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Anatomical and functional perspectives of the cervical spine: Part I: the "normal" cervical spine†

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This is the first of a three part series describing the clinical issues surrounding the radiographic assessment of the cervical spine. Defined in this literature review is the working definition of cervical stability. Described are the "normal" anatomical relationships between the cervical vertebrae for both the adult and the child, as portrayed by lateral radiographs. Also presented is a review of available documentation regarding the normal segmental function of the vertebrae in the upper and in the lower cervical spine. The next two parts in this series will deal with the definitions and radiographic evaluation of cervical hypermobility and instability respectively. (JCCA 1989; 33(3): 123–129)

KEY WORDS: cervical spine, stability, normal segmental function, chiropractic, manipulation.

Voici la première d'une série de trois parties décrivant les questions cliniques entourant l'évaluation radiographique de la colonne cervicale. On trouvera dans cette documentation la définition de travail de la stabilité cervicale. Les rapports anatomiques normaux entre les vertèbres cervicales de l'adulte et de l'enfant, indiqués par la radiographie latérale, sont décrits. Un examen de la documentation disponible concernant la fonction segmentaire normale des vertèbres dans la colonne cervicale supérieure et inférieure est également présenté. Les deux parties suivantes de cette série traitent des définitions et de l'évaluation radiographique de l'hypermobilité et de l'instabilité cervicales. (JCCA 1989; 33(3): 123–129)

MOTS CLÉS: colonne cervicale, stabilité, fonction segmentaire normale, chiropractie, manipulation.

Introduction

Since x-rays were first discovered, we have struggled to define the most appropriate and effective means for their application. No where is this struggle more evident than in their usefulness in contributing to the understanding of spinal mechanics. When no major organic pathology is evident, faulty biomechanics have long been considered a cause of painful spinal syndromes. In this regard, recommendations have been made concerning the use of x-rays both statically and dynamically[1,2,3], with the intent of identifying the patient's source of pain and dysfunction and eventually alleviating it.

In this three part series concerning the cervical spine, we will explore the functional and clinical issues which make up the radiographic definitions of cervical structure as they specifically pertain to excessive inter-vertebral motion. The most widely used terms in this regard, either by implication or direct statement are "stability", "hypermobility" and "instability". In 1976, White, Southwick and Panjabi[4] presented the following excerpt with their definition of clinical instability:

> *"I don't know what you mean by "glory",' Alice said. Humpty Dumpty smiled contemptuously. 'Of course you don't – till I tell you. I mean "there's a nice knock-down argument for you"!*
> *'But "glory" doesn't mean a nice knock-down argument,' Alice objected.*
> *'When I use a word,' Humpty Dumpty said, 'it means just what I choose it to mean, neither more nor less.'*
> *'The question is,' said Alice, 'whether you can make words mean so many different things.'*
> *'The question is,' said Humpty Dumpty, 'which is to be Master – that's all.' "*
>
> *Alice in Wonderland, Lewis Carroll*

Now, over ten years later, the definitions of all three terms remain no clearer than "glory". They have been defined using clinical terms, radiologic terms, or both[4,5,6,7,8,9,10,11,12,13,14,15,16] but universal acceptance of any one frame of reference is no closer.

Part of this confusion lies in the variability of the criteria for their application. For example, the accepted use of flexion-extension films has come with a paucity of information concern-

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ing its relationship to pain and pathology. As such, it is important for the chiropractic profession to evaluate and understand how these issues relate to the patient and their clinical picture.

In order to appreciate extremes of motion, clearly a review of the concept of the "stable" cervical spine is required. Part I then will relate specifically to this term. Parts II and III in later issues will deal with cervical intervertebral "hypermobility" and "instability", respectively.

Stability

Farfan and Gracovetsky adopted the Oxford Universal Dictionary definition of the word "stable"[8] so as to refer to it as "the capacity for resistence, the condition of being in stable equilibrium" and "tendency to recover the original position after displacement". When applied to the vertebral motion units in the cervical spine, this general definition can be refined with respect to "stability" to state:

> The ability of the cervical spine to maintain equilibrium, and for each unit comprising it to work harmoniously in action and reaction – that is, the ability of each motion unit to recover its original position after displacement.

White and Panjabi[15] defined "clinical stability" as:

> "The ability of the spine to limit its patterns of displacement under physiologic loads, so as *not* to damage or irritate the spinal cord or nerve roots."

This definition is suitable from a neurological perspective, however, neither address other clinical manifestations of joint malfunction which should also be absent where stability exists. The working clinical definition of stability then, as it pertains to the cervical spine, and as it will be used throughout this paper is:

The ability of each motion unit to work harmoniously in motion to recover its original position after displacement, without damaging or irritating its anatomical components or adjacent neurological structures.

In order to evaluate "stability" then, one must have a clear understanding of two important components of the cervical spine. They are the definition of normal structures ("original position") and the definition of normal function ("in motion").

The "normal" cervical spine

Adults

The authoritative consensus regarding the cervical spine is that the curve is lordotic in nature – that is, convex anteriorly when viewed in the sagittal plane. The range in degree of convexity that constitutes what is designated "normal" is, however, poorly understood.

Boreadis-Borden, Rechtman and Gershon-Cohen[17] in 1959 completed one of the few studies which evaluated the depth of the "normal" curve in lateral radiographs. The authors took a right lateral x-ray of the cervical spine, from a distance of 6 feet in 180 white subjects (90 men and 90 women – 15 subjects for each decade in age, ranging from 20 to 80 years). The x-rays were taken sitting using a consistent procedure, and the patients were apparently selected at random from those presenting for a routine chest examination. In this case series they found that the mean depth in 177 of the 180 asymptomatic subjects was 11.8 mm (approximately 12 mm). The remaining three subjects in their sample who also had no history of neck complaints or trauma, exhibited a reversal of kyphotic curve and were thus labelled "abnormal". The basis for this labelling was not specified in their publication; neither did they consider whether these three "abnormal" findings were merely extremes of what could be considered a normal range.

In observing the x-rays of their sample, Boreadis-Borden and his associates noted that a loss in curve was found mainly in subjects after the age of fifty and was proportionate to the degree of hypertrophic degenerative change. This attests to the clinically held belief that failure of the curve is related to biomechanical problems. Unfortunately, these observations were not substantiated by data, and the authors also state later in the text, that they found an *increase* in the curve in women over the age of 50.

Most other authors of this time period are even more descriptive in presenting their results, claiming that a smooth lordosis is generally accepted, and that loss of the curve clinically represents signs of weakness or injury.[18,19,20,21] Fineman et al.[22] on the other hand, observed a relationship between the inclination of the cervical lordosis, and alterations in the position of the patient's chin. On the basis of their work, they concluded that the loss of the cervical lordosis may indeed be associated with spondylosis, and it can also be attributed to many other factors, including a simple radiographic positional error.

Children

The parameters of this "normal" lordotic curve are even less clear in children. By nature of their skeletal immaturity and accompanying growth patterns, children have been considered to have excessively flexible rather than stable spines.[23] As a result, cervical x-rays in children and adolescents[24] may reveal apparent displacement of one vertebra over another, (usually C2 over C3) which seems to represent a "pseudo-subluxation", (i.e. the false appearance of abnormal placement – but not complete displacement of one vertebrae on another). This appears as a structural abnormality[19,25] in what would otherwise be considered a relatively "stable" spine. Like Fineman and his associates[22] studying these technical errors affecting the lordosis, Juhl et al. in 1962[26], found that such problems could be attributed to "military projection". That is, the retraction of the patient's chin while the cervical spine was radiographed. They concluded that apparent abnormalities of this nature were unremarkable and could thus be considered normal.

In some cases this error has been attributed to the challenges involved in positioning children. The excesses of motion and "aberrations" in alignment encountered by authors who have observed "pseudosubluxations" may, therefore, be the result of simple postural variations due to a child who does not know how, or does not want to co-operate in the taking of the radiograph.

This appearance presents a significant diagnostic dilemma when true subluxation is suspected. In 1984, Pennecot et al.[27] observed that the border between normal and pathological in cases involving trauma is hazy since pseudosubluxations at the C2–C3 and/or C3–C4 levels, make diagnosis so difficult. They also emphasized the frequency with which such diagnostic errors are initially made.

Because of this confusion, the concepts of "harmonious movement" and "recovery after displacement" involved in cervical spine stability are much broader for the youngster. Consequently, in these cases the definition of stability leans more heavily on the clinical aspects of the absence of irritation or damage to the surrounding structures.

Normal movement of the cervical spine

Much work has been done to set the parameters of normal movement in the cervical spine. Interest in measuring and defining intersegmental motion in this area began as early as 1827. Lysell[28] described how Weber, who in the early 19th century dissected three spinal specimens, inserted pins in the spinous processes and transverse processes and measured the distance between these pins during flexion and extension. This interest continues today with a myriad of anatomical and radiological techniques for assessment. For purposes of such analysis, the spine is typically divided into "upper" (occiput (C0), atlas (C1) and axis (C2)), and "lower" (C2 through C7) segments.

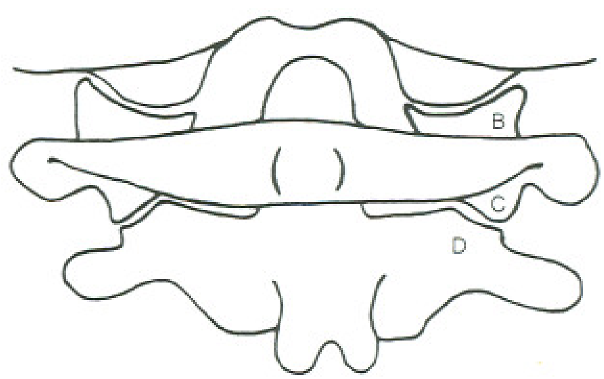


Figure 1

Upper cervical spine

The upper cervical spine consists of the joints between the occiput and the atlas, and the atlas and axis. They are evaluated separately from the rest of the cervical spine due mainly to the uniqueness of their anatomical structures. (Figure 1) According to Penning[29], the essential movement in this area takes place between the occiput and the axis, while the atlas functions as a regulator, sandwiched between the two. Hohl, in 1964[30] stated that the joint between occiput and atlas permitted only flexion and extension, while the atlanto-axial joint also allowed for rotation, vertical approximation and glide.

Kapandji[31], on the other hand, depicted the atlanto-occipital joint from a variety of angles and noted that flexion-extension, lateral flexion, and axial rotation were all anatomically possible. He did, however, contend that rotation between C0 and C1 was secondary to rotation of the atlas about the odontoid, accompanied by secondary minimal linear displacement to the same side, and lateral flexion on the opposite side. Penning[29], on the other hand stated that if rotation between occiput and atlas was possible, it was so small that it could not be measured and, therefore, not confirmed radiologically.

Jirout in 1972[32] did, however, use x-ray analysis to formulate his conclusions regarding linear displacement and rotation of the cervical spine. He described this complex motion by defining rotation of the axis as secondary to lateral flexion of the head and neck. In this model, rotation had two phases. The first phase he attributed to the facet joints themselves, and referred to rotation here as "symmetrical", while in the second phase he described the addition of muscle traction and resultant "asymmetrical" movement. Jirout concluded that because they observed this type of motion in 135/372 lateral flexion x-rays, this indeed must be "normal motion". Given the potential for bias which may have resulted from using only approximately one-third of the sample to derive his conclusions, Jirout's work does little to clarify the issue of "normal" upper cervical spine motion.

The difficulty in defining upper cervical motion continues with the literature available concerning the joints between the atlas and axis. Penning[29], theorized that because the odontoid is fixed by the alar ligaments, lateral bending of the C0–C1 joint is always combined with the lateral bending and slight rotation of the C1–C2 joint. Kapandji's[31] work conflicts with this suggesting that lateral bending is possible at the atlanto-axial joint. He maintained that this was due to a "slipping" of the occipital condyles during flexion to the side, and a consequent limitation of motion imposed by the capsular ligaments.

This conflict regarding the directional component of movement remains unresolved. With the advent of more sophisticated methods of clinical assessment, some more objective measures of movement are being made. Dvorak et al.[33], for example, recently evaluated the maximal rotational excursion of the upper cervical spine with the aid of computerized tomography. They concluded that there is a total rotation of about 10 degrees at the occiput-atlas, and a total rotation of about 64 degrees at the atlas-axis articulation.

Overall, there is little available information regarding the radiologic numerical limits of "normal" motion in this unique area of the spine. One clinically accepted parameter for this region is the excursion in forward flexion of the anterior tubercle of the atlas, from the odontoid (i.e. the atlanto-dental interval (ADI)). It is currently believed that an ADI of 4 mm or more in adults, is excessive and is considered unstable[34]. One of the few estimates of total flexion-extension is provided by Penning[29] who did overlay studies of 20 healthy adults. He found between 25 and 45 degrees movement in each of C0–C1 and C1–C2 joints.

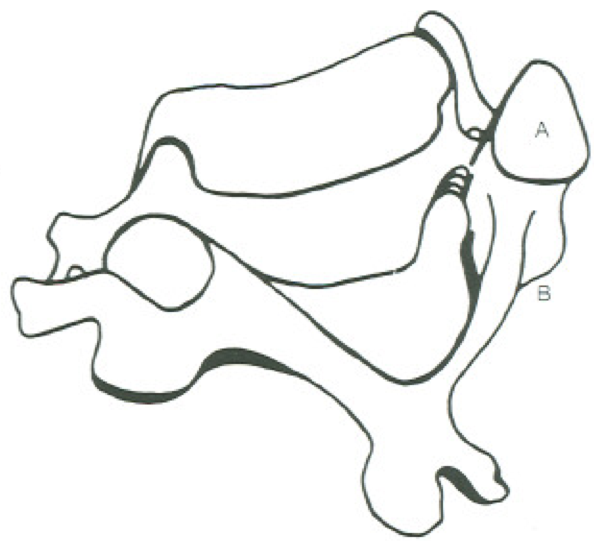
For the most part then, past studies concerned with the upper cervical spine, have been descriptive rather than analytical in nature. It is more the consistency of these descriptions and historical clinical belief which has substantiated the information provided.

Lower cervical spine

Although these two anatomically defined areas of the cervical spine have been considered independently, the interrelationship of their function must be noted. In 1974, Jirout[35] cited the strict dependence of the lower cervical spine on even slight movements of the occiput. He stated that with occipital retroflexion and anteflexion such that the axis was not visibly affected on x-ray, marked ventral tilting and dorsal tilting (respectively) were apparent in the lower cervical spine. As with the discussion of "military positioning" and children, the normal configuration of the spine may change with even slight movements.

The configuration of a vertebra from the lower cervical spine is shown in Figure 2. From the C2–C3 motor unit to the C6–C7 unit, structure and function are relatively the same. Each unit works in harmony to produce the total motion required by the head and neck. Flexion and extension occur as the upper vertebra of the motion segment tilts and slides anteriorly and posteriorly on the articular surfaces of the facet joints[31,28]. During lateral flexion, lateral tilting obviously takes place, however, some authors[31] maintain, again due to the anatomical structure of the articulations, that rotation and extension always accompany this movement. In fact, Kapandji clearly states that due to the orientation of the facets, pure rotation and pure lateral flexion can never occur separately[31]. Penning[29] agrees with this statement pointing out that lateral bending occurs as a result of an upward tilt on one side and a downward tilt on the other. Due

LOWER CERVICAL VERTEBRAE



A: Superior Articulating Facet
B: Inferior Articulating Facet

Figure 2

to the obliquity of the intervertebral joints, this motion is then coupled with forward motion on the up side and backward motion on the down side, hence the rotational component. Lysell[28] expanded on this, providing details to show that with lateral tilt, rotation occurs to the same side. That is, with lateral flexion to the right, rotation is clockwise in direction.

Because of the difficulty noted with coupled movements and the clarity of x-rays taken, most clinicians studying the biomechanics of the normal cervical spine have concentrated largely on the movements of flexion and extension in the sagittal plane. Many different approaches have been taken in an effort to define normal and appropriate limitations of intersegmental motions.

Penning in 1964[19] used "motor diagrams", which were popular in Europe in the 1950's, to determine the excursion of each motion segment from neutral to full flexion, and then from neutral to full extension. Following the example in Figure 3, an outline is traced of the inferior vertebral body and spinous process (e.g. C6). Measuring normal excursion required that an

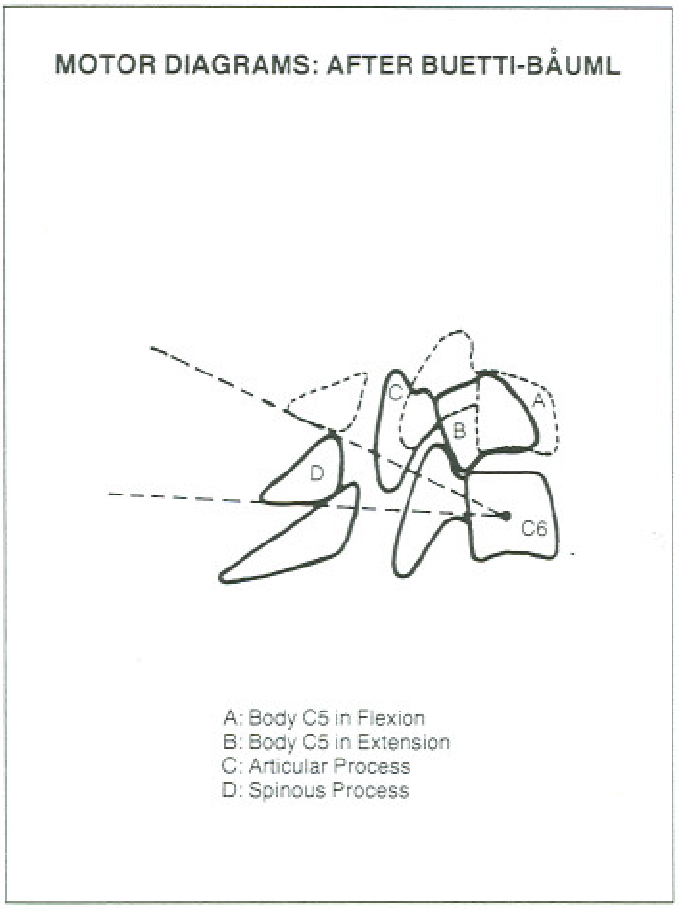


Figure 3

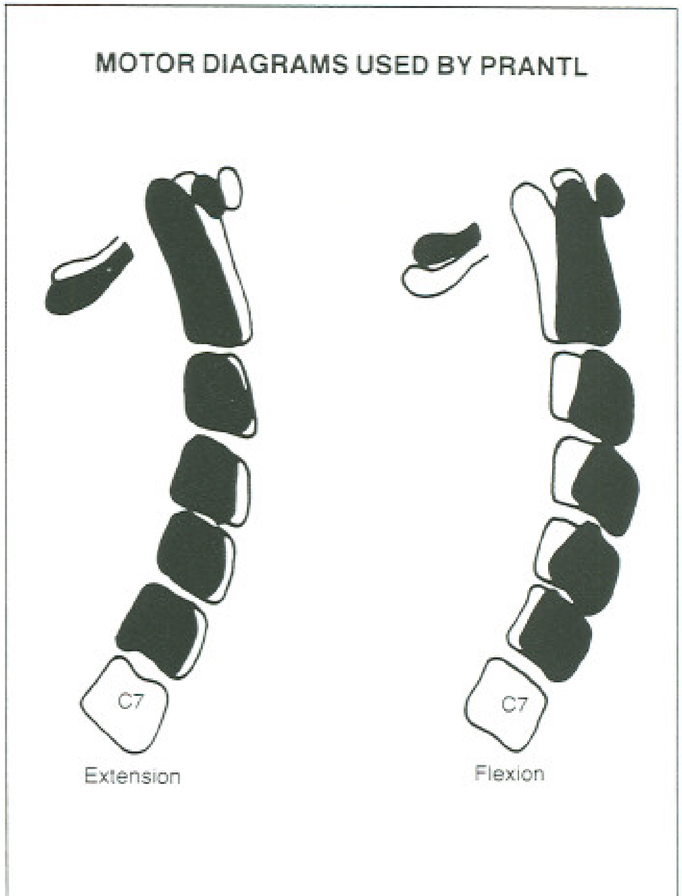


Figure 4

overlay be made such that the inferior body and spinous of the segment (C6) was superimposed over a radiograph of the same vertebra taken in extreme flexion. A new outline then had to be drawn of the superior vertebra (in this case C5). This was repeated for a radiograph of the cervical spine in extreme flexion. The centre of the inferior body was then determined and lines extending from the spinous process of the superior vertebrae (C5) in flexion and in extension to this central point formed an angle which was measured. Despite the fact that the choice of the centre of the body of the base vertebra is reasonably subjective, and although Penning did not statistically compare his results to those of others, simple "eyeballing" of the data indicates that Penning's measures of excursion are very close to those he reports of Buetti-Bauml[19], who studied the same movements in 1954. Indeed they are comparable to those of Bakke[19], who used this method of analysis in 1931, and in line with modern thought regarding increased motion between C3 and C5.

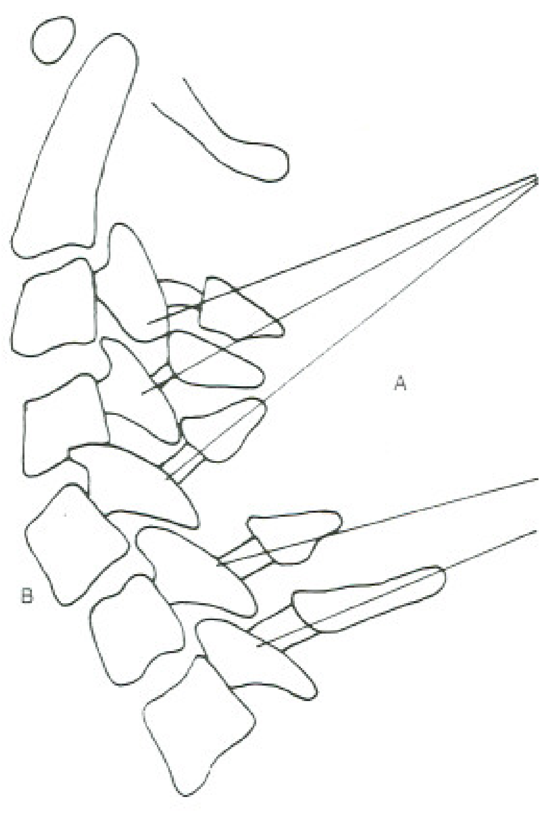
Similar diagrams have been used by Prantl[36] who discussed the value of Buetti-Bauml's overlay diagrams, as modified by Arlen, (Figure 4) in dealing with discrepancies between neutral x-ray films and clinical findings. Prantl suggested in his case series, that these overlay studies need not be evaluated numerically, but simply used to describe areas which required manual therapy. A similar method was reported by Grice[37], in his preliminary series of 50 patients. He concluded that this overlay method provided accurate quantitative measurement of the comparative intersegmental movements of flexion and extension. No numerical values, however, were presented for these movements.

Bhalla and Simmons[38] in 1969 reiterated the need for information regarding movement at individual spinal levels in an effort to understand and then treat abnormalities. They evaluated the normal ranges of motion for the intervertebral joints from the levels C2–T1, by taking lateral cervical x-rays in neutral, flexion, and extension. In order to measure the range of movement at each segment, intersecting lines were drawn along the posterior border of the vertebrae from T1 cephalad. The angles were measured relative to the line drawn from T1 (arbitrarily, but logically assigned the first "stable" vertebra). Angles were measured for flexion and extension and totalled for a measurement of excursion. As with Penning's study, the greatest total excursion was evident in the C4–C6 region. Greatest flexion was noted at C5–C6 with a mean of 15 degrees, and at C4–C5 with a mean of 13 degrees. Greatest extension on the other hand was observed at C6–C7 with 10 degrees and at C4–C5 with 9 degrees. Bhalla and Simmons emphasized the issue of understanding that some intervertebral levels are naturally more mobile than others, concluding that the patient's symptoms, as well as discography, were still considered the best indicators of the location of a problem requiring treatment.

More recently, Henderson and Dorman[2] analyzed calculations from 30 subjects with no history of neck pain in an attempt to describe hypothetical boundaries for normal and abnormal excursion. Using a template analysis similar to that described by Prantl and overcoming magnification problems by calculating the percent sagittal body diameter, these researchers developed yet another set of "normal" or "average" figures about which the population values fall. They found total excursion greatest at the level C4 for both men and women, followed by both C3 and C5. Using the percent sagittal body diameter, the movements of the vertebrae themselves rather than that of the motion segments were determined.

In a further effort to detail the kinematic and geometric parameters of cervical motion in the sagittal plane, Dimnet et al.[39] reported on a new technique for evaluation. Using lateral cervical x-rays for full flexion, full extension, and 3 intermediate positions, they presented angles and centres of movement for each vertebrae, as well as the patterns of curvature in the neck. Although they did not provide numerical values for normal motion, the conclusions drawn from the observational diagrams were consistent with previous data.

An exciting new method has been described by Gertzbein et al.[40,41,42] for analyzing the "centrode" between adjacent vertebrae where function is either normal or abnormal as a result of degeneration or mobility dysfunction. The centrode is defined as the locus of instantaneous axes of rotation about which the motion segment moves. Through the use of cadaveric specimens and a form of Moiré fringes, the authors tracked changes in motion patterns in the lumbar spine according to the degree of dysfunction. They reported that the technique is being tested for in vivo situations, creating the potential for more accurate, quantitative clinical data. The application of this method to the cervical spine, however, remains unreported.



A: Divergence of Spinous Processes
B: Acute Kyphotic Angulation

Figure 5

Summary

As noted above, researchers from the late 1940's have used a tremendous variety of methods for evaluating excursion in the joints of the cervical spine. It is apparent that the C0–C1–C2 or upper cervical spine complex works in harmony to assist with movements of the head and neck. Some discrepancies remain in opinions regarding precisely which motions occur where. In the lower cervical spine, greater consistency and access to observation have aided researchers in defining the limits of motion. Lateral bending and rotation are considered coupled movements, and are difficult to assess radiologically. Much work has been done to evaluate the intersegmental vertebral motion in flexion and extension, as well as to define the "normal" cervical lordosis.

Although results and methods vary, the general consensus is that the lordotic curve is a smooth one when viewed on the lateral radiograph, and that intersegmental movement is highest at the midcervical level.

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References

1 Bechar M, Front D, Bornstein B, Matz S. Cervical myelopathy caused by narrowing of the cervical spinal canal. The value of x-ray examination of the cervical spinal column in extension. Clin Radiol 1971; 22: 63–68.
2 Henderson DJ, Dormon TM. Functional roentgenometric evaluation of the cervical spine in the sagittal plane. J Manipulative Physiol Ther 1985; 8: 219–227.
3 Webb JK, Broughton BK, McSweeney T, Park WM. Hidden flexion injury of the cervical spine. J Bone Joint Surg (Br) 1976; 58: 322–327.
4 White AA, Southwick WO, Panjabi MM. Clinical instability in the lower cervical spine: A review of past and current concepts. Spine 1976; 1: 15–27.
5 Bird HA, Tribe CR, Bacon PA. Joint hypermobility leading to osteoarthrosis and chondrocalcinosis. Ann Rheum Dis 1978; 37: 203–211.
6 Davey JR, Rorabeck CH, Bailey SI, Bourne RB, Dewar FP. A technique of posterior cervical fusion for instability of the cervical spine. Spine 1985; 10: 722–728.
7 Dohler JR, Kahn MRH, Hughes SPF. Instability of the cervical spine after anterior body fusion – a study of its incidence and clinical significance in 21 patients. Arch Orthop Trauma Surg 1985; 104: 247–250.
8 Farfan HF, Gracovetsky S. The nature of instability. Spine 1984; 9: 714–719.
9 Friedenberg ZB, Miller WT. Degenerative disc disease of the cervical spine: a comparative study of asymptomatic and symptomatic patients. J Bone Joint Surg (Am) 1963; 45: 1171–1178.
10 Grieve GP. Lumbar instability. Physiotherapy 1982; 68: 2–9.
11 Herkowitz HN, Rothman RH. Subacute instability of the cervical spine. Spine 1985; 9: 348–357.
12 Nachemson A. The role of spine fusion, question 8: how do we define instability? how is this diagnosed and what surgical treatment policy do you follow? Spine 1981; 6: 306–307.
13 Nash CL. Acute cervical soft-tissue injury and late deformity. J Bone Joint Surg (Am) 1979; 61: 305–307.
14 Scott D, Bird H, Wright V. Joint laxity leading to osteoarthrosis. Rheumatol Rehabil 1979; 18: 167–169.
15 White AA, Johnson RM, Panjabi MM, Southwick WO. Biomechanical analysis of clinical instability in the cervical spine. Clin Orthop 1975; 109: 85–96.
16 Wright V. Hypermobile states. Manuelle Medizin 1981; 19: 78–80.
17 Boreadis-Borden AG, Rechtman AM, Gershon-Cohen J. The normal cervical lordosis. Radiology 1960; 74: 806–809.
18 Evans DK. Anterior cervical subluxation. J Bone Joint Surg (Br) 1976; 58: 318–321.
19 Penning L. Nonpathologic and pathologic relationships between the lower cervical vertebrae. Am J Roentgenol 1964; 91: 1036–1050.
20 Scher AT. Ligamentous injury of the cervical spine – two radiographical signs. S Afr Med J 1978; 53: 802–804.
21 Scher AT. Radiographic indicators of traumatic cervical instability. S Afr Med J 1982; 69: 562–565.
22 Fineman S, Borrelli FJ, Rubinstein BM, Epstein H, Jacobson HG. The cervical spine: transformation of the normal lordotic pattern into a linear pattern in the neutral posture. J Bone Joint Surg (Am) 1963; 45: 1179–1183.
23 Cattell HS, Filtzer DL. Pseudosubluxation and other normal variations in the cervical spine in children. J Bone Joint Surg (Am) 1965; 45: 1295–1309.
24 Fechtel SG. Pseudosubluxation of the cervical spine in adolescents: a case report. J Manipulative Physiol Ther 1985; 8: 219–227.
25 Babcock JL. Cervical spine injuries. Arch Surg 1976; 3: 646–651.
26 Juhl JH, Miller SM, Roberts GW. Roentgenographic variations in the normal cervical spine. Radiology 1962; 78: 591–597.
27 Pennecot GF, Leonard P, Peyrot Des Gachons S, Hardy JR, Pouliquen JC. Traumatic ligamentous instability of the cervical spine in children. J Pediatr Orthop 1984; 4: 339–345.
28 Lysell E. Motion in the cervical spine. Acta Orthop Scand Suppl 1969; 123: 1–61.
29 Penning L. Normal movements of the cervical spine. Am J Roentgenol 1978; 130: 317–326.
30 Hohl M. Normal motions in the upper portion of the cervical spine. J Bone Joint Surg (Am) 1964; 46: 1777–1781.
31 Kapandji IA. The physiology of the joints – volume three: the trunk and the vertebral column. London: Churchill Livingstone, 1974.
32 Jirout J. Changes in the atlas-axis relations on lateral flexion of the head and neck. Neuroradiol 1973; 6: 215–218.
33 Dvorak J, Panjabi M, Gerber M, Wichmann W. CT-functional diagnostics of the rotatory instability of upper cervical spine. 1. an experimental study on cadavers. Spine 1987; 12: 197–205.
34 Hinck VC, Hopkins CE. Measurement of atlas-odontoid distance. Am J Roentgenol 1960; 84: 945.
35 Jirout J. The dynamic dependence of the lower cervical vertebrae on the atlanto-occipital joints. Neuroradiol 1974; 7: 249–252.
36 Prantl K. X-ray examination and functional analysis of the cervical spine. Manuelle Medicine 1985; 2(1): 5–15.
37 Grice AS. Preliminary evaluation of 50 sagittal cervical motion radiographic examinations. J Can Chiro Assoc 1977; 21: 33–34.
38 Bhalla SK, Simmons EH. Normal ranges of intervertebral joint motion of the cervical spine. Can J Surg 1969; 12: 181–187.
39 Dimnet J, Pasquet A, Krag MH, Panjabi MM. Cervical spine motion in the sagittal plane: kinematic and geometric parameters. J Biomechanics 1982; 15: 959–969.
40 Gertzbein SD, Seligman J, Holtby R, Chan KH, Kapasouri A, Tile M, Cruickshank B. Centrode patterns and segmental instability in degenerative disc disease. Spine 1985; 10: 257–261.
41 Gertzbein SD, Seligman J, Holtby R, Chan KW, Ogston N, Kapasouri A, Tile M. Centrode characteristics in the lumbar spine as a function of segmental instability. Clin Orthop 1986; 208: 48–51.
42 Seligman JV, Gertzbein SD, Tile M, Kapasouri A. Computer analysis of spinal segment motion in degenerative disc disease with and without axial loading. Spine 1984; 9: 566–573.