Cervical Spine Deformity—Part 1: Biomechanics, Radiographic Parameters, and Classification

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Cervical spine deformities can have a significant negative impact on the quality of life by causing pain, myelopathy, radiculopathy, sensorimotor deficits, as well as inability to maintain horizontal gaze in severe cases. Many different surgical options exist for operative management of cervical spine deformities. However, selecting the correct approach that ensures the optimal clinical outcome can be challenging and is often controversial. We aim to provide an overview of cervical spine deformity in a 3-part series covering topics including the biomechanics, radiographic parameters, classification, treatment algorithms, surgical techniques, clinical outcome, and complication avoidance with a review of pertinent literature.

KEY WORDS: Cervical spine deformity, Cervical kyphosis, Osteotomies, Smith-Petersen osteotomy, Pedicle subtraction osteotomy, Anterior osteotomy, Total subaxial reconstruction, Cervical lordosis, SVA, T1 slope

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The fundamental functions of the cervical spine include transmitting axial load from the cranium, maintaining horizontal gaze, allowing normal head and neck movement, and protecting important neurovascular structures such as spinal cord, nerve roots, and vertebral arteries. A healthy and normally functioning cervical spine is the basis for performing many activities of daily living and is essential for maintaining a good quality of life. Cervical spine deformities, however, can significantly limit the normal function of the neck and thereby diminish the patient's quality of life.

The most common form of cervical spine deformity is cervical kyphosis. These patients most commonly present with neck pain, but may also have myelopathy, and sensorimotor deficits due to compression of the neural elements and impaired cord perfusion from an overstretched spinal cord. If the kyphotic deformity is severe (ie, chin-on-chest deformity, dropped head syndrome, etc.), patients can have significant difficulty with swallowing and maintaining horizontal gaze. Surgical treatment is often required for these symptomatic patients. The general goals of cervical spine deformity surgery include correction of deformity, restoration of the horizontal gaze, decompression of the neural elements as necessary, solid arthrodesis to maintain the surgical correction and spinal alignment, and avoidance of complications.

Various surgical strategies include anterior-only, posterior-only, anterior–posterior, or posterior–anterior–posterior. Specific surgical techniques include anterior cervical discectomy and fusion, anterior cervical corpectomy, anterior osteotomy, Smith-Petersen osteotomy, pedicle subtraction osteotomy (PSO), or any combination of these techniques. Regardless of which specific surgical approach is used, a solid understanding of spine biomechanics, a thorough preoperative neurological examination, a detailed review of preoperative images, along with careful surgical planning and meticulous surgical techniques are essential to ensure the best clinical outcome in cervical deformity correction.

We aim to provide an overview of cervical spine deformity including: Part 1—biomechanics, radiographic parameters, and classification; Part 2—treatment algorithms

ABBREVIATIONS: AS, ankylosing spondylitis; **CBVA,** chin-brow vertical angle; **CL,** cervical lordosis; **COM,** center of mass; **CT,** computed tomography; **CVJ,** craniovertebral junction; **HPT,** Harrison's posterior tangent; **IAR,** instantaneous axis of rotation; **JOA,** Japanese Orthopedic Association; **JPS,** Jackson physiological stress; **LL,** lumbar lordosis; **mCM,** modified Cobb method; **PI,** pelvic incidence; **PT,** pelvic tilt; **PSO,** pedicle subtraction osteotomy; **ROM,** range of motion; **SVA,** sagittal vertical axis; **T1S,** T1 slope; **TIA,** thoracic inlet angle

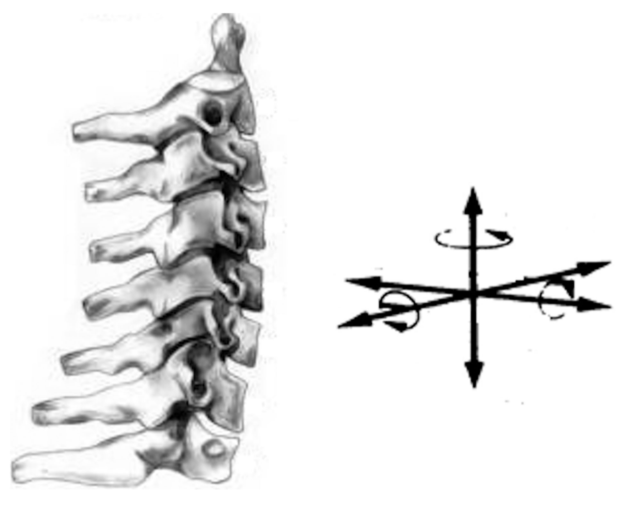

FIGURE 1. *An illustration demonstrating the 6 degrees of freedom in the cervical spine.*

and anterior techniques; and Part 3—posterior techniques, clinical outcome, and complication avoidance.

Biomechanics of the Cervical Spine

The cervical spine is a weight-bearing mechanical structure with 6 degrees of freedom of movement. The principle motions of the cervical spine include flexion/extension, axial rotation and lateral bending, along with a small amount of coupled anterior/posterior translational movements along the Cartesian coordinates (Figure 1). The cervical spine is able to move within the neutral zone with relatively little force, therefore requires very little energy expenditure from the paraspinal muscles. Additional movement beyond the neutral zone, however, requires more effort to overcome the elastic force from the soft tissues; therefore, this zone is called the elastic zone. Adding the movement realized in both the neural and elastic zones provides the total range of motion (ROM) at a given segment. An abnormal increase in neutral zone or ROM may indicate ligamentous injury or spinal instability.

The global physiological ROM in the cervical spine is approximately 90° of flexion, 70° of extension, 20° to 45° of lateral bending, and up to 90° of rotation on each side.[1] The atlanto-occipital joint is a strong synovial joint formed by the interface between the convex occipital condyle and the concave C1 superior articular facet. They form a "ball-and-socket" joint reinforced by a strong joint capsule. This configuration allows a large degree of flexion/extension, but very little movement in lateral bending or axial rotation.[2] The atlantoaxial joint includes 4 synovial joint interfaces, which exist between the anterior arch of C1 and the odontoid process, the odontoid process and the transverse ligament, as well as the paired C1-2 facet joints. In contrast to the atlanto-occipital joint, the atlantoaxial joint allows a large degree of axial rotation, with more limited flexion/extension and lateral bending. The articular cartilages on the atlantal and the axial facets are both convex, therefore forming a "biconvex" joint filled with fibro-adipose meniscoids.[3,4] In the neutral position, the apex of the 2 articular surfaces rests on each other. When rotation occurs, the C1 inferior facet glides posteriorly over the C2 superior facet on the ipsilateral side, and glides anteriorly over the C2 superior facet on the contralateral side to facilitate a smooth rotational movement. Panjabi et al[5] found that the ROMs at for flexion, extension, lateral bending, and axial rotation were 3.5°, 21.0°, 5.5°, and 7.2°, respectively, at the atlanto-occipital joint, and 11.5°, 10.9°, 6.7°, and 38.9° at the atlantoaxial joint. The greatest motion between 2 vertebral segments is the axial rotation at the atlantoaxial joint, with the neutral zone (29.6°) accounting for 75% of this motion. The subaxial cervical spine (C3-7) is responsible for the remainder of ROM in the cervical spine.

There are several basic physical parameters that dictate the biomechanical properties of the cervical spine. These include mass (m), force (F), standard gravity (g), moment arm (L), bending moments (M), and instantaneous axis of rotation (IAR). In the upright position, the head exerts a gravitational force on the cervical spine with the magnitude, $F = m \times g$. This gravitational force then creates a forward bending moment M around a fulcrum of rotation, also known as the IAR. The magnitude of the bending moment is calculated by $M = F \times L$, in which L is the distance between the IAR and the center of gravity line.

The center of mass (COM) of the cranium is estimated to be approximately 10 mm anterior to the supratragic notch just above the head of the mandible. In a normally aligned lordotic cervical spine, the posterior tension band and paraspinal muscles counterbalance the forward bending movement created by the weight of the head, thus maintaining the natural cervical alignment (Figure 2). The axial load from the cranium is initially transferred from occipital condyles to the C1 lateral masses, then to the C1-2 facet joints, C2 lateral masses, and subsequently distributed to the rest of the spinal column via C2-3 intervertebral disc and facet joints. The facet joints in the subaxial cervical bears about 2/3 of the axial load, while the remaining 1/3 of the axial load is transmitted via the intervertebral discs.

When cervical kyphotic deformity is present, the head COM moves anteriorly and the movement arm L increases relative to the IAR, thus creating a larger bending moment M. The resultant larger bending moment requires greater paraspinal muscle contraction to keep the head erect, which in turn can cause muscle fatigue and pain. In addition, kyphotic cervical deformity shifts the axial load anteriorly, thus can potentially accelerate cervical disc degeneration. Decreased disc height from degenerative changes can cause more cervical kyphosis, thus creating the notion "kyphosis begets kyphosis."

Furthermore, kyphotic deformity can also lead to stretching and lengthening of the spinal cord, resulting in increased tension and impaired microcirculation, eventually leading to spinal cord ischemia and resultant myelopathy over time. However, one should keep in mind that not all kyphotic deformities are

FIGURE 2. *A lateral x-ray showing natural spinal alignment with proportional CL, thoracic kyphosis and lumbar lordosis, along with the center of gravity line passing through the femoral heads demonstrating good sagittal balance.*

symptomatic. It has been estimated that cervical kyphosis can be found in 2% to 35% of asymptomatic patients.[6-8]

Radiographic Parameters

There are several radiographic parameters commonly used to assess the cervical spine, including cervical lordosis (CL), C2-7 sagittal vertical axis (C2-7 SVA), chin-brow vertical angle (CBVA), T1 slope (T1S), thoracic inlet angle (TIA), and neck tilt. An overview of these parameters is provided below along with a brief discussion on cervical deformity classification.

CL

In 1977, Bagnall et al[9] found that at 9.5 wk of gestation, 83% of fetuses had CL, 11% had a military configuration, and only 6% of fetuses had cervical kyphosis. From this result, the authors deduced that 94% of fetuses began to use their posterior cervical muscles to form cervical curve by 9.5 wk of gestation. This finding supports the theory that CL begins to form even before birth, and more CL develops as an infant learns to support the weight of the head by sitting up, and further increases after standing and walking. However, there is no universally accepted definition currently for "normal" CL. By convention, a lordotic alignment is usually reported as a negative angle, whereas a kyphotic alignment is generally reported as a positive angle. The 4 most common methods for measuring CL include the modified Cobb method (mCM), Jackson physiological stress lines (JPS), Harrison's posterior tangent method (HPT), and the Ishihara index (Figure 3).[10-12]

To measure CL using the mCM, 2 lines are drawn along C2 and C7 inferior end plates first, then additional lines perpendicular to the first 2 lines are drawn, respectively, and the angle subtended by the perpendicular lines equals CL. Alternatively, most modern digital imaging software has the built-in capability of measuring lordosis by simply drawing lines tangent to the endplates of the vertebrae of interest and measuring the angle between them as described by Drexler.[13] Some authors also use a line connecting the anterior and posterior tubercles of C-1 instead of end plate of C2 as the upper reference line to estimate CL. The JPS can be obtained by drawing a line along posterior vertebral walls of C2 and C7, respectively; the intersection of these 2 lines will give an estimate of CL. The HPT method involves drawing lines parallel to the posterior surfaces of all cervical vertebral bodies from C2 to C7, and then summing all the segmental angles for an overall cervical curvature angle. The Ishihara index, also known as the cervical curvature index, can be calculated by the following steps: (1) draw a line from the posterior-inferior edge of C2 to the posterior-inferior edge of C7 vertebra; (2) draw 4 lines starting from the posterior-inferior edges of the C3, C4, C5, and C6 vertebrae, perpendicular to the previous line connecting C2 to C7; (3) calculate the total length of the 4 horizontal lines at C3, C4, C5, and C6, and then divide it by the length of the line connecting C2 to C7. A higher ratio of the Ishihara index corresponds to a more lordotic cervical spine, whereas a lower ratio corresponds to a "straighter" cervical spine. If the

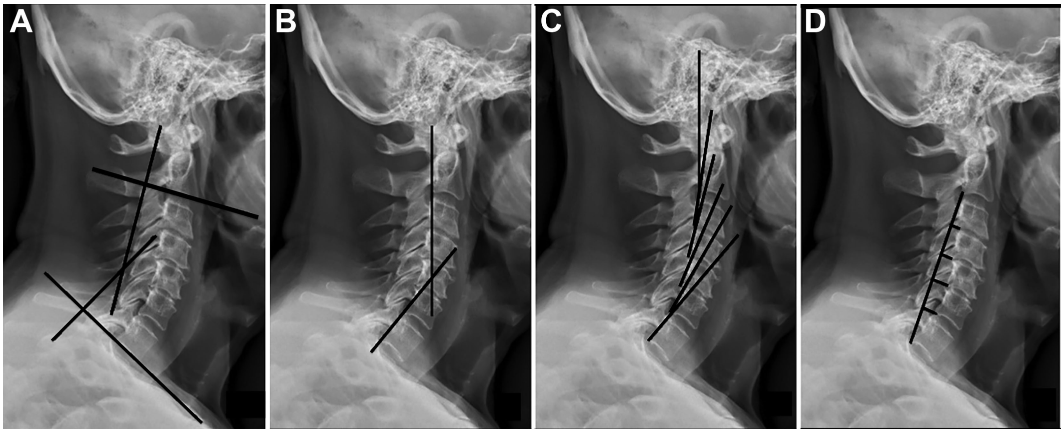

FIGURE 3. *Lateral cervical x-rays showing the 4 common methods for measuring CL:* **A**, *mCM,* **B**, *JPS lines,* **C**, *HPT method, and* **D**, *the Ishihara index.*

cervical spine is perfectly straight, then the Ishihara index equals to zero.

Hardacker et al[14] reported an average C1 to C7 lordosis of –39.4° ± 9.5° after studying 100 asymptomatic volunteers. The majority of CL (77%) occurred at the C1–2 level, with the subaxial cervical segments accounting for the remaining 23% of CL. Iyer et al[15] studied 120 asymptomatic adults and found a mean C2-7 lordosis to be –12.2° (measured with HPT method). This result is similar to the mean C2-7 lordosis of –9.9° reported by Lee et al.[16]

Janusz et al[17] studied 44 upright lateral cervical x-rays and compared the CL results using mCM, JPT, and HPT methods. All three methods showed excellent intra- and interobserver reliability. The average C2-7 lordosis was –10.5° ± 13.9°, –17.5° ± 15.6°, and –17.7° ± 15.9° for mCM, JPS, and HPT methods, respectively. These results suggested that the mCM method may underestimate CL. Takeshita et al[18] studied the relationship between the Ishihara index and C2-7 lordosis (measured using the mCM) in 295 asymptomatic patients. The average Ishihara index was 10.9 with a standard deviation of 15.3. The average C2-7 lordosis was –20.3° with a standard deviation of 14.3°. There was a highly significant correlation between the Ishihara index and CL ($r = 0.95$). However, their correlation diminished in patients with S-shaped cervical spine, and this must be taking into consideration when dealing with cervical deformity.

It is also important to note that CL can be influenced by posture and thoracic kyphosis. Hey et al[19] demonstrated an average increase of CL by 3.45° from standing to sitting. In addition, CL tends to increase with age as a compensatory mechanism for the increased thoracic kyphosis and reduced lumbar lordosis to maintain the horizontal gaze.[12,20]

C2-7 SVA

Regional sagittal alignment of the cervical spine is usually measured by C2-7 SVA, which has been shown to correlate (albeit weakly) with health-related quality of life.[21] The C2-7 SVA is obtained by measuring the distance between the C2 plumb line and the vertical line drawn from the posterior superior end plate of C7 (Figure 4). Park et al[22] found a mean C2-7 SVA of 4.74 mm in 80 asymptomatic patients. However, the measurements were obtained from cervical computed tomography (CT) images, thus the results are almost certainly erroneous due to the supine position. Iyer et al[15] reported a mean C2-7 SVA of 21.3 mm in 120 asymptomatic patients from upright radiographs obtained from EOS imaging system. Tang et al[21] retrospectively reviewed 113 patients receiving multilevel posterior cervical fusions, and found that a C2-7 SVA > 40 mm was correlated with increased disability. However, this correlation is less clear in patients undergoing laminoplasty for ossification of posterior longitudinal ligament.[23]

Nonetheless, from the biomechanical standpoint, increased C2-7 SVA will increase the flexion bending moment of the cervical spine, which in turn increases the muscle energy expenditure required to keep the head erect; overtime, this will likely lead to muscle fatigue, pain, and disability. However, Level 1 evidence that definitively proving the correlation between increased C2-7 SVA and increased disability is still lacking and further study on this topic is needed to further clarify the significance of C2-7 SVA in the cervical spine deformity.

CBVA

The CBVA is an indirect measure of horizontal gaze and can be obtained by measuring the angle subtended by the line connecting the patient's chin to the eyebrow, and the vertical line drawn from the eyebrow. This can be measured from clinical photographs or

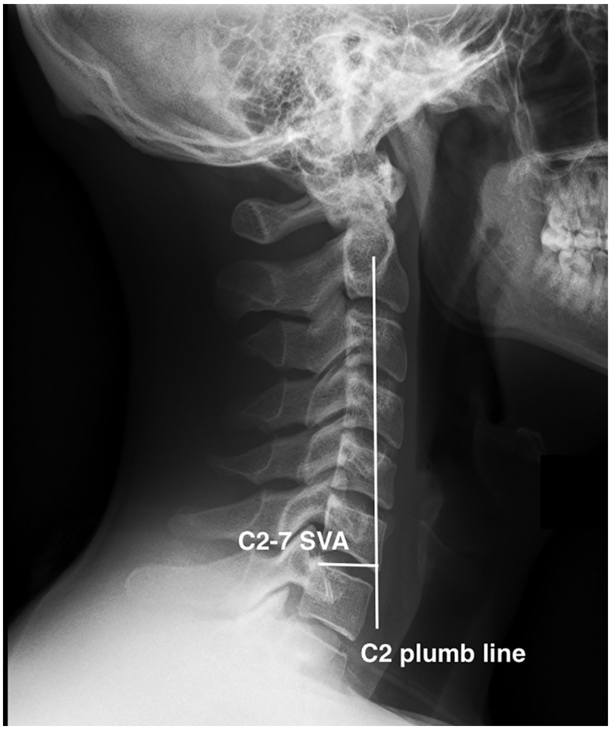

FIGURE 4. *A lateral cervical x-ray showing C2-7 SVA.*

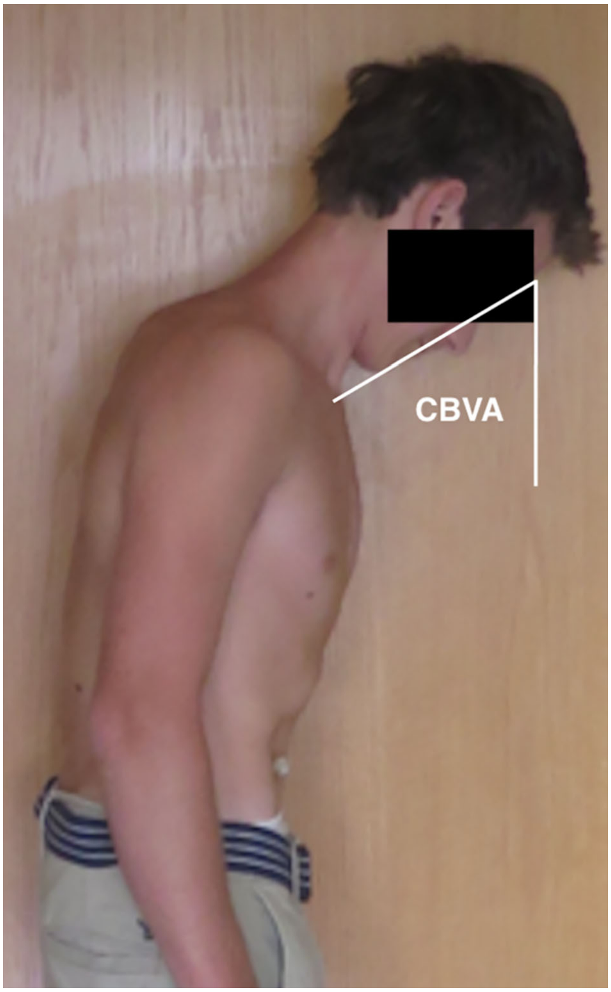

FIGURE 5. *Clinical photo demonstrating a patient with chin-on-chest deformity with CBVA measurement (the patient consented to publish his image).*

full-body EOS x-rays (Figure 5). The patient must be standing with hips and knee extended and the cervical spine in the neutral position. When the head is tilted down, the CBVA is positive; when the head is tilted up, the CBVA is negative; when the head is perfectly erect and neutral, the CBVA is zero.

Iyer et al[15] reported a mean CBVA of –1.7° after analyzing 120 asymptomatic adults. Lafage et al[24] found that a CBVA between –4.7° and +17.7° correlated with the lowest Oswestry Disability Index after studying a series of 303 patients. Suk et al[25] conducted a prospective study including 34 patients with ankylosing spondylitis (AS) patients who had undergone PSO for correction of kyphotic deformity and recommended a CBVA range of –10° to +10° for optimized horizontal gaze. Interestingly, a more recent study by Song et al[26] suggested that AS patients with a postoperative CVBA between +10° and +20° (ie, slight flexion) had best overall results with both indoor and outdoor activities. In the senior authors' experience (KDR, VCT), over correction of cervical kyphosis can be extremely detrimental to patients' daily activities such as cooking, walking, and toileting where downward vision is required; neutral at the most or a slight downward head tilt that balances appearance and function will mostly likely achieve the optimal clinical outcome.

TIA, T1S, and Neck Tilt

In 2012, Lee et al[16] introduced the concept of TIA after studying lateral x-rays of 77 asymptomatic adults. This concept was analogous to the principle pelvic parameters in the lumbosacral region. The authors defined TIA as the angle subtended by the line connecting the sternum to the middle of T1 upper end plate, and the line perpendicular to the T1 upper end plate (Figure 6). Although originally measured on lateral x-rays, other authors[27,28] had found that using CT or magnetic resonance imaging maybe a good alternative with better visualization of relevant structures and improved reliability. The T1S is the angle formed by the T1 upper end plate and the horizontal plane, similar to the sacral slope. The neck tilt is defined as the angle between the line connecting the sternum to the middle of T1 upper end plate and the vertical axis, similar to the pelvic tilt.

Lee et al[16] proposed that TIA is a fixed, morphological parameter given the thoracic inlet is relatively immobile due to articulations between the sternum, T1 ribs and the T1 vertebral body. However, Janusz et al[17] found varying TIA values

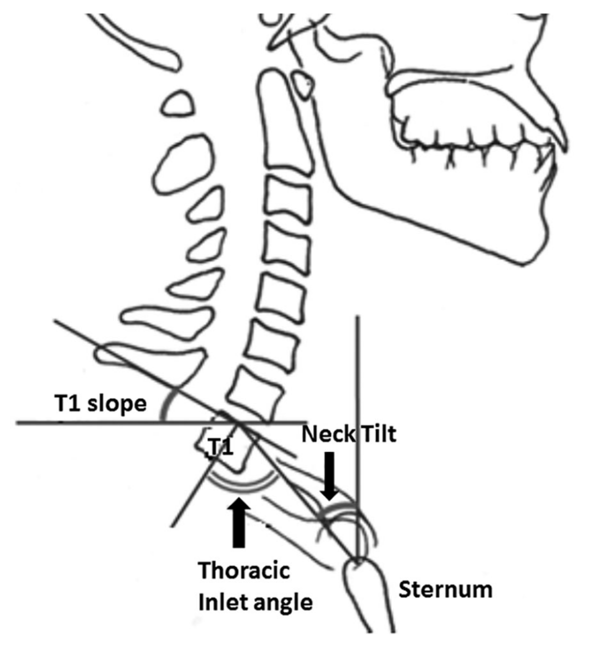

FIGURE 6. *A drawing demonstrating TIA, T1S, and neck tilt.*

depending on the position of the cervical spine (neutral, flexion vs extension) after studying 60 patients. Interestingly, Kim et al[29] also demonstrated that the TIA values changed when the patient slept on pillows of varying heights, as well as in the sitting position. This finding further argued against the notion that the TIA is a morphological parameter that does not change with cervical motion and posture.

Oe et al[30] conducted a study on 656 volunteers aged from 50 to 89 yr. The mean T1S for each decade was 32°, 31°, 33°, and 36° for men, and 28°, 29°, 32°, and 37° for women, respectively. They found that C2-C7 SVA > 40 mm or more, T1S > 40°, and T1S-CL > 20° had worse EQ-5D health status scores. Knott et al[31] demonstrated that when the T1S was >25°, all patients had at least +10 cm of C7-S1 SVA in a series of 52 patients. They proposed that the T1S could be useful in evaluating the overall sagittal balance. They also proposed that patients with neck tilt outside the range of 13° to 25° should be sent for scoliosis radiographs for a complete evaluation of their overall sagittal balance.

In recently years, there has been a trend in the subgroup of spinal surgeons who are focused on deformity to obtain 36-inch scoliosis films in all patients to assess overall sagittal balance and to aid surgical planning. This strategy has not yet been proven to be necessary. Although TIA, T1S, and neck tilt are helpful in characterization of cervical spinal deformity, their role in surgical planning and clinical outcome are still unclear and further investigations are required.

Cervical Deformity Classification

Given the paucity of high-level evidence data and relative rarity compared to other more common degenerative conditions of cervical spine, there has not been a universally accepted classification system for cervical deformity. More importantly, it is of dubious benefit to classify cervical deformities other than with terms already in use, such as flexible, rigid, kyphotic, scoliotic, etc. Unlike scoliosis, where classifications are used to determine fusion levels and research requires uniform descriptors, in the cervical spine, the levels of deformity are rather obvious.

In 2015, Ames et al[32] proposed a classification system for cervical spine deformity including a deformity descriptor plus 5 modifiers (Table). The 5 deformity descriptors include C (cervical), CT (cervicothoracic), T (thoracic), S (coronal), and CVJ (craniovertebral junction), which are selected based on the apex of the cervical deformity. The 5 modifiers included C2-7 SVA, CBVA, T1–C2-7 lordosis, modified Japanese Orthopedic Association (JOA) score, and SRS-Schwab classification for thoracolumbar deformity. The authors reported moderately good inter- and intraobserver reliability. However, the methodology of the study, wherein all the angular measurements were provided to the readers, makes the high reliability a foregone conclusion. The classification is therefore a work-in-progress; further

TABLE. Cervical Deformity Classification System Proposed by Ames et al[32]

Deformity descriptor				
C	Apex of sagittal deformity in cervical spine			
CT	Apex of sagittal deformity at cervicothoracic junction			
T	Apex of sagittal deformity in thoracic spine			
S	Primary coronal deformity			
CVJ	Deformity located at craniovertebral junction			
Five Modifiers				
C2-7 SVA	CBVA	CL minus T1S	Mylopathy (mJOA)	SRS-Schwab classification
0: < 4 cm	0: 1° to 10°	0: < 15°	0: 18 (none)	T, L, D or N (curve)
1: 4 to 8 cm	1: –10° to 0° or 11° to 25°	1: 15° to 20°	1: 15-17 (mild)	0, +, or ++ (PI–LL)
2: > 8 cm	2: <–10° or >25°	2: > 20°	2: 12-14 (moderate)	0, +, or ++ (PT)
			3: <12 (severe)	0, +, or ++ (C7-S1 SVA)

PI = pelvic incidence; LL = lumbar lordosis; PT = pelvic tilt.

modifications and correlation with clinical outcome are needed before it can be deemed a useful tool.

CONCLUSION

Cervical spine deformity is a complex problem to treat. A solid understanding of spinal biomechanics and a working knowledge of various cervical radiographic parameters are essential components in formulating a sound surgical plan that optimizes clinical outcome.

Disclosures

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