occipital and atlanto-axial joints, the head, atlas, and axis normally function as a composite unit. During axial rotation of the head, the head and atlas move in concert on the axis at the atlantoaxial joints, when there is no relative motion between the head and the atlas. It is the head that primarily moves, and the atlas is passively drawn with it. For that reason it should not be surprising that the alar ligaments essentially bypass the atlas and bind the axis to the occiput. It is the movement of the head that they resist, not the movement of the atlas.

During sagittal rotation, the head moves on the axis with the atlas functioning as an interposed washer with essentially passive movements. Certain muscles, such as rectus capitis posterior minor, obliquus superior, and the rectus capitis anterior and lateralis, arise from the atlas and act on the skull; few muscles act on the atlas itself in order to move it. Although the atlas does provide an origin for 1 of the 4 fascicles of levator scapulae this fascicle is directed downwards and so is not responsible for physiological movement of the atlas. The obliquus inferior aids in axial rotation, but the terminal fibres of longus cervicis is the only other muscle that inserts the atlas. Acting on the anterior tubercle of the atlas, the longus cervicis is able to flex the atlas, but conspicuously there is no reciprocal extensor of the atlas. This lack of an extensor predicates the passive nature of the kinematics of the atlas in the sagittal plane.
Flexion of the head and neck is executed by the longus capitis and cervicis and by the sternocleidomastoid. Extension is executed by semispinalis capitis in concert with other posterior neck muscles. All of these muscles bypass the atlas, but nevertheless exert compression loads on it. This effect combined with the biconvex structure of the lateral atlanto-axial joints accounts for what is known as the paradoxical motion of the atlas during flexion-extension of the head and neck.

During flexion of the neck the atlas may flex or extend (Figure 4). During extension of the neck, the atlas may extend or flex. This paradox arises because the atlas is perched on the convexities of the superior facets of the axis and is therefore susceptible to small variations in the eccentricity of compression loads exerted on its lateral masses. If the compression load is exerted anterior to the contact point between the facets of the lateral atlanto-axial joint, the effect will be to tilt the atlas into flexion. If the compression load is exerted behind the contact point, the atlas will extend. In essence, the atlas tilts because its lateral masses are squeezed between the occiput and the axis; it tilts backwards if the compression force runs posterior to the center of the lateral mass and forwards if the compression load is anterior to the center of the lateral mass. This occurs irrespective of how the other cervical vertebrae move.

Protruding the chin as the neck flexes favors an anterior displacement of the compression load on the atlas, and the atlas will flex in concert with the other cervical vertebrae. On the other hand, tucking the chin backwards favors a posterior displacement of the compression load, and the atlas will extend when the other cervical vertebrae flex. The movement, however, is no longer paradoxical if it is understood that it is a reflection of the line of transmission of compression loads across the atlas (Figure 4). It also highlights how the atlas moves essentially passively under the load of the head.

During sidebending of the head, an involved series of events occurs. Radiography reveals that upon bending to the left, C1 rotates to the right but C2 rotates to the left. Students are sometimes taught these combinations as clinically relevant rules of thumb, but without explanation. Inspection of the anatomy of the upper cervical vertebrae explains why these movements occur. Lateral bending exerts an axial compression force along the ipsilateral side of

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**FIGURE 2.** Atlanto-axial rotation. At rest, the apex of the cartilage of the inferior facet of the atlas balances on the apex of the superior articular cartilage of the axis (a). As the inferior articular process of the atlas is displaced anteriorly on the axis, it slides down the anterior slope of the axis (b). As the inferior articular process of the atlas is displaced posteriorly on the axis, it will slide down the posterior slope of the axis (c).
FIGURE 4. Paradoxical motion of the atlas during neck motion. Lateral view of the convex inferior facet of the atlas perched on the convex superior facet of the axis (a). Line of transmission of compression load exerted anterior to the contact point, resulting in flexion of the atlas (b). Line of transmission of compression load posterior to the contact point resulting in extension of the atlas (c).

the vertebral column (Figure 5). The ipsilateral lateral mass of the atlas is compressed and transmits the compressive force caudally to C2–3 and subsequent facet joints. Subjected to this vertical load, the ipsilateral inferior articular process of C2 is driven downwards but also backwards along the sloping superior articular process of C3. This backward displacement causes C2 to rotate towards the direction of the sidebending. If simultaneously there was no movement of the atlanto-axial joints, the head and face would also rotate to the same side. However, if the face is to be directed forward, a compensatory derotation must occur at the lateral atlanto-axial joints and the atlas must rotate to the opposite side. The overall result is that in lateral flexion of the head, C2 is squeezed into ipsilateral rotation, while the atlas undergoes contralateral rotation.

To understand this seemingly complex pattern of movement, it should be realized that the contralateral rotation of the atlas is not a direct consequence of the lateral torque applied to the head. It is artificially produced by the examiner for aesthetic reasons. Sidebending naturally induces ipsilateral rotation of the head; however, to create the illusion of bending only in the coronal plane, the examiner or the subject must subtly apply a torque to the head in order to keep the face looking forwards. It is this subtle torque that rotates the atlas to the opposite side.

Motion of the Lower Cervical Vertebrae

The cervical vertebrae C3 through C7 form a column whose functions are to support the head, keep it upright, yet allow mobility. The vertebrae accordingly exhibit features that reflect these load-bearing, stabilizing, and mobility functions.

Each vertebra consists of 3 pillars set in a triangular arrangement that when stacked form 3 parallel columns. The anterior pillars are the vertebral bodies, which are united by interposed intervertebral discs to form the anterior column. The 2 posterior columns are formed by the articular pillars of the cervical vertebrae. The superior and inferior articular processes of consecutive vertebrae are opposed to one another and united by a joint capsule to form the zygapophysial joints. In a longitudinal sense, these 3 columns subserve the load-bearing functions of the cervical spine.

The articular facet of each superior articular process faces superiorly and posteriorly at an angle about 45 degrees to the transverse plane.26 The superior orientation allows the articular process to bear the weight of the pillar above. The posterior orienta-
tion stabilizes that vertebra by impeding its anterior translation (Figure 6).

In the past, the slope of the articular facets of the typical cervical vertebrae has been implicated in determining patterns of segmental motion in the sagittal plane. It has been shown, however, that it is the height of the superior articular processes that is the major determinant. Flexion of a typical cervical spinal segment is a movement composed of anterior sagittal rotation and anterior translation to various extents. Irrespective of its slope, the taller the superior articular process, the more it impedes anterior translation for any degree of anterior sagittal rotation. The height of the superior articular process therefore, determines the extent of coupling between sagittal rotation and sagittal translation. The greater the ratio between rotation and translation, the closer the axis of flexion-extension lies to the moving vertebra. The superior articular processes are taller at lower cervical levels. Consequently the axes of flexion-extension at these levels lie closer to the intervertebral disc of the segment. At upper cervical levels, the superior articular processes are short; the segments exhibit a relatively greater amplitude of translation; and their axes of motion lie substantially below the disc of the segment (Figure 6).

Traditional teaching would maintain that 2 other forms of motion occur at typical cervical segments, viz. sidebending, and axial rotation. An examination of the structure of the typical cervical joints, however, reveals that this is not the case. The joints between the bodies of cervical vertebrae are essentially saddle joints and allow movements in only 2 planes. In the sagittal plane, the inferior surface of the vertebral body is gently concave, consistent with its freedom to rotate in that plane about a transverse axis. The posterior inferior surface of the vertebral body is rounded into a gentle convexity that is accommodated by the concavity presented by the uncinate processes of the vertebra below. This concavity, however, is oriented at approximately 45 degrees above the transverse plane (ie, in a plane parallel to the plane of the zygapophyssal joints) (Figure 7).

When viewed in this plane, the joint between the vertebral bodies presents the appearance of an ellipsoid joint. That joint allows rotation of the upper vertebra of a segment but around an axis perpendicular to the plane of the zygapophyssal joints. Moreover, that axis passes through the anterior inferior edge of the vertebral body (Figure 7). Consequently, when rotating, the vertebra pivots about this anterior edge while its tail swings left or right in an arcuate fashion in the concavity of the uncinate processes. Meanwhile, as the vertebral body swings, its inferior articular processes glide freely across the planar surface of the superior articular processes below (Figure 7). Rotations perpendicular to this plane are not possible. Any attempt at rotation sideways results in immediate impaction of the ipsilateral inferior facet against its opposing superior articular facet.

These patterns of movements are also reflected in the structure of the cervical intervertebral discs. The cervical discs are not like archetypical lumbar discs. Anteriorly the anulus fibrosus is thick and strong, where it binds the anterior edge of the upper vertebra of the segment. Moreover, its fibers do not assume a criss-cross pattern but converge upwards in a lambdoid fashion to anchor the anterior edge of the vertebral body near the midline, at a point coincident with the path of the axis of axial rotation. In effect, the anterior anulus constitutes a strong interosseous ligament located at the pivot point of axial rotation (Figure 8).

Laterally, around the perimeter of the intervertebral disc, the anulus progressively attenuates and dissipates, and is all but lacking opposite the anterior edge of the uncinate process on each side. Posteriorly, the anulus fibrosus is represented only by a thin bundle of longitudinal fibers restricted to the paramedian plane. Otherwise, the back of the disc is marked by a transverse fissure (Figure 8). This fissure develops as central extensions of clefts in the uncovertebral regions on each side and is a normal feature of cervical discs. It is this fissure that effectively forms the joint cavity of the ellipsoid joint between the vertebral bodies, and which allows for the swinging movement of the upper vertebral body.

This description of the morphology and movements of the typical cervical segments can be recon-
FIGURE 7. Morphology of typical cervical joints. Sketch of the transverse concavity (t) of the superior surface of the vertebral body and the sagittal concavity (s) of the inferior surface of the vertebral body above (a). Sketch of the morphology of the interbody joint as seen in the plane of the zygapophyseal joints (superior view), the convex posterior aspect of the superior vertebral body accommodated by the concavity of the uncinate processes of the vertebra below (b). Rotation in the plane of the zygapophyseal joint as the vertebral body swings and its inferior articular processes glide freely across the superior articular processes of the vertebra below (c).

ciled with traditional descriptions and interpretations. Axial rotation about a longitudinal axis and lateral rotation about a sagittal axis are not natural or pure movements of the cervical spine. For this reason, they are always coupled with one another (axial rotation is always accompanied by ipsilateral lateral rotation). What might be called pure axial rotation occurs about an obliquely set axis perpendicular to the plane of the zygapophyseal joints. But when axial rotation is forced artificially about a longitudinal axis, the moving vertebra encounters the 45 degree slope of the superior articular facets, and that slope drives the vertebra into lateral rotation. A reciprocal combination occurs when lateral rotation is artificially forced about a sagittal axis. The coupling between axial and lateral rotation is therefore a consequence of the artificial expectation that movements must occur about longitudinal and sagittal axes, which is not consistent with the morphology of the cervical joints. Their anatomy dictates that they are saddle joints with movements in only 2 planes. If clinicians reoriented their expectations to movements in the sagittal plane and movements in the plane of the zygapophysial joints, they would access the pure movements of the cervical segments, and the apparent complexity of coupled movements would disappear.

FIGURE 8. Sketch of the cervical intervertebral disc. Lateral view depicting the transverse fissuring of the fibrocartilaginous core of the intervertebral disc. The posterior anulus fibrosus has been removed (a). Top view of the nucleus pulposis where the anterior anulus fibrosus (crecentric in shape) is dissipating opposite the uncinate processes and the posterior anulus fibrosus (thin) is restricted to the paramedian plane (b).

CONCLUSIONS

Close attention to details of anatomy of the cervical spine provides explanations for many aspects of its biomechanics. Prominent in this regard is the passive behavior of the atlas, whose movements are predicated by the shape of the articular cartilages of
the lateral atlanto-axial joints and dictated more by forces applied from the head than by muscle action. Also, new observations on the structure of the cervical intervertebral discs dictate that the motion of typical cervical segments is more accurately viewed as saddle joints than as triaxial joints. Awareness of anatomical and biomechanical detail should serve to prevent misinterpretation of clinical signs and the perpetuation of false models of cervical pathology.

REFERENCES

Invited Commentary

Dr Susan Mercer's and Dr Nikolai Bogduk's treatise on joints of the cervical vertebral column has enormous clinical implications. Their description of the morphology of the cervical discs leaves little doubt that the cervical spine cannot function like the lumbar spine and, therefore, requires examination and treatment that accounts for its idiosyncrasies.

Drs Mercer and Bogduk's differentiation of the cervical spine into the craniocervical and lower cervical underscores the different morphology and therefore function between these regions. I would suggest another separation, that of cervico-thoracic, where C7-T1, T1-T2 and T2-T3 segments can be considered as a separate region with its concomitant special functions requiring special evaluations and treatments. I think of C2 as a transitional vertebra. The articulation from above is certainly part of the craniovertebral unit; however, the action of C2 confers upon C3 as the initiator of the concomitant side-bending and rotation to the same side. Therefore, C2 often requires evaluation with both the cervical and craniocervical regions.

On the segmental level, range of motion can, and does, exceed the total range of motion available in the cervical spine. This can be easily demonstrated by using an inclinometer and having a subject perform flexion and extension of the cervical spine from different postures of the thoracic spine. The observations that thoracic posture (ie, slump versus military posture) alters range of motion have led us to standardize our protocol so that we place the inclinometer just once for each plane of movement (ie, we record flexion and extension, always starting in flexion, but we only record as significant changes those which encompass both sagittal plane motions). Lateral bendings and rotations are similarly affected, so that the lateral bendings are again recorded individually but considered more significant when total coronal plane movement is changed. Rotation, because it is tested in the supine position, is not as interdependent right and left as the neutral position, which is more easily obtained and stabilized; however, it is not assumed that the supine rotation is comparable to rotation in the anti-gravity postures. Segmental mobility testing, using passive forces exerted on the skull, does not necessarily follow a predictable pattern of coupled motion and, in view of the small amount of range of motion, should probably be abandoned in favor of the direct palpation of anatomical landmarks.

Finally, some of the findings of Drs Mercer and Bogduk may be applied in the clinical examination. For example, sidebending of the head is accompanied by C2 rotation to the same side with rotation of C1 to the opposite, as long as the subject's transverse plane posture is maintained in neutral. By using deductive reasoning, this phenomena allows us to determine whether craniocervical or midcervical problems are productive of symptoms by utilizing the 3 degrees of freedom present in the cervical spine and recording the range of motion and the production or alteration of symptoms.

In summary, I'd like to thank Drs Mercer and Bogduk for their excellent contribution to the Special Issue on the Cervical Spine in the Journal.

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REFERENCE