# Chapter 25
# Biomechanical Considerations for Stabilization of the Craniovertebral Junction

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The goal of surgery for stabilization of the craniovertebral junction (CVJ) is to restore biomechanical stability with minimal compromise of physiological range of motion. The CVJ, comprising the basiocciput, atlas, and axis, is highly mobile, contributing to more than half of spinal axial rotation and making major contributions to flexion-extension, particularly at C1-2 and C0-1, respectively. This article discusses the normal biomechanics of the CVJ, the effect of pathology on these normal relationships, and the role of instrumentation in restoring stability.

## NORMAL BIOMECHANICS OF THE CVJ

Biomechanically, motion at any given vertebral segment can be fully described by angular movements around three orthogonal axes in addition to linear displacements along the same axes. Clinically, for axes x, y, and z, where the x axis lies in the axial plane, y lies in the coronal plane, and z in the sagittal plane, angular movements around the x, y and z axes correspond to flexion-extension, axial rotation, and lateral bending, respectively. Linear movements are manifested clinically as subluxations and, in the case of the y axis, as vertical displacement or distraction (Fig. 25.1A).

This range of motion is divided into neutral and elastic zones. The neutral zone corresponds to the midpoint of the range of bilateral deflections that occurs in response to minimal forces. The elastic zone, in contrast, is that which occurs at the limits of the range of motion because greater forces are required for marginal movements of the joint. According to Panjabi (21), pathological increases in neutral zone motion are reflective of instability. Biomechanical experiments have corroborated that after destabilizing procedures, the largest component of increased motion occurs in the neutral zone.

Any given bending movement of one vertebral body on another can be described by its instantaneous axis of rotation (Fig. 25.1B). This is the point in a given plane where motion at that point in time occurs. The sum of the instant axes of rotation is called the centrode of the axis of rotation. The centrode also corresponds anatomically to the site of greatest stress forces. Consequently, if the centrode is displaced from its physiologic location (as occurs in instability or may occur in spinal fixation), abnormal stress is placed on anatomical structures not adapted for this function. For example, the dens of the axis is the location for the centrode of the axes of rotation for axial rotation of C1 on C2. After transoral odontoidectomy, the axis of rotation for axial rotation of C1 on C2 becomes diffuse, reflecting the unconstrained movement of C1 on C2 and coupling of translational movements with axial rotation. Instrumentation tends to displace the axis of rotation in a given plane toward the hardware as occurs during flexion and extension after posterior wiring. The implications of this phenomenon are discussed in greater detail below.

The physiologic ranges of motion of the atlantooccipital and atlantoaxial articulations are heavily influenced by the anatomy of their respective joints (Fig. 25.2). The occipital condyles are relatively rounded structures that articulate with the cup-shaped upper surfaces of the C1 lateral masses, forming “ball and socket” joints that allow moderate sagittal deflections (i.e., flexion-extension) but severely limit the degree of axial rotation or lateral bending. In the normal state, 21 degrees of flexion and 3.5 degrees of extension occur at C0-1. This is the largest contribution to flexion and extension from any single motion segment in the cervical spine. As one could predict from the anatomy of the joint, lateral bending and axial rotation are much more restricted at 5.5 and 7.2 degrees, respectively. In contrast, the articular surfaces of C1 and C2 are both convex, allowing a much greater degree of freedom at C1-2 for axial rotation around the dens, as well as lateral bending and flexion-extension. Although not as prominent of a contribution to flexion and extension is made at this level compared with C0-1 (12.5 and 13.1 degrees, respectively), the extent of lateral bending (6.7 degrees) and especially of axial rotation (38.8 degrees) is much greater. The latter accounts for approximately half of all axial rotation of the cervical spine.

The stability of the bony articulations of the CVJ is determined by ligaments that constrain the movements of the CVJ articulations. The attachments of the ligaments at the CVJ are complex, but they can be simplified into four broad categories: the odontoid-specific ligaments, the articular ligaments, and the ligaments of the anterior and posterior columns (3). The odontoid-specific ligaments, especially the alar ligaments and transverse-atlantal ligament, are the most important for CVJ stability. Other odontoid-specific ligaments, such as the apical ligament, atlantodental ligament, and atlantoalar ligaments, perform accessory roles. The alar ligaments run laterally from the odontoid to the occipital condyle. Their function is to limit axial rotation between C2 and C0. The transverse-atlantal ligament is the horizontal portion of the cruciate ligament, which is the strongest and thickest ligament in the spine. Its biomechanical role is to limit the anterior movement of C1 on C2, preventing anterior translation and flexion. Disruption of these ligamentous structures destabilizes the CVJ.

## BIOMECHANICS OF CVJ PATHOLOGY

Instability of the CVJ can be congenital (as in Down’s syndrome or skeletal dysplasias) or can occur secondary to destructive lesions such as infections, tumor, or rheumatoid arthritis. Traumatic injury to the bony or ligamentous elements of the CVJ can also cause instability, such as that which occurs in odontoid fractures and atlantoaxial and atlantooccipital dislocations. Finally, instability can occur iatrogenically as a result of surgery (e.g., after transoral odontoidectomy or far-lateral skull base exposures).

Pathology can affect CVJ biomechanics and kinematics in a number of ways. The best understood alterations in kinematics of the CVJ are those that result from iatrogenic injury (e.g., after odontoidectomy). A rational approach to stabilization of the CVJ is possible with a thorough understanding of how the normal biomechanics change in response to established models of CVJ instability. For example, type II odontoid fractures, os odontoideum, and transverse-atlantal ligamentous disruption are all functionally analogous to transoral odontoidectomy. Biomechanically, they are characterized by the disconnection of C1 from its axis of rotation around the dens. The biomechanical effect of odontoidectomy was studied in vitro by Dickman et al. (5). Clinically, patients become overtly unstable after transoral odontoidectomy, requiring fusion (7). After odontoidectomy, Dickman et al. (5) found statistically significant increases in flexion, extension, and lateral bending (Fig. 25.3). Flexion increased 70.8%. Extension increased 104%. Lateral bending increased an average of 95%. The neutral zone contributed almost extensively to these increases in range of motion. However, the overall increase in range of motion for axial rotation did not increase significantly, possibly because the degree of axial rotation at C1-2 is so high already. Further axial rotation is impeded by the capsular ligaments of the C1-2 facets joints, which were not destabilized experimentally. However, the axes of rotation for axial rotation were profoundly deranged by odontoidectomy (Fig. 25.4). Before resection, the centrode of the axes of rotation for axial rotation was tightly centered around the dens. After odontoidectomy, the centrode was diffuse across almost the entire body of C2, reflecting the disorganized, unconstrained, and hypermobile motion at the joint after resection of the physiological axis of rotation—the dens.

Furthermore, significant translational instability occurred after odontoidectomy. Linear deflections (i.e., subluxations) were less than 1 mm in all directions before odontoidectomy. After odontoidectomy, mean subluxations in the human cadaveric specimens were 12.7 mm, 6.7 mm, and 2.0 mm in the anteroposterior, lateral, and superior-inferior directions, respectively. Similar analyses have been performed to evaluate biomechanical instability resulting from atlas fractures (22) and atlantooccipital instability after occipital condyle resection (29). Controlled traumatic fractures of the atlas were associated with a 44% increase in the range of motion during flexion-extension and a 20% increase in lateral bending. As occurred after odontoidectomy, the increase in range of motion during flexion and extension was disproportionately related to a 90% increase in the neutral zone. Resection of the occipital condyle is associated with overt atlantooccipital instability. When 50% of the condyle was resected, the range of motion increased 153% during flexion and extension, 40.8% during lateral bending, and 28.1% during axial rotation. Interestingly, condylectomy was also associated with increased range of motion at C1-2, although not significantly, when the condyle was resected less than 75%.

As mentioned earlier, disruption of the stabilizing ligaments of the CVJ, with or without bony injury, is sufficient to destabilize the CVJ. Biomechanically, disruption of the transverse-atlantal ligament functions in a manner equivalent to an odontoidectomy. The transverse-atlantal ligament is the predominant stabilizer of the atlas, constraining the dens against the anterior tubercle of C1. When the ligament is ruptured, the axes of rotation become unconstrained and mobile, as is the case after odontoidectomy. Alar ligament disruption is associated with modest increases in axial rotation if the disruption is unilateral. Bilateral alar ligament injury, however, significantly increases axial rotation, lateral bending, and flexion-extension (20). Finally, in a model of occipitoatlantal dislocation, severing the ligamentous attachments of the occiput while sparing the condyle-C1 joint capsules produced such overt, gross instability of the CVJ that it could not be quantitated (11).

## BIOMECHANICS OF CVJ FIXATION

There are many different approaches to instrumentation of the CVJ (2). Screw-plates (10), screw-rods, wires with threaded (1) or smooth contoured rods, transarticular screws (9), laminar hooks, and any combination of the above are available. The choice of technique is influenced by a priori biomechanical principles and by the realities of a given patient's anatomy, which may make one or another technique attractive or impossible. Where there is biomechanical equipoise between two or more alternate fixation strategies, the choice of instrumentation may be dictated by the surgeon's preference and comfort level. This section discusses some of the general biomechanical considerations of fixation of the CVJ and details the specific biomechanics of fixation strategies for the atlantoaxial and atlantooccipital joints, respectively.

### Anterior versus Posterior

Few authors advocate anterior fixation of the CVJ at the time of ventral decompression (e.g., odontoidectomy). Traditionally, anterior instrumentation has been reserved as a salvage strategy for failed posterior fusions for two reasons (4). First, the transoral approach is associated with increased risks of infection related to the hardware. Second, anterior fixation of the CVJ is biomechanically inferior to posterior fixation.

Kanziora et al. (14) demonstrated that anterior Harms plating was significantly biomechanically inferior to both posterior transarticular screws and to Harms plating used in conjunction with a Brooks fusion. Kim et al. (15) found that anterior Harms plating failed to restore biomechanical stability during flexion-extension and lateral bending to that of the intact spine. That anterior Harms plating is a less stable construct for C1-2 fixation could be predicted from a biomechanical perspective. The proximity of the plate to the axis of rotation during flexion exposes the plate to very large moments, and thus to a greater likelihood, of failure. Anterior fixation is also limited because of difficulties with graft anchorage and applied mechanical loads.

In contrast, posterior wiring techniques take advantage of the distance between the site of fixation and the anterior axis of rotation. The construct functions as a lever arm, augmenting the tension band and buttress effects of interspinous fusion. Thus, as one would expect from a priori biomechanical principles and experimental data, anterior fixation strategies are less likely to provide sufficiently rigid fixation for CVJ stabilization and should be reserved as salvage techniques only.

The one exception to this rule is anterior odontoid screw placement. For type II odontoid fractures, direct fracture reduction via an anterior screw is the preferred means of fracture fixation because it preserves normal C1-2 mobility. This is true, even though anterior transoral odontoid screw fixation only restores approximately 50% of the stability of the intact dens. Sasso et al. (28) found that biomechanically, one and two screw techniques for odontoid screw fixation were surprisingly equivalent. They attributed the absence of a significant difference to the relatively greater role in restoring stability played by reduction of the fracture itself. In either case (i.e., one or two screws), failure loads occurred at levels beyond the failure load threshold of the screws themselves. We prefer a single cannulated odontoid screw for fixation of type II odontoid fractures with a hard cervical orthosis to supplement immobilization of the dens.

Screws versus Wires

Several constructs have been used for CVJ stabilization using sublaminar wires or braided cables to fixate C1 and C2 with incorporation of a bone graft that acts as a posterior buttress. The Brooks and interspinous fusions have the advantage of placing the graft under compression. A transarticular screw technique developed by Magerl and introduced for C1-2 fusion can be used with posterior graft wiring to obtain a three-point fixation construct. Both cable and screw techniques can be extended cranially to the occiput or inferiorly as required. Wires or cables and screws engage the bone in different ways, the mechanical properties of the hardware differ, and they distribute loads on the fusion construct differently (13). Although these techniques can be used to complement one another, an understanding of the intrinsic biomechanical differences between wire and screw constructs can aid in approaching fixation of the CVJ.

In general, screw fixation is biomechanically superior to wire or cable fixation. Unlike cables or wires, which fixate the bone through a cerclage effect, screws rigidly engage bone. The holding power of a screw is a function of both its physical properties and the characteristics of the adjacent bone. When a screw fails, it can do so in two ways: either pull out or break/bend. The pull-out strength of a screw is proportional to its major diameter and length. Its bending strength is proportional to the cube of its inner diameter. However, the bone-screw interface is the weakest point of screw fixation (i.e., screw fixation is only as good as the underlying bone).

The disadvantages of screws include the potential for neurovascular injury, such as injury to the vertebral artery in the sulcus arteriosus or to the hypoglossal nerve in C1-2 and C0-1 transarticular screws, respectively. Occipital screws risk penetration of the inner table of the calvarium or the dura. These potential complications can be minimized with careful preoperative planning and measurement of the appropriate distances for screw trajectories. Although biomechanically superior, placement of screws is sometimes contraindicated by anatomy. Paramore et al. (23) found that as many as 23% of at least one side of C2 vertebral bodies were inappropriate for transarticular screw placement because of high-riding transverse foramina.

Dickman et al. (8) tested the mechanical properties of eight different monofilament, multifilament, steel, titanium, and polyethylene wire constructs for C1-2 fusion. Steel cables and multifilament cables were stronger than monofilaments and titanium. Polyethylene cable is nonabrasive, conforms to the bone, and exhibits superior fatigue strength. However, unlike metal wires, polyethylene experiences significant creep. All of the wire constructs tested were clinically acceptable to promote fusion. However, if cables are used alone, a halo brace is required to provide additional stability. We prefer titanium braided cable because of its compatibility with imaging. Polyethylene can be superior for soft or cartilaginous bone if used with a rigid orthosis to prevent creep.

No matter how rigid the instrumentation is, the fixation construct will be predisposed to failure if the underlying bone stock is compromised. Similarly, weak or osteopenic bone is subject to abrasion by wires. Thus, in the setting of poor bone quality, as is often found in patients with rheumatoid arthritis, we recommend that a rigid cervical orthosis be used as an adjunct to promote fusion.

### Bone Grafts

Even the most solid fixation construct will fail if bony fusion does not occur. Requirements for arthrodesis include rigid immobilization, a vascularized tissue bed to promote graft incorporation, and autogenous bone graft. Iliac crest, rib (2), and calvarium (27) have all been used with CVJ fusion. The inclusion of an interspinous autogenous bone graft, whether as a stand-alone construct or used in conjunction with screw- or hook-based techniques, provides an ideal substrate to promote bony fusion because the graft is placed under compression.

## BIOMECHANICS OF C1-2 FIXATION

Approaches to fixation of the atlantoaxial joint fall into three categories: posterior wiring techniques, C1-2 transarticular screws, and C1 lateral mass/C2 pars interarticularis or pedicle polyaxial screws used with a rod or plate (Fig. 25.5). As previously discussed, anterior approaches are biomechanically inferior and are not advocated.

Dickman et al. (6) compared Gallie, Brooks, and interspinous fusions and found that no wiring technique used alone provides truly rigid fixation in any direction. All three constructs experienced significant fatigue and allowed large amounts of rotation and subluxation to occur. Posterior wiring techniques resisted flexion and extension, especially when an interspinous bone graft (i.e., Brooks or interspinous fusions) was incorporated. The interspinous graft acts as an additional buttress in resisting extension.

In contrast, transarticular screws provide rigid fixation in all directions. Their use reduces the range of motion 61.4%

during flexion, 82.7% during lateral bending, and 94.8% during axial rotation. Placement of transarticular screws, however, is limited by unsuitable anatomy in as many as 23% of cases (23). When transarticular screws cannot be placed, the combination of C1 lateral mass and C2 polyaxial screws, connected by either a rod or plate, can be used. Biomechanically, the overall rigidity of C1 lateral mass and C2 pars screws is similar to that achieved with transarticular screws (16). However, lateral mass and pars interarticularis screws allow statistically greater axial rotation than transarticular screws (25). This finding has been attributed to the four cortical surfaces that the transarticular surfaces cross (18). C1-2 polyaxial screws are especially useful when the C1-2 articulation has been compromised by pathological processes such as a tumor or infection. Lateral mass screws used with pars interarticularis or pedicle screws also permit reduction of a deformity. Finally, C1-2 transarticular screws can be used unilaterally in combination with C1 lateral mass and C2 pars screws when the C1-2 articulation is compromised unilaterally (12).

Naderi et al. (17) compared wiring to screw constructs for atlantoaxial fixation. Increasing from one to two and from two to three points of fixation significantly increased stability. Importantly, three-point fixation, whether the third point was a second screw or the addition of a cable graft to two screws, significantly decreased both translational and angular movement. The addition of an interspinous fusion, which provides better control of flexion and extension, to transarticular screws, which provide better control of lateral bending and axial rotation, was the most stable construct in all directions. Moreover, with one or two point fixation, the axis of rotation was shifted toward the hardware during axial rotation (caudally or anteriorly). With three-point fixation, the axis of rotation was maintained closest to normal. They concluded that it is mechanically advantageous to include as many fixation points as possible.

## BIOMECHANICS OF C0-1 FIXATION

CVJ fixation can be extended to the occiput with cables or “inside-out” screws (19) or by placing screws directly in the occipital bone. Hurlbert et al. (13) compared occipitocervical wiring techniques with and without incorporation of C1 to different screw-based fixation constructs, including the Cotrel-Dubousett horseshoe, rod-loops, and a combined transarticular screw and occipital plate (the OCTA screw-plate). The Steinmann pin allowed the most motion (including 4–6 mm of vertical displacement) followed by combined wiring and plating (the CD rod-plate). Complete screw-based techniques (both the rod-loop and OCTA plate) were the most stable. Wiring techniques were the most susceptible to fatigue. Perhaps most important, screw-based techniques reduced the number of vertebral motion segments that needed to be incorporated into the fusion construct while providing superior rigidity of fixation and resistance to fatigue. They concluded that screw fixation is superior to all types of cable fixation. The key determinant of stability was the presence of screw purchase into both the occiput and the atlantoaxial complex.

Roberts et al. (26) found that although the thickness of the occipital bone varies, its thickness is significantly greater in the midline than in its lateral portions. Given that pull-out strength is related to the length of bone engaged by the screw, the strength of occipital screws was directly associated with the thickness of the bone. In bone thicker than 7 mm, there was no difference in the strength of cortical or cancellous screws. In fact, the pull-out strength of screws placed in the midline keel of the occipital bone was greater than the failure load of the screws themselves. Failures occurred more from screw breakage than pull out per se, as long as at least 7 mm of bone was engaged.

Oda et al. (18) measured the stiffness of five different occipitocervical fusion constructs. They compared occipital-sublaminar wiring with rods to occipital midline screw and “Y” plating, six lateral occipital screws and C2 pedicle screws, and a combination of wiring, foramen magnum screws, and hooks. Across the occipitocervical junction, hook or wire constructs or both consistently demonstrated the least stiffness; there was no significant difference between them. During anterior-posterior translation, wiring constructs were not significantly different than in the destabilized state. In contrast, both Y plating with midline occipital screws connected to C1-2 transarticular screws and lateral occipital screws used with C2 pedicle screws significantly increased stiffness. The most stable construct was C2 pedicle screws combined with six lateral occipital screws. However, this construct was superior to transarticular screws-based techniques only during axial rotation and anterior-posterior translation.

Puttlitz et al. (24) directly compared C1-2 transarticular screws and occipital plating (with lateral occipital screws) to polyaxial C1 lateral mass screws, C2 pedicle screws, and midline occipital screws with rods. Both methods provided rigid fixation of the CVJ, reducing the range of motion of the occipital-to-C2 motion segments by 96.5% during flexion-extension and reducing lateral bending from 33.9 degrees to 1.3 degrees and 2.4 degrees, respectively. Both methods reduced axial rotation from 86.7 degrees to 2.6 degrees. There were no statistical differences among the stability of either the transarticular screws plus plate construct versus the C1 lateral mass, C2 pedicle screw, and rod constructs. Plating diminished motion at the C2-3 motion segment, which the authors attributed to compromised motion at the subjacent vertebral level (i.e., C2-3) caused by the plate overhanging the C2-3 facet. This variable, however, did not reach statistical significance.

Given that the goal of CVJ stabilization is to provide stability with minimal compromise of physiologic range of motion, strategies that fixate C0-1 without incorporating C2 would be more desirable alternatives than occipitocervical fusion constructs that incorporate the occiput as an extension of atlantoaxial fixation techniques. Although in practice the indications for isolated C0-1 fixation are limited, we used transarticular C0-1 screws to stabilize the CVJ after traumatic occipitoatlantal dislocation (Fig. 25.6). In this case, the transverse-atlantal ligament was intact on magnetic resonance imaging, and the extent of injury was limited to the occipital condyle-C1 articulation.

Biomechanical analysis of C0-1 transarticular screws performed at our institution has shown that C0-1 transarticular screws provide significant CVJ rigidity during lateral bending and axial rotation that was equivalent to occipitocervical screw-plates (Fig. 25.7). C0-1 transarticular screws did not reduce flexion by 74.6% and extension by 80.5%. However, they also do not significantly reduce the elastic zone during flexion when compared with normal specimens. Although C1-0 screws are probably not advantageous as an adjunct to occipitocervical plating, they are sufficiently rigid to be used as stand-alone instrumentation (in conjunction with a halo orthosis) to allow C0-1 fusion to occur, thereby preserving C1-2 motion.

## CERVICAL ORTHOSES

External orthoses continue to play an important role in the neurosurgical management of occipitocervical instability, despite the relatively modest biomechanical immobilization provided by any device other than a halo brace (Fig. 25.8). We favor halo immobilization as an adjunct to instrumentation, particularly when bone quality is poor or when rigid immobilization is not obtained through instrumentation alone, such as with wiring techniques.

## CONCLUSION

Understanding the kinematics and biomechanics of the normal and destabilized CVJ is critical for rational surgical planning and to optimize surgical outcomes. As elsewhere, basic general principles of fixation, such as the importance of rigid immobilization for fusion, the impact of bone quality on fixation, and the advantages of screw fixation over wire fixation, apply in this region. Because the anatomy of the CVJ is unique, posterior approaches are preferable to anterior approaches, such as those frequently used in the subaxial spine. Similarly, because of the high degree of mobility and pseudarthrosis at the CVJ, a premium is placed on the use of the three-point fixation, which consists of rigid screw fixation in conjunction with interspinous autogenous bone grafts, when possible. Ongoing research is assessing the biomechanical merits of recent advances in CVJ instrumentation, such as C1 lateral mass and C2 pedicle and pars interarticularis screws, as well as ways of fixating the CVJ that provide immediate rigid fixation while preserving the maximal amount of normal motion segments.

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Fig. 25.1 A, cartesian coordinate system for the description of spinal motion. Arrows indicate the six degrees of rotational and translational motion of the vertebrum. B, instantaneous axes of rotation measured experimentally in a cadaver. Note the cluster of the instantaneous axes at the level of the dens (the centrode). Courtesy of Barrow Neurological Institute, Phoenix, Arizona.

Fig. 25.2. A, coronal and, B, lateral views illustrate the “cup and socket” nature of the C0-1 articulation and the biconvexity of the C1-2 articulation. Courtesy of Barrow Neurological Institute, Phoenix, Arizona.

Fig. 25.3. After transoral odontoidectomy, increases are seen in all, A, rotational and, B, translational axes of motion. Courtesy of Barrow Neurological Institute, Phoenix, Arizona.

Fig. 25.4. Distribution of the instantaneous axes of rotation (centrode) during axial rotation before and after transoral odontoidectomy. Courtesy of Barrow Neurological Institute, Phoenix, Arizona.

Fig. 25.5. C1-2 fixation can be achieved with either wire-based approaches such as, A, interspinous fusion or, B, screw-based techniques such as C1-2 transarticular screws or C1-2 polyaxial screws and rod construct. Three-point fixation is obtained by combining a screw-based approach with interspinous fusion (not shown). Figure 5A is courtesy of Barrow Neurological Institute, Phoenix, Arizona. (Figure 5B from, Gonzalez LF, Theodore N, Dickman CA, Sonntag VKH: Occipitoatlantal and atlantoaxial dislocation. Operative Techniques in Neurosurgery 7:16–21, 2004.)

Fig. 25.6. Sagittal computed tomography reconstruction demonstrating occipitoatlantal dislocation, A, before and, B, after reduction with internal fixation with C0-1 transarticular screws. Courtesy of Barrow Neurological Institute, Phoenix, Arizona.

Fig. 25.7. Angular motion at, A, C0-1 and, B, C1-2 for C0-1 for the described combinations of transarticular screws with or without OCTA plating or OCTA plating alone. Full columns represent total range of motion (ROM). Horizontal bars demarcate the elastic zone from the neutral zone. Error bars indicate the standard deviation of the ROM. (From, Gonzalez LF, Crawford NR, Chamberlain RH, et al: Craniovertebral junction fixation with transarticular screws: Biomechanical analysis of a novel technique. J Neurosurg 98:202–209, 2003.)

Fig. 25.8. Kinematic comparison of several different cervical orthoses. Note that halo brace fixation is superior in providing rigid immobilization when compared to other cervical orthoses. Courtesy of Barrow Neurological Institute, Phoenix, Arizona.