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Review paper

Biomechanics of the cervical spine. I: Normal kinematics

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Abstract

This review constitutes the first of four reviews that systematically address contemporary knowledge about the mechanical behavior of the cervical vertebrae and the soft-tissues of the cervical spine, under normal conditions and under conditions that result in minor or major injuries. This first review considers the normal kinematics of the cervical spine, which predicates the appreciation of the biomechanics of cervical spine injury. It summarizes the cardinal anatomical features of the cervical spine that determine how the cervical vertebrae and their joints behave. The results are collated of multiple studies that have measured the range of motion of individual joints of the cervical spine. However, modern studies are highlighted that reveal that, even under normal conditions, range of motion is not consistent either in time or according to the direction of motion. As well, detailed studies are summarized that reveal the order of movement of individual vertebrae as the cervical spine flexes or extends. The review concludes with an account of the location of instantaneous centres of rotation and their biological basis.

Relevance

The facts and precepts covered in this review underlie many observations that are critical to comprehending how the cervical spine behaves under adverse conditions, and how it might be injured. Forthcoming reviews draw on this information to explain how injuries might occur in situations where hitherto it was believed that no injury was possible, or that no evidence of injury could be detected.

Keywords: Cervical spine; Biomechanics; Movements; Anatomy

1. Introduction

Amongst its several functions, the head can be regarded as a platform that houses the sensory apparatus for hearing, vision, smell, taste and related lingual and labial sensations. In order to function optimally, these sensory organs must be able to scan the environment and be delivered towards objects of interest. It is the cervical spine that subserves these facilities. The cervical spine constitutes a device that supports the sensory platform, and moves and orientates it in three-dimensional space.

The movements of the head are executed by muscles but the type of movements possible depend on the shape and structure of the cervical vertebrae and interplay between them. The kinematics of the cervical spine are, therefore, predicated by the anatomy of the bones that make up the neck and the joints that they form.

2. Functional anatomy

For descriptive purposes, the cervical spine can be divided and perceived as consisting of four units, each with a unique morphology that determines its kinematics and its contribution to the functions of the complete cervical spine. In anatomical terms the units are the atlas, the axis, the C2–3 junction and the remaining, typical cervical vertebrae. In metaphorical, functional terms these can be perceived as the cradle, the axis, the root, and the column.

2.1. The cradle

The atlas vertebra serves to cradle the occiput. Into its superior articular sockets it receives the condyles of the occiput. The union between the head and atlas,

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through the atlanto-occipital joints, is strong, and allows only for nodding movements between the two structures. In all other respects the head and atlas move and function essentially as one unit.

The stability of the atlanto-occipital joint stems largely from the depth of the atlantial sockets. The side walls of the sockets prevent the occiput from sliding sideways; the front and back walls prevent anterior and posterior gliding of the head, respectively. The only physiological movements possible at this joint are flexion and extension, i.e. nodding. These are possible because the atlantial sockets are concave whereas the occipital condyles are convex.

Flexion is achieved by the condyles rolling forwards and sliding backwards across the anterior walls of their sockets (Fig. 1). If the condyles only rolled, they would roll up and over the anterior wall of their sockets. Axial forces exerted by the mass of the head or the muscles causing flexion prevent this upward displacement and cause the condyles to slide downwards and backwards across the concave surface of the socket. Thereby the condyles remain within their sockets, and the composite movement is a rotation, or a spin, of each condyle across the surface of its socket. A converse combination of movements occurs in extension. This combination of roll and contrary glide is typical of condylar joints.

The ultimate restraint to flexion and extension of the atlanto-occipital joint is impaction of the rim of the socket against the base of the skull. Under normal conditions, however, flexion is limited by tension in the posterior neck muscles and by impaction of the submandibular tissues against the throat. Extension is limited by the occiput compressing the suboccipital muscles.

Axial rotation and lateral flexion are not physiological movements of the atlanto-occipital joints. They cannot be produced in isolation by the action of muscles. But they can be produced artificially by forcing the head into these directions while fixing the atlas. Axial rotation is prohibited by impaction of the contralateral condyle against the anterior wall of its socket and simultaneously by impaction of the ipsilateral condyle against the posterior wall of its socket. For the head to rotate, the condyles must rise up their respective walls. Consequently, the occiput must separate from the atlas (Fig. 2). This separation is resisted by tension in the capsules of the atlanto-occipital joints. As a result, the range of motion possible is severely limited. Lateral flexion is limited by similar mechanisms. For lateral flexion to occur the contralateral condyle must lift out of its socket, which engages tension in the joint capsule.

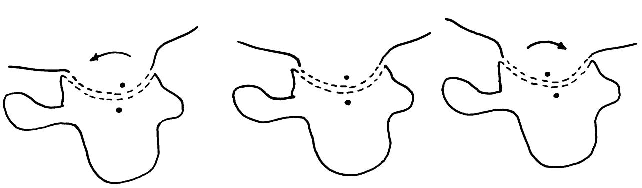

Fig. 1. Right lateral views of flexion and extension of the atlanto-occipital joints. The centre figure depicts the occipital condyle resting in the atlantial socket in a neutral position. The dots are reference points. In flexion the head rotates forwards but the condyle also translates backwards, as indicated by the displacement of the references dot. A converse combination of movements occurs in extension.

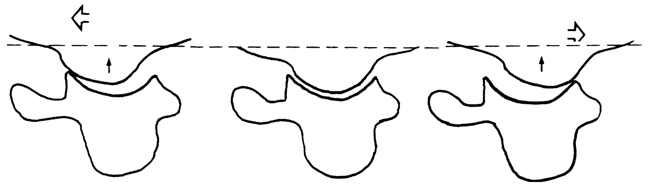

Fig. 2. Right lateral views of axial rotation of the atlanto-occipital joints. Rotation requires forward translation of one condyle and backward translation of the other. Translation is possible only if the condyles rise up the respective walls of the atlantial sockets. As a result, the occiput rises relative to its resting position (centre figure).

2.2. The axis

Carrying the head the atlas sits on the atlas, with the weight being borne through the lateral atlanto-axial joints. After weight-bearing, the cardinal function of the atlanto-axial junction is to permit a large range of axial rotation. This movement requires the anterior arch of the atlas to pivot on the odontoid process and slide around its ipsilateral aspect; this movement being accommodated at the median atlanto-axial joint (Fig. 3(A)). Meanwhile, at the lateral atlanto-axial joint the ipsilateral lateral mass of the atlas must slide backwards and medially while the contralateral lateral mass must slide forwards and medially (Fig. 3).

Radiographs of the lateral atlanto-axial joints belie their structure. In radiographs the facets of the joint appear flat, suggesting that during axial rotation the lateral atlanto-axial joints glide across flat surface. But radiographs do not reveal cartilage. The articular cartilages both of the atlantial and the axial facets of the

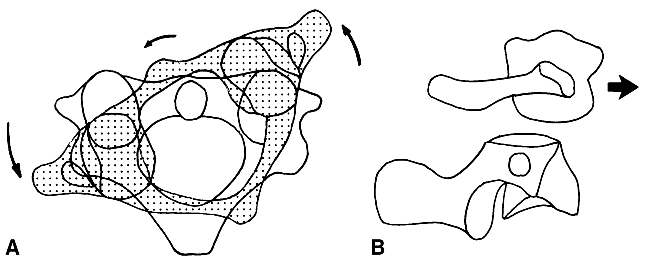

Fig. 3. Atlanto-axial rotation. A: top view. The anterior arch of the atlas (shaded) glides around the odontoid process. B: right lateral view. The lateral mass of the atlas subluxates forwards across the superior articular process of the axis.

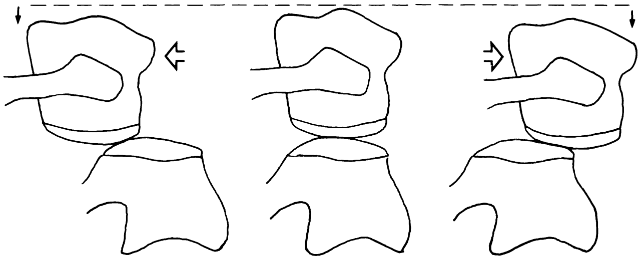

Fig. 4. Lateral view of a right lateral atlanto-axial joint (centre figure) showing the biconcave structure of the articular cartilages. Upon forward or backward displacement, the lateral mass of the atlas settles as it slips down the slope of the cartilage.

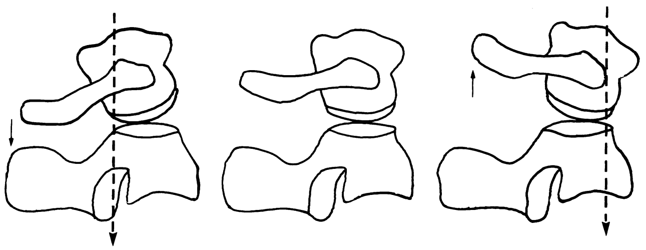

Fig. 5. The mechanism of paradoxical movements of the atlas. In the neutral position (centre figure) the atlas is balanced on the convexities of its articular cartilages. If the atlas is compressed anterior to the balance point, it flexes. If compressed behind the balance point, it extends.

joint are convex, rendering the joint biconvex [1] (Fig. 4). The spaces formed anteriorly and posteriorly, where the articular surfaces diverge, are filled by intra-articular meniscoids [2]. In the neutral position the summit of the atlantial convexity rests on the convexity of the axial facet. As the atlas rotates, however, the ipsilateral atlantial facet slides down the posterior slope of its axial fact, and the contralateral atlantial facet slides down the anterior slope of its facet. As a result, during axial rotation the atlas descends, or nestles into the axis (Fig. 4). Upon reversing the rotation the atlas rises back onto the summits of the facets.

Few muscles act directly on the atlas. The levator scapulae arises from its transverse process but uses this point of suspension to act on the scapulas; it does not move the atlas. Obliquus superior and rectus capitis posterior minor arise from the atlas and act on the occiput, as do rectus anterior and rectus lateralis. Attaching to the anterior tubercle, longus cervicis is the one muscle that acts directly on the atlas, to flex it. But paradoxically there is no antagonist to this muscle.

This paradox underscores the fact that the atlas acts as a passive washer, interposed between the head and the cervical spine proper. Its movements are essentially passive and governed essentially by the muscles that act on the head. Accordingly, rotation of the atlas is brought about by splenius capitis and sternocleidomastoid acting on the head. Torque is then transferred from the head, though the atlanto-occipital joints, to the atlas. The fibres of splenius cervics that insert into the atlas supplement this effect.

The passive movements of the atlas are most evident in flexion/extension of the neck where, indeed, the atlas exhibits paradoxical motion. At full flexion of the neck the atlas can extend, and usually does so [3]. This arises because the atlas, sandwiched between the head and axis, and balanced precariously on the summits of the lateral atlanto-axial facets, is subject to compression loads. If the net compression passes anterior to the contact point in the lateral atlanto-axial joint, the lateral mass of the atlas will be squeezed into flexion (Fig. 5). Conversely, if the line of compression passes behind the contact point, the atlas will extend; even if the rest of the cervical spine flexes (Fig. 5). If, during flexion, the chin is tucked backwards, paradoxical extension of the atlas is virtually assured, because retraction of the chin favours the line of weight-bearing of the skull to fall behind the centre of the lateral atlanto-axial joints.

The restraints to flexion/extension of the atlas have never been formally established. No ligaments are disposed to limit this motion. The various atlanto-occipital membranes are fascial in nature and would not constitute substantive ligamentous restraints. Essentially, the atlas is free to flex or extend until the posterior arch hits either the occiput or the neural arch of C2, respectively.

The restraints to axial rotation are the capsules of the lateral atlanto-axial joints and the alar ligaments. The capsules contribute to a minor degree; the crucial restraints are the alar ligaments [4]. Dislocation of the atlas in rotation does not occur while so long as the alar ligaments remain intact. This feature further underscores the passive nature of the atlas, for the alar ligaments do not attach to the atlas; rather, they bind the head to the odontoid process of the axis. By limiting the range of motion of the head they secondarily limit the movement of the atlas.

Backward sliding of the atlas is limited absolutely by impaction of the anterior arch of the atlas against the odontoid process, but there is no bony obstruction to forward sliding. That movement is limited by the transverse ligament of the atlas and the alar ligaments. As long as either ligament remains intact, dislocation of the atlas is prevented [5].

Lateral gliding involves the ipsilateral lateral mass of the atlas sliding down the slope of its supporting superior articular process while the contralateral lateral mass slides upwards. The movement is primarily limited by the contralateral alar ligament, but is ultimately blocked by impaction of the lateral mass on the side of the odontoid process [6].

2.3. The root

The C2–3 junction is commonly regarded as the commencement of the typical cervical spine, where all segments share the same morphological and kinematic features. However, the C2–3 junction differs from other segments in a subtle but obscure way.

The differences in morphology are not readily apparent and, for this reason, have largely escaped notice. A pillar view of the region reveals the difference. (A pillar view is obtained by beaming X-rays upwards and forwards through the cervical spine, essentially along the planes of the zygapophysial joints.) In such a view the body of the axis looks like a deep root, anchoring the apparatus, that holds and moves the head, into the typical cervical spine (Fig. 6). Moreover, in such view, the atypical orientation of the C2–3 zygapophysial joints is seen. Unlike the typical zygapophysial joints whose planes are transverse, the superior articular processes of C3 face not only upwards and backwards but also medially, by about 40° [7]. Together, the processes of both sides form a socket into which the inferior articular processes of the axis are nestled. Furthermore, the superior articular processes of C3 lie lower, with respect to their vertebral body, than the processes of lower segments [8].

These differences in architecture imply that the C2–3 joints should operate in a manner different from that of lower, typical cervical segments. One difference is that during axial rotation of the neck, the direction of coupling with lateral flexion at C2–3 is opposite to that seen at lower segments (see Table 4). Instead of bending towards the same side as rotation, C2 rotates away from that side, on the average. The lower location of the superior articular process of C3 correlates with the lower location of the axis of sagittal rotation of C2 (see Fig. 14). Other differences in how C2–3 operates have not been elaborated, but the unique architecture of C2–3 suggests that further differences are open to discovery.

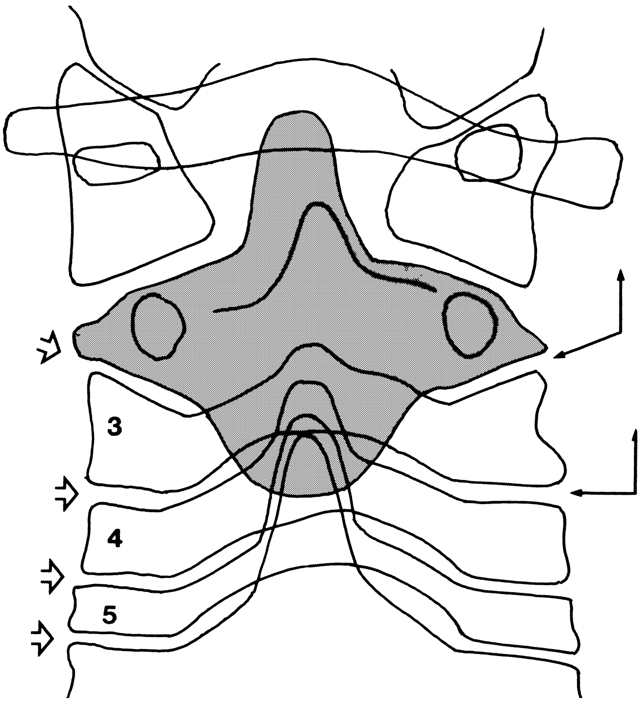

Fig. 6. A tracing of a pillar view of the upper cervical spine, showing the unique morphology of C2 (shaded). (A pillar view is a radiographic projection of the cervical spline obtained by directing the beams upwards and forwards from behind the cervical spine, essentially along the planes of the lower cervical zygapophysial joints.) Note how the zygapophysial joints at lower levels (arrowed) are orientated transversely whereas at C2–3 they are inclined medially, cradling the posterior elements of the axis while its vertebral body dips like a deep root into the cervical vertebral column.

2.4. The column

At typical cervical segments, the vertebral bodies are stacked on one another, separated by intervertebral discs. The opposing surfaces of the vertebral bodies, however, are not flat as they are in the lumbar spine. Rather, they are gently curved in the sagittal plane. The anterior inferior border of each vertebral body forms a lip that hangs downwards like a slight hook towards the anterior superior edge of the vertebra below. Meanwhile, the superior surface of each vertebral body slopes greatly downwards and forwards. As a result, the plane of the intervertebral disc is set not perpendicular but somewhat oblique to the long axes of the vertebral bodies. This structure reflects, and is conducive to, flexion–extension being the cardinal movement of typical cervical segments.

The vertebral bodies are also curved from side-to-side, but this curvature is not readily apparent. It is revealed if sections are taken through the posterior ends of the vertebral bodies, either parallel to the planes of the zygapophysial joints, or perpendicular to these planes. Such sections reveal that the inferior surface of the hind end of the vertebral body is convex, and that convexity is received by a concavity formed by the body below and its uncinate processes (Fig. 7). The appearance is that of an ellipsoid joint (like the wrist). This structure suggest that vertebral bodies can rock side-to-side in the concavity of the uncinate processes. Further consideration reveals that this is so, but only in one plane.

If sections are taken through the cervical spine along planes perpendicular to the zygapophysial joints, and if the sections through the uncinate region and through the zygapophysial joints are superimposed, the appearance is revealing [9,10] (Fig. 8). The structure of the interbody junction is ellipsoid and suggests that rocking could occur between the vertebral bodies. However, in this plane the facets of the zygapophysial joints are directly opposed. Therefore, any attempted rocking of the vertebral body is immediately prevented by the facets (Fig. 8).

If sections are taken through the plane of the zygapophysial joints, the ellipsoid structure of the interbody joint is again revealed, but the zygapophysial joints

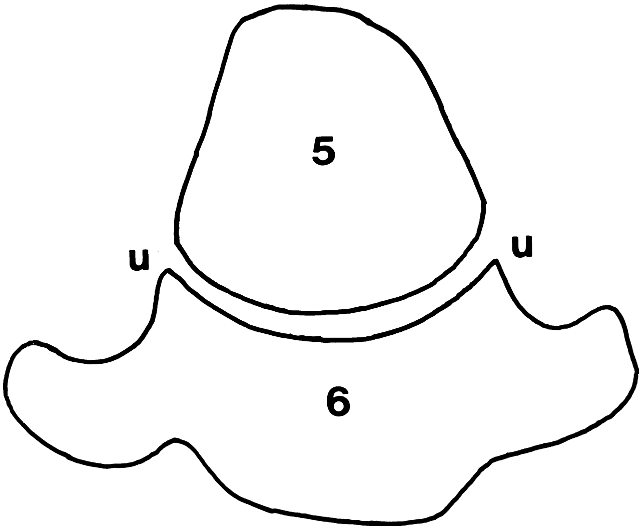

Fig. 7. A sketch of a section taken obliquely through the posterior end of a C5–6 interbody joint, along a plane parallel to the plane of the zygapophysial joints. Between the uncinate processes (u) the C6 vertebral body presents a concave articular surface that receives the convex inferior surface of C5.

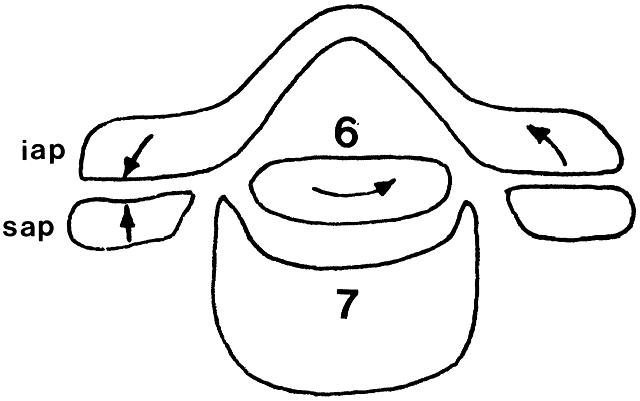

Fig. 8. The appearance, viewed from above, of a section of a C6–7 cervical intervertebral joint taken through the uncinate region and the zygapophysial joints, along a plane perpendicular to the zygapophysial joints. In this plane, if the C6 vertebral body rotates to the left, its right inferior articular process (iap) immediately impacts, en face, into the superior articular process (sap) of C7; which precludes lateral rotation of C6.

present en face. Consequently the facets do not impede rocking of the vertebral bodies in this plane. Indeed, the facets slide freely upon one another (Fig. 9).

These observations indicate that the cervical intervertebral joints are saddle joints: they consist of two concavities facing one another and set at right angles to one another [9,10]. Across the sagittal plane the inferior surface of the vertebral body is concave downwards, while across the plane of the zygapophysial joints the uncinate region of the lower vertebral body is concave

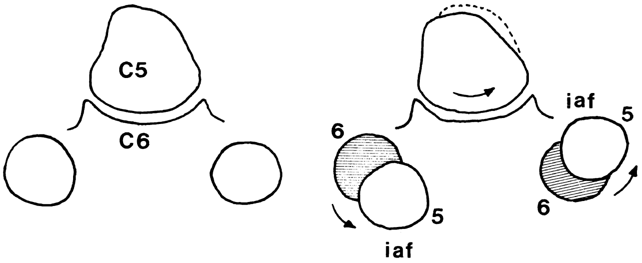

Fig. 9. The appearance, viewed from above, of superimposed sections of a C5–6 cervical intervertebral joint taken through the uncinate region and through the zygapophysial joints, along a plane parallel to that of the zygapophysial joints. In this plane, if the C5 vertebral body rotates, its inferior articular facets (iaf) are free to glide across the surface of the superior articular facets of C6.

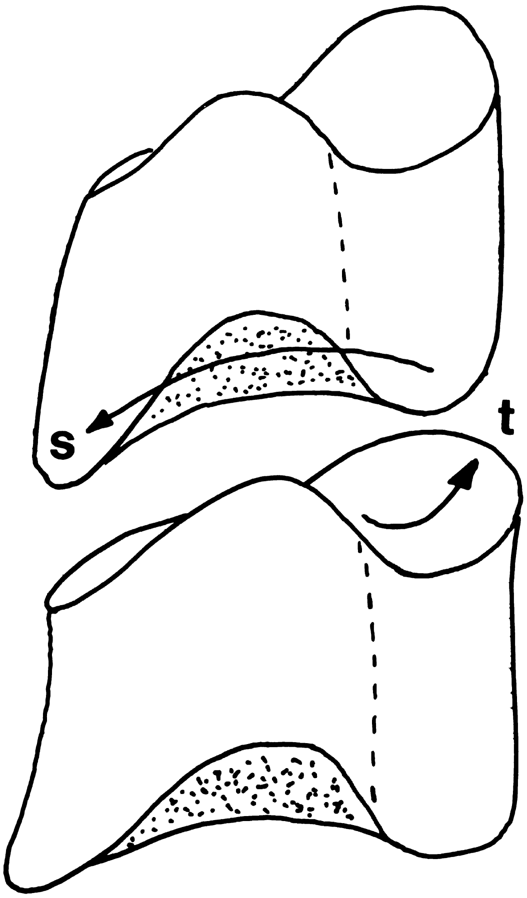

Fig. 10. The saddle shape of cervical intervertebral joints. The inferior surface of the upper vertebral body is concave downwards in the sagittal plane (s). The superior surface of the lower vertebral body is concave upwards in the transverse plane (t).

upwards (Fig. 10). This means that the vertebral body is free to rock forwards in the sagittal plane, around a transverse axis, and is free to rock side-to-side in the place of the facets, around an axis perpendicular to the facets (Fig. 11). Motion in the third plane – side-to-side around an oblique anterior – posterior axis is precluded by the orientation of the facets.

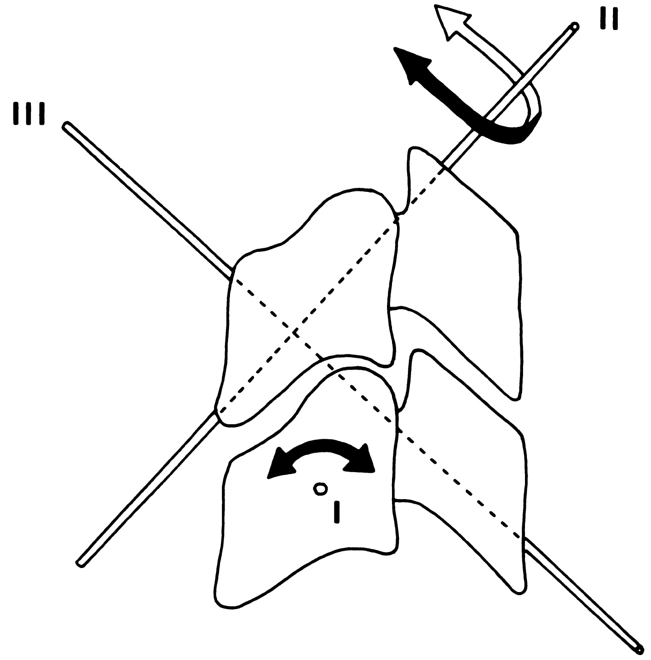

Fig. 11. The planes of motion of a cervical motion segment. Flexion and extension occur around a transverse axis (axis I). Axial rotation occurs around a modified axis (axis II) passing perpendicular to the plane of the zygapophysial joints, and this motion is cradled by the uncinate processes. The third axis (axis III) lies perpendicular to both of the first two axes but no motion can occur about this axis (see Fig. 8).

This description appears dissonant with traditional ideas that typical cervical segments exhibit flexion/extension, lateral flexion, and axial rotation; but it is not. Rather it allows flexion/extension but stipulates that the only other pure movement is rotation around an axis perpendicular to the facets. Since the facets are orientated at about 45° to the transverse plane of the vertebrae,[8] the axis of rotation is 45° from the conventional axes of both horizontal axial rotation and lateral flexion.

This geometry stipulates that conventional horizontal axial rotation and lateral flexion and trigonometric projections of the true axial rotation that occurs in the cervical spine. Moreover, it stipulates that horizontal rotation is inexorably coupled with lateral flexion, and vice-versa. If horizontal rotation is attempted, the inferior articular process must ride up this slope. As a result, the vertebra must tilt to the side of rotation. A reciprocal combination of events obtains when lateral flexion is attempted. Downward movement of the ipsilateral inferior articular process is arrested by the upward facing superior articular process; but is permitted if the inferior process slides backwards down the slope of the superior process. As a result, the vertebrae must rotate to the side of lateral flexion.

The axis of rotation in the plane of the zygapophysial joints passes through the anterior end of the moving vertebral body [9,10]. This means that the anterior end does not swing but pivots about the axis without gliding. Meanwhile, the posterior end of the vertebral body must be able to swing (because it is displaced from the axis). These requirements are reflected in the structure of the intervertebral disc.

The cervical intervertebral discs are not like lumbar discs; they lack a concentric anulus fibrosis around their entire perimeter [11]. The cervical anulus is well developed and thick anteriorly; but it tapers laterally and posteriorly towards the anterior edge of the uncinate process on each side (Fig. 12). Moreover, a criss-cross arrangement of collagen fibres as seen in lumbar discs, is absent. Instead, fibres of the anterior anulus consistently converge upwards towards the anterior end of the upper vertebra [11]. This arrangement is consistent with that vertebra pivoting about its anterior end. In effect, the anterior anulus is an interosseous ligament, disposed like an inverted "V" whose apex points to the axis of rotation.

An anulus is lacking posteriorly [11]. It is represented only by a few fibres near the median plane that are longitudinally orientated and gathered in a lamina only about 1 mm thick. Lateral to these fibres, as far as the uncinate process, the anulus is absent. The back of the disc is covered only by the posterior longitudinal ligament.

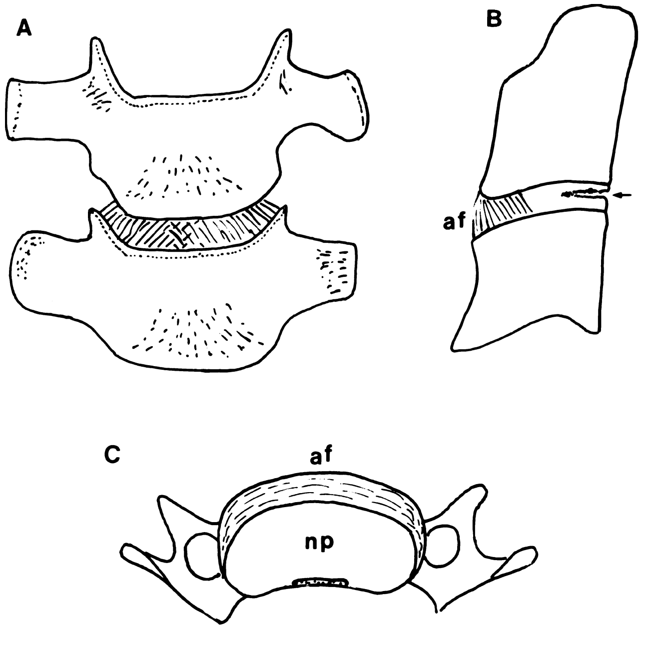

Fig. 12. Sketches of the structure of a cervical intervertebral disc. A: front view, showing how the fibres of the anterior anulus fibrosus converge upwards towards the midline. B: lateral view, showing how the annulus fibrosus (af) constitutes an anterior interosseous ligament. Meanwhile the nucleus pulposus is split posteriorly by a transverse cleft (arrow). C: top view, showing the crescentic shape of the anulus fibrosus, thick anteriorly but tapering towards the uncinate process as it surrounds the nucleus pulposus (np). Posteriorly, the anulus is represented only by a small bundle of vertical, paramedian fibres.

This structure arises in adults through the development of transverse fissures across the back the cervical discs [12]. The fissures commence, at about the age of nine years, as clefts in the uncovertebral region. Progressively they extend medially across the disc, ultimately to form transverse clefts by the third decade. These clefts are a normal feature of cervical discs. What is not known is whether they constitute some form of programmed attrition of the posterior anulus, or they arise as a result of repeated attempts at axial rotation during early life. Whatever the explanation, their presence allows, or facilitates, axial rotation.

In the absence of a posterior anulus, and given a posterior transverse cleft the posterior end of the vertebral body is free to swing about an anteriorly located axis. As it swings, its posterior inferior border glides up and down the concavity of the uncinate processes, while its inferior articular processes glide freely across the superior articular facets below (Fig. 9).

The restraints to true axial rotation of a typical cervical segment have not been determined by experiment. Theoretically they would appear to be tension in the capsules of the zygapophysial joints, and tension developed in the anterior anulus fibrosus as this structure twists about the axis of rotation. If rotation is attempted in the horizontal plane, the slope of the zygapophysial joints is the primary impediment to rotation.

Flexion is resisted in concert by the posterior longitudinal ligament, the ligamentum flavum, the capsules of the zygapophysial joints, and the interspinous ligaments. Stability is maintained if either the posterior longitudinal ligament or the zygapophysial joints remain intact [13,14]. Extension is principally limited by the anterior longitudinal ligament and the anulus fibrosus, and ultimately by impaction of spinous processes or laminae posteriorly.

3. Kinematics

3.1. Atlanto-occipital joint

Studies of the atlanto-occipital joint in cadavers found the range of flexion–extension to be about 13°; that of axial rotation was 0°; but about 8° was possible when the movement was forced [15]. A detailed radiographic study of cadaveric specimens [16,17] found the mean ranges (SD) to be flexion–extension: 18.6°(0.6), axial rotation 3.4°(0.4), and lateral flexion 3.9° (0.6). It also revealed that when flexion–extension was executed, it was accompanied by negligible movements in the other planes; but when axial rotation was executed as the primary movement, 1.5° of extension and 2.7° of lateral flexion occurred. However, rather than indicating a normal or "natural" coupling of movements, these figures more likely reflect how and where the axial torque was applied to the cadavers. A different degree of coupling could apply in vivo when axial rotation is attempted by the action of muscles.

Table 1
Results of studies of normal ranges of flexion–extension at the atlanto-occipital joint

Source	Mean	Range of motion (deg)	
		Range	SD
Brocher [18]	14.3	0–25	
Lewit and Krausova [19]	15		
Markuske [20]	14.5		
Fielding [21]	35		
Kottke and Mundale [22]		0–22	
Lind et al. [23]	14		15

Radiographic studies of the atlanto-occipital joints in vivo have addressed only the range of flexion–extension because axial rotation and lateral flexion are impossible to determine accurately from plain radiographs. Most studies agree that the average range of motion is 14–15° (Table 1). For some reason, the values reported by Fielding [21] are distinctly out of character. What is conspicuous in Table 1 is the enormous variance in range exhibited by normal individuals, which indeed led one group of investigators [22] to refrain from offering either an average or representative range. This is reflected formally by the results of Lind et al. [23] in which the coefficient of variation is over 100%. The reasons for these discrepancies in findings is not readily apparent from the original publications, but could be due to differences in the way in which occipital flexion/extension were executed and the paradoxical motion of the atlas that different strategies induce.

3.2. Atlanto-axial joint

In cadavers the atlanto-axial joints exhibit about 47° of axial rotation and some 10° of flexion–extension [15]. Lateral flexion measures about 5° [24]. In living individuals, plain radiography cannot be used to determine accurately the range of axial rotation of the atlas, for direct, top views of the moving vertebra cannot be obtained. Consequently, the range of axial rotation can only be inferred from plain films. For this reason, most investigators using plain radiography have reported only the range of flexion–extension exhibited by the atlas (Table 2).

One approach to obtaining values of the range of axial rotation of the atlas has been to use biplanar radiography [26]. The results of such studies reveal that the total range of rotation (from left to right) of the occiput versus C2 is 75.2° (SD, 11.8). Moreover, axial rotation is, on the average, accompanied by 14° (SD, 6) of extension and 24° (SD, 6) of contralateral lateral flexion. Axial rotation of the atlas is thus, not a pure

Table 2
Ranges of motion of the atlanto-axial joints

Source	Ranges of motion (deg)		
	Axial rotation		Flexion–extension
	One side	Total	
Brocher [18]			18 (2–16)
Kottke and Mundale [22]			11
Lewit and Krausova [19]			16
Markuske [20]			21
Lind et al. [23]			13 (±5)
Fielding [21]		90	15
Hohl and Baker [25]	30		(10–15)

movement; it is coupled with a substantial degree of extension, or in some cases – flexion. The coupling arises because of the passive behavior of the atlas under axial loads from the head; whether it flexes or extends during axial rotation depends on the shape of the atlanto-axial joints and the exact orientation of any longitudinal forces acting through the atlas from the head.

Another approach to studying the range of axial rotation of the atlas has been to use CT scanning. This facility was not available to early investigators of cervical kinematics, and data stemming from its application have appeared only in recent years. In a rigorous series of studies, Dvorak and colleagues examined the anatomy of the alar ligaments [27], the movements of the atlas in cadavers [4,28,29], and how these could be demonstrated using CT [30]. Subsequently, they applied the same scanning technique to normal subjects and to patients with neck pain following motor vehicle trauma in whom atlanto-axial instability was suspected clinically [31,32].

They confirmed earlier demonstrations [5] that the transverse ligament of the atlas was critical in controlling flexion of the atlas and its anterior displacement [29]. They showed that the alar ligaments were the cardinal structures that limit axial rotation of the atlas [28,29], although the capsules of the lateral atlanto-axial joints contribute to a small extent [4,29]. In cadavers, 32° (SD, 10) of axial rotation to either side could be obtained; but if the contralateral alar ligament was transected, the range increased by some 30% (i.e. by about 11°) [30].

In normal individuals, the range of axial rotation, as evident in CT scans, is 43° (SD, 5.5) to each side, with an asymmetry of 2.7° (SD, 2) [31]. These figures establish 56° as a reliable upper limit of rotation, above which pathological hypermobility can be suspected, with rupture of the contralateral alar ligament being the most likely basis [31].

In studying a group of patients with suspected hypermobility Dvorak et al. [31,32] found their mean range of rotation, to each side, to be 58°. Although the number of patients so afflicted is perhaps small, the use of functional CT constitutes a significant breakthrough. Functional CT is the only available means of reliably diagnosing patients with alar ligament damage. Without the application of CT these patients would continue to remain undiagnosed, and their complaint ascribed to unknown or psychogenic causes.

3.3. Lower cervical spine

Most studies of the lower cervical spine have addressed flexion–extension movements, for these are the cardinal movements exhibited by these segments. Indeed, in the literature it has been almost traditional for yet another group each year to add another contribution to issues such as the range of movement of the neck [33–54]. The study of axial rotation is more demanding, and required the advent of biplanar radiography and CT.

3.4. Axial rotation

As explained previously, axial rotation of typical cervical segments occurs most freely in the plane of the zygapophysial joints; but no one has determined the range of rotation in this plane. When attempted in the horizontal plane, axial rotation is inexorably coupled with ipsilateral lateral flexion. Consequently, CT scanning across the conventional, horizontal plane is confounded by movement of the plane of view, and does not reveal pure axial rotation. CT, therefore, provides only an approximate estimate of the range of axial rotation of the typical cervical vertebrae. One study has provided normative data using this technique [8] (Table 3).

More valid measures can obtained from trigonometric reconstructions of movements studied by biplanar radiography. However, the accuracy of this method depends on the accuracy of identifying like points on four separate views of the same vertebra (an antero-posterior and a lateral view in each of two positions).

Table 3
Mean values and ranges of axial rotation of cervical motion segments as determined by CT scanning[a]

Segment	Range of motion (deg)	
	Mean	Range
Occ–C1	1.0	−2–5
C1–C2	40.5	29–46
C2–C3	3.0	0–10
C3–C4	6.5	3–10
C4–C5	6.8	1–12
C5–C6	6.9	2–12
C6–C7	2.1	2–10
C7–T1	2.1	−2–7

[a] Based on Penning and Wilmink [10].

Table 4
Normal ranges of motion of cervical spine in axial rotation, and ranges of coupled motions, as determined by Biplanar radiography[a]

Segment	Coupled movement		
	Axial rotation mean degrees (SD)	Flexion/ extension mean degrees (SD)	Lateral flexion mean degrees (SD)
Occ–C2	75 (12)	−14 (6)	−2 (6)
C2–3	7 (6)	0 (3)	−2 (8)
C3–4	6 (5)	−3 (5)	6 (7)
C4–5	4 (6)	−2 (4)	6 (7)
C5–6	5 (4)	2 (3)	4 (8)
C6–7	6 (3)	3 (3)	3 (7)

[a] Based on Mimura et al. [26].

Accuracy in this process is not easy to achieve [16]. Nevertheless, one study [26] has provided normative data using this technique (Table 4). What is noticeable from these data is that biplanar radiography reveals a somewhat more generous range of axial rotation than does CT, but that this rotation is coupled with a lateral flexion of essentially the same magnitude.

By applying trigonometric corrections to the data obtained from CT and biplanar radiography, the range of axial rotation in the plane of the zygapophysial joints can be calculated (see Appendix A). If the plane of the joints is orientated at an angle of $\theta°$ to the horizontal plane; and if α is the rotation in the horizontal plane, and φ is the rotation in the plane of the facets, $\tan\alpha = \tan\phi\cos\theta$. Allowing for a 45° slope of the cervical facets, for a range of horizontal rotation of 6° the range of rotation in the plane of the zygapophysial joints would be about 8°.

3.5. Flexion–extension

Early studies of the cervical spine examined the range of movement of the entire neck, typically by applying goniometers to the head [39–41,44,51]. Fundamentally, however, such studies describe the range of movement of the head. Although they provide implicit data on the global function of the neck, they do not reveal what actually is happening inside the neck.

Some investigators studied cadavers [42,45,50]. Such studies are an important first iteration for they establish what might be expected when individual segments come to be studied in vivo, and how it might best be measured. However, cadaver studies are relatively artificial; the movement of skeletons without muscles does not accurately reflect how intact, living individuals move.

Investigators recognized that for a proper comprehension of cervical kinematics radiographic studies of normal individuals were required; [32–38,43–48,52–54] and a large number of investigators produced what might be construed as normative data on the range of motion of individual cervical segments and the neck as a whole [7,22,33–35,37,38,46–48].

What is conspicuous about these data, however, is that while ranges of values were sometimes reported, standard deviations were not. It seems that most of these studies were undertaken in a era before the advent of statistical and epidemiological rigour. Two early studies [36,46] provided raw data from which means and standard deviations could be calculated, and two recent studies [23, 52] provided data properly described in statistical terms (Table 5).

The early studies of cervical motion were also marred by lack of attention to the reliability of the technique used; inter-observer and intra-observer errors were not reported. This leaves unknown the extent to which observer errors and technical errors compromise the accuracy of the data reported. Only those studies conducted in recent years specify the inter-observer error of their techniques; [23,52] so only their data can be considered acceptable.

The implication of collecting normative data is that somehow it might be used diagnostically to determine abnormality. Unfortunately, without means and standard deviations and without values for observer errors, normative data is at best illustrative, and cannot be adopted for diagnostic purposes. To declare an individual or a segment to be abnormal, an investigator must clearly be able to calculate the probability of a given observation constituting a normal value, and must determine whether or not technical errors have biased the observation.

One study has pursued this application using reliable and well-described data [52]. For active and passive

Table 5
Results of those studies of cervical flexion and extension that reported both mean values and (standard deviations)

Source	Number	Mean range and standard deviation of motion (°)				
		C2–3	C3–4	C4–5	C5–6	C6–7
Aho et al. [36]	15	12 (5)	15 (7)	22 (4)	28 (4)	15 (4)
Bhalla and Simmons [46]	20	9 (1)	15 (2)	23 (1)	19 (1)	18 (3)
Lind et al. [23]	70	10 (4)	14 (6)	16 (6)	15 (8)	11 (7)
Dvorak et al. [52]	28	10 (3)	15 (3)	19 (4)	20 (4)	19 (4)

cervical flexion, mean values and standard deviations were determined for the range of motion of every cervical segment, using a method of stated reliability. Furthermore, it was claimed that symptomatic patients could be identified on the basis of hypermobility or hypomobility [52]. However, the normal range adopted in this study was one standard deviation either side of the mean [52]. This is irregular and illusory.

It is more conventional to adopt the two standard deviation range as the normal range. This convention establishes a range within which 96% of the asymptomatic population lies; only 2% of the normal population will fall above these limits, and only 2% will fall below. Adopting a one standard deviation range classifies only 67% of the normal population within the limits, leaving 33% of normal individuals outside the range. This means that any population of putatively abnormal individuals will be "contaminated" with 33% of the normal population. This reduces the specificity of the test, and increases its false-positive rate.

3.6. Directional and temporal consistency

Regardless of how fashionable it may have been to study ranges of motion of the neck, and regardless of how genuine may have been the intent and desire of early investigators to derive data that could be used to detect abnormalities, a definitive study has appeared which has put paid to all previous studies and renders irrelevant any further studies of cervical motion using conventional radiographic techniques. No longer are any of the earlier data of any great use.

Van Mameren and colleagues [3] used an exquisite technique to study cervical motion in flexion and extension in normal volunteers. High-speed cineradiographs were taken to produce upto 25 exposures fore each excursion form full flexion to full extension, or from full extension to full flexion. When printed and converted to a static view, each frame provided an image equal in quality and resolution to a conventional lateral radiograph of the cervical spine. These images could be reliably digitized, and each could be compared to any other in the series in order to reconstruct and plot the pattern of motion either algebraically or geometrically. Their technique differed from videofluoroscopy in that instead of viewing dynamic films, each frame was fastidiously studied as a static film and compared to every other.

Ten subjects undertook flexion from full extension, and also extension from full flexion. The experiments were repeated two weeks and 10 weeks after the first observation. These studies allowed the ranges of motion of individual cervical segments to be studied and correlated against total range of motion of the neck, and against the direction in which movement was undertaken. Moreover, the stability of the observations over time could be determined. The results are most revealing.

The maximum range of motion of a given cervical segment is not necessarily reflected by the range apparent when the position of the vertebra in full flexion is compared to its position in full extension. Often the maximum range of motion is exhibited at some stage during the excursion but prior to the neck reaching its final position. In other words, a vertebra may reach its maximum range of flexion, but as the neck continues towards "full flexion", that vertebra actually reverses its motion, and extends slightly. This behavior is particularly apparent at upper cervical segments: Occ–C1, C1–2. A consequence of this behavior is that the total range of motion of the neck is not the arithmetic sum of its intersegmental ranges of motion.

A second result is that segmental range of motion differs according to whether the motion is executed from flexion to extension or from extension to flexion. At the same sitting, in the same individual, differences of 5–15° can be recorded in a single segment, particularly at Occ–C1 and C6–7. The collective effect of these differences, segment by segment, can result in differences of 10–30° in total range of cervical motion.

There is no criterion by which to decide which movement strategy should be preferred. It is not a question of standardizing a convention as to which direction of movement should (arbitrarily) be recognized as standard. Rather, the behavior of cervical motion segments simply raises a caveat that no single observation defines a unique range of movement. Since the direction of movement used can influence the observed range, an uncertainty arises. Depending on the segment involved, an observer may record a range of movement that may be five or even 15° less or more the range of which the segment is actually capable. By the same token, claims of therapeutic success in restoring a range of movement must be based on ranges in excess of this range of uncertainty.

The third result is that ranges of movement are not stable with time. A difference in excess of 5° for the same segment in the same individual can be recorded if they are studied by the same technique but on another occasion, particular at segments Occ–C1, C5–6 and C6–7. Rhetorically, the question becomes – which observation was the true normal? The answer is that, within an individual, normal ranges do not come as a single value; they vary with time, and it is variance and the range of variation that constitute the normal behavior, not a single value. The implication is that a single observation of a range must be interpreted carefully and can be used for clinical purposes only with this variance in mind. A lower range today, a higher range tomorrow, or vice-versa, could be only the normal, diurnal variation and not something attributable to a disease or to a therapeutic intervention.

3.7. Cadence

Commentators in the past have maintained that as the cervical spine as a whole moves there must a set order in which the individual cervical vertebra move, i.e. there must be a normal pattern of movement, or cadence. Buonocore et al. [55] asserted that "The spinous processes during flexion separate in a smooth fan-like progression. Flexion motion begins in the upper cervical spine. The occiput separates smoothly from the posterior arch of the atlas, which then separates smoothly from the spine of the axis, and so on down the spine. The interspaces between the spinous processes become generally equal in complete flexion. Most important, the spinous processes separate in orderly progression. In extension the spines rhythmically approximate each other in reverse order to become equidistant in full extension."

This idealized pattern of movement is not what normally occurs. During flexion and extension, the motion of the cervical vertebrae is regular but is not simple; it is complex and counter-intuitive. Nor is it easy to describe. Van Mameren [56] undertook a detailed analysis of his cineradiographs of 10 normal individuals performing flexion and extension of the cervical spine. His descriptions are complex, reflecting the intricacies of movement of individual segments. However, a general pattern can be discerned.

Flexion is initiated in the lower cervical spine (C4–7). Within this block, and during this initial phase of motion, the C6–7 segment regularly makes its maximum contribution, before C5–6, followed by C4–5. That initial phase is followed by motion at C0–C2, and then by C2–3 and C3–4. During this middle phase, the order of contribution of C2–3 and C3–4 is variable. Also during this phase, a reversal of motion (i.e. slight extension) occurs at C6–7 and, in some individuals, at C5–6. The final phase of motion again involves the lower cervical spine (C4–7), and the order of contribution of individual segments is C4–5, C5–6, and C6–7. During this phase, C0–C2 typical exhibits a reversal of motion (i.e. extension). Flexion is thus initiated and terminated by C6–7. It is never initiated at mid cervical levels. C0–C2 and C2–3, C3–4 contribute maximally during the middle phase of motion, but in variable order.

Extension is initiated in the lower cervical spine (C4–7), but the order of contribution of individual segments is variable. This is followed by the start of motion at C0–C2 and at C2–C4. Between C2 and C4 the order of contribution is quite variable. The terminal phase of extension is marked by a second contribution by C4–7, in which the individual segments move in the regular order – C4–5, C5–6, C6–7. During this phase the contribution of C0–C2 reaches its maximum.

The fact that this pattern of movements is reproducible is remarkable. Studied on separate occasions, individuals consistently show the same pattern with respect to the order of maximum contribution of individual segments. Consistent between individuals is the order of contribution of the lower cervical spine and its component segments during both flexion and extension. Such variation as does occur between individuals applies only to the mid cervical levels: C2–C4.

3.8. Instantaneous centres of rotation

Having noted the lack of utility of range of motion studies, some investigators explored the notion of quality of motion of the cervical vertebrae. They contended that although perhaps not revealed by abnormal ranges of motion, abnormalities of the cervical spine might be revealed by abnormal patterns of motion within individual segments.

When a cervical vertebra moves from full extension to full flexion its path appears to lie along an arc whose center lies somewhere below the moving vertebra. This center is called the instantaneous centre of rotation (ICR) and its location can be determined using simple geometry. If tracings are obtained of lateral radiographs of the cervical spine in flexion and in extension, the pattern of motion of a given vertebra can be revealed by superimposing the tracings of the vertebra below. This reveals the extension position and the flexion position of the moving vertebra in relation to the one below (Fig. 13). The location of the ICR is determined by

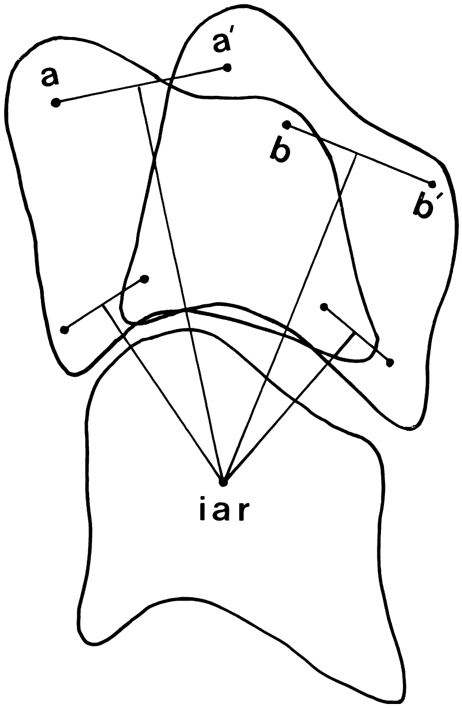

Fig. 13. A sketch of a cervical motion segment illustrating how the location of its instantaneous centre of rotation (ICR) can be determined by geometry.

drawing the perpendicular bisectors of intervals connecting like points on the two positions of the moving vertebra. The point of intersection of the perpendicular bisectors marks the location of the ICR (Fig. 13).

The first normative data on the ICRs of the cervical spine were provided by Penning [9,37,43]. He found them to be located in different positions for different cervical segments. At lower cervical levels, the ICRs were located close to the intervertebral disc of the segment in question but, at higher segmental levels the ICR was located substantially lower than this position.

A problem emerged, however, with Penning's data [9,37,43]. Although he displayed the data graphically he did not provide any statistical parameters such as the mean location and variance; nor did he explain how ICRs from different individuals with vertebra of different sizes were plotted onto a single, common silhouette of the cervical spine. This process requires some form of normalization but this was not described by Penning [9,37,43].

Subsequent studies pursued the accurate determination of the location of the ICRs of the cervical spine. First, it was found that the technique used by Penning [9,37,43,49] to plot ICRs was insufficiently accurate; the basic flaw lay in how well the images of the cervical vertebrae could be traced [57]. Subsequently, an improved technique with smaller inter-observer errors was developed [58] and was used to determine the location of ICRs in a sample of 40 normal individuals [59].

Accurate maps were developed of the mean location and distribution of the ICRs of the cervical motion segments (Fig. 14) based on raw data normalized for vertebral size and coupled with measure of inter-observer errors. The locations and distributions were concordant with those described by Penning [9,37,43] but the new data offered the advantage that because they were described statistically they could be used to test accurately hypotheses concerning the normal or abnormal locations of ICRs.

Some writers have protested against the validity and reliability of ICRs, but the techniques they have used to determine their location have been poorly described and not calibrated for error and accuracy [60]. In contrast, van Mameren et al. [61] have rigorously defended ICRs. They showed that a given ICR can be reliably and consistently calculated within a small margin of technical error. Moreover, in contrast to range of motion, the location of the ICR is independent of whether it is calculated on the basis of anteflexion or retroflexion films; and strikingly the ICR is stable over time; no significant differences in location occur if the ICR is recalculated two weeks or 10 weeks after the initial observation [61]. Thus, the ICR stands as a reliable, stable parameter of the quality of vertebral motion through which abnormalities of motion could be explored.

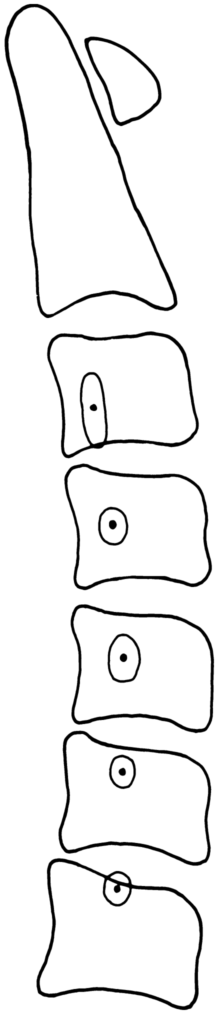

Fig. 14. A sketch of an idealized cervical vertebral column illustrating the mean location and two standard deviation range of distribution of the instantaneous axes of rotation of the typical cervical motion segments.

From above downwards the ICRs are located progressively higher and closer to the intervertebral disc of their segment (Fig. 14). A critical determinant of this progression is the height of the articular pillars [8]. These are low at C2–3 and progressively higher towards C6–7. The height of the superior articular process at a given level predicates how much sagittal rotation must occur in the segment to allow a unit amount of translation [8]. Tall processes preclude translation unless rotation is relatively large. The ratio between translation and rotation determines the location of the ICR (see below).

3.9. Abnormal ICRs

The first exploration of abnormal quality of cervical motion was undertaken by Dimnet and colleagues [62]. They proposed that abnormal quality of motion would be exhibited by abnormal locations of the ICRs of the cervical motion segment. In a small study of six symptomatic patients they found that in patients with neck pain, the ICRs exhibited a wider scatter than in normal individuals. However, they compared samples of patients and not individual patients; their data did not reveal in a given patient which and how many ICRs were normal or abnormal or to what extent.

A similar study was pursued by Mayer et al. [63] who claimed that patients with cervical headache exhibited abnormal ICRs of the upper cervical segments. However, their normative data were poorly described with respect to ranges of distribution; nor was the accuracy described of their technique used to determine both normal and abnormal centres.

Nevertheless, these two studies augured that if reliable and accurate techniques were to be used it was likely that abnormal patterns of motion could be identified in patients with neck pain, in the form of abnormal locations of their ICRs. This contention was formally investigated.

Amevo et al. [64] studied 109 patients with post-traumatic neck pain. Flexion–extension radiographs were obtained and ICRs were determined for all segments from C2–3 to C6–7 where possible. These locations were subsequently compared with previously determined normative data [59]. It emerged that 77% of the patients with neck pain exhibited an abnormally located centre at one segmental level at least. This relationship between axis location and pain was highly significant statistically (Table 6); there was clearly a relationship between pain and abnormal patterns of motion.

Further analysis revealed that most abnormal centres were at upper cervical levels, notably at C2–3 and C3–4. However, there was no evident relationship between the segmental level of an abnormally located ICR and the segment found to be symptomatic on the basis of provocation discography or cervical zygapophysial joint blocks [64]. This suggested that perhaps abnormal ICRs were not caused by intrinsic abnormalities of a painful segment but were secondary to some factor such as muscle spasm. However, this contention could not be explored because insufficient numbers of patients had undergone investigation of upper cervical segments with discography or joint blocks.

Table 6
Chi-squared analysis of the relationship between the presence of pain and the location of instantaneous centres of rotation[a]

	Instantaneous centre of rotation		
	Normal	Abnormal	
Pain	31	78	109
No pain[b]	44	2	46
	75	80	155

[a] $X^2 = 58.5$; df = 1; $P < 0.001$.

[b] $n = 46$, and by definition 96% of these (44) exhibit normal ICRs. Based on Amevo et al. [64].

3.10. Biological basis

Mathematical analysis shows that the location of an ICR is a function of three basic variables: the amplitude of rotation (θ) of a segment, its translation (T), and the location of its center of rotation (CR) [65]. In mathematical terms, with respect to any universal coordinate system (X, Y), the location of the ICR is defined by the equations:

$$X_{\mathrm{ICR}} = X_{\mathrm{CR}} + T/2,$$

$$Y_{\mathrm{ICR}} = Y_{\mathrm{CR}} - T/[2\tan(\theta/2)],$$

where (X_{ICR}, Y_{ICR}) is the location of the ICR, and (X_{CR}, Y_{CR}) is the location of the center or reaction.

In this context, the center of reaction is a point on the inferior endplate of the moving vertebra where compression loads on that vertebra are maximal, or the mathematical average point where compression loads are transmitted from the vertebra to the underlying disc. It is also the pivot point around which the vertebra rocks under compression, or around which the vertebra would rotate in the absence of any shear forces that add translation to the movement [65].

The equations dictate that the normal location, and any abnormal location, of an ICR is governed by the net effect of compression forces, shear forces and moments acting on the moving segment. The compression forces exerted by muscles and by gravity, and the resistance to compression exerted by the facets and disc of the segment determine the location of the center of reaction. The shear forces exerted by gravity and muscles, and the resistance to these forces exerted by the intervertebral disc and facets determine the magnitude of translation. The moments exerted by gravity and by muscles, and the resistance to these exerted by tension in ligaments, joint capsules and the anulus fibrosus determine the amplitude of rotation.

These relationships allow the location of an ICR to be interpreted in anatomical and pathological terms. Displacement of an ICR from its normal location can occur only if the normal balance of compression loads, shear loads, or moments is disturbed. Moreover, displacements in particular directions can occur only as a result of certain, finite, combinations of disturbances to these variables. For example, the ICR equations dictate that downward and backward displacement of an ICR can occur only if there is a simultaneous posterior displacement of the center or reaction and a reduction in rotation [65]. Mechanically, this combination of disturbances is most readily achieved by increased posterior muscle tension. On one hand, this tension eccentrically loads the segment in compression, displacing the center or reaction posteriorly; meanwhile, the increased tension limits forward flexion and reduces angular rotation. An abnormal ICR, displaced downwards and backwards is, therefore, a strong sign of increased posterior muscle tension. Although the tension is not recorded electromyographically or otherwise, its presence can be inferred from mathematical analysis of the behavior of the segment. Although the tension is not "seen", the effects of its force are manifest (just as the presence of an invisible planet can be detected by the gravitational effects it exerts on nearby celestial bodies).

Upward displacement of an ICR can occur only if there is a decrease in translation, or an increase in rotation, all other variables being normal. This type of displacement of displacement is most readily produced if flexion–extension is produced in the absence of shear forces, i.e. the segment is caused to rotate only by forces acting essentially parallel to the long axis of the cervical spine. This type of movement occurs during the early phases of whiplash [66], and will explored in a later review.

3.11. Applications

A major, but clinically unexciting, application of ICRs is in the field of biomechanical modeling. A challenge for any model is validation. For a model to operate, estimates need to be applied of the forces acting on the vertebrae, such as the compression stiffness of the discs, tension in the capsules and ligaments, and the action of muscles. But these estimates usually stem from a variety of separate sources. There is no guarantee that when combined into a single model they accurately reflect what happens in a normal cervical spine. One test, however, is to determine the ICRs produced by the model as the neck moves.

If the estimates of forces are wrong, their net effect will be to execute movements about abnormal ICRs. Conversely, if the resultant movements occur about normal centres of movement, investigators can be confident that their estimates of forces are realistic. Although possible, it seems highly improbable that incorrect estimates would accidentally combine to produce correct ICRs at all segments simultaneously.

This approach to validation has been used to good effect in the most detailed model of the cervical spine developed to date [67]. The model generates normal ICRs at lower cervical segments; but errors obtain at upper cervical segments. This calls for a refinement of the forces exerted across upper cervical segments, in terms of the magnitude or direction of the vectors of the upper cervical muscles, or the details of upper cervical vertebral geometry.

More relevant clinically is the potential application of ICRs in cervical diagnosis. To date, it has been firmly established that abnormal ICRs correlate with neck pain [64]. However, the abnormal ICRs do not necessarily lie at the symptomatic segment. Therefore, they do not reflect damage to that segment. Rather, abnormal ICRs seem to reflect secondary effects of pain.

Theoretically, it is possible to apply the ICR equations to resolve, case by case, whether an abnormal ICR is due to muscle spasm, impairment of ligament tension, or altered compression stiffness of the disc. The necessary studies, however, have not yet been conducted. For interested clinicians, this field remains open.

Appendix A. The relationship between horizontal rotation and rotation in the plane of the cervical facets

In a plane orientated at an angle of $\theta°$ to the horizontal plane (Fig. 15), point P rotates to P' through and angle $PAP' = \psi$, about an axis at A perpendicular to the plane of motion. $AP = AP'$, and is the radius of rotation in the plane of motion. If P is set to lie in the horizontal plane, Q is the projection of P' in that plane. In the horizontal plane, P appears to rotate to Q through an angle $QAP = \alpha$. R is the perpendicular projection of Q to AP, and by definition $P'RA$ is a right angle.

In $\Delta RP'A$, $AR = P'A \cdot \cos\psi$.
In ΔQRA, $QR = AR \cdot \tan\alpha$.
Therefore, $QR = P'A\cos\psi \cdot \tan\alpha$.
In $\Delta QP'R$, $QR = P'R\cos\theta$.
In $\Delta RP'A$, $P'R = P'A \cdot \sin\psi$.
Therefore, $QR = P'A \cdot \sin\psi \cdot \cos\theta$.
Whereupon, $P'A\cos\psi \cdot \tan\alpha = P'A \cdot \sin\psi \cdot \cos\theta$
and $\tan\alpha = \tan\psi \cdot \cos\theta$.

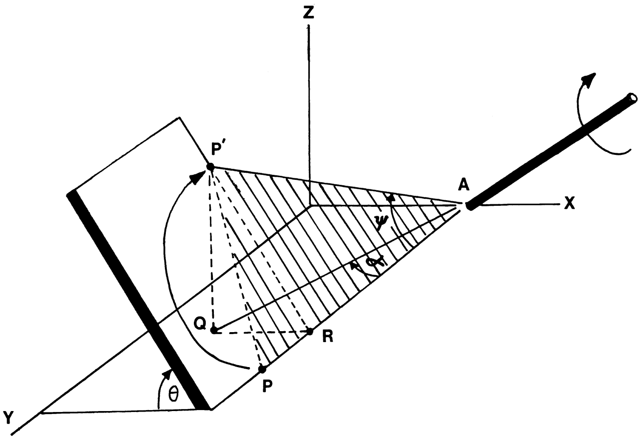

Fig. 15. In an X, Y, Z coordinate system, the plane of a zygapophysial joint is orientated at $\theta°$ to the horizontal (X, Y) plane. A point P rotates in the plane of the joint to P' through an angle ψ about an axis at A set perpendicular to the lane of the joint. In the horizontal plane, the rotation of P is projected as a rotation from P to Q through an angle α.

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