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BIOMECHANICS

Part of "32 - FRACTURES OF THE UPPER CERVICAL SPINE"

Normal Functional Anatomy

The three bony components of the upper cervical spine, consisting of skull base, atlas, and axis, form an integrated functional unit. The unconstrained five joints of the upper cervical spine entirely rely on an intact, multilayered ligamentous check rein and muscular control for stability. With this arrangement, the upper cervical spine contributes a substantial portion of neck motion by means of complex, still incompletely understood joint kinematics. With its relatively large, loose fitting joints, the upper cervical spine enables rapid response, large-scale head excursion, while the design of the lower cervical spine articulations and muscles seems to be suited for a fine adjustment type of projection of the head.

Using cadaveric studies and rotational CT scans in cadaver specimens, Dvorak and colleagues (35) quantified the contributions of the upper cervical spine to overall neck motion at approximately 60% of rotation, 40% of flexion-extension, and 45% of overall neck motion. The normal axial plane C1–2 rotational excursion amounts to 80 to 88 degrees from left to right. The C0–1 and C1–2 flexion/extension excursion is similar for both joints at 20 to 30 degrees at each level. Total left to right lateral bending at the C1–2 segment amounts to 20 degrees, as opposed to 5 to 10 degrees at the C0–1 joint (25,97). This amount of motion requires strong ligamentous support to avoid excessive motion and structural failure in an area containing highly vulnerable neurovascular structures.

The alar ligaments play a key role in protecting normal craniocervical motion. With an average *in vitro* load to failure of 210 N, however, these vitally important ligaments tolerate less than half of the load to failure compared to the cruciate ligaments of the knee (36). The fibers within each alar ligament are arranged in a multiplanar fashion, rostrally originating from the medial surfaces of the occipital condyles and converging in a **V**-shaped fashion on either side of the tip of the odontoid process. This complex composition allows the alar ligaments to serve a variety of functions. At midposition of the head these ligaments are slack. The alar ligaments are the primary restraint in limiting rotation of the occipitoaxial motion unit. By turning the head in one direction, the alar ligament contralateral to the direction of turning tightens, while the ipsilateral ligament slackens. Together with the tectorial membrane the alar ligaments limit flexion; however, they play no role in limiting extension. The contralateral alar ligament limits lateral bending. By sectioning one alar ligament in a cadaveric model, an increase of flexion, rotation, and lateral bending approximating 30% to 40% in each direction can be expected (97) (Fig. 32-13).

Important other ligamentous stabilizers of the craniocervical junction are the cranial portions of the anterior and posterior longitudinal ligaments of the spine as well as joint capsules of the respective articulations. Anteriorly, the well-developed atlanto-occipital membrane limits extension, with the thinner anterior atlantoaxial membrane contributing to a less significant degree. The broad tectorial membrane effectively limits axial distraction and atlanto-occipital flexion.

Supplemental ligamentous support of the craniocervical junction is provided by a number of smaller ligaments, such as the apical and cruciate ligaments, the obliquely aligned accessory atlantoaxial ligaments, the anterior atlantodental ligament, and the facet joint capsules.

The prime stabilizing ligament of the atlantoaxial motion unit is the cruciate ligament complex with the TAL. Its *in vitro* load to failure is 350 N (36). With the TAL crossing the odontoid at its waist level, atlantoaxial flexion, translation, and distraction are minimized, yet rotation is allowed. In flexion, the

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cruciate ligament is placed under tension, thereby preventing the odontoid from pushing into the spinal cord.

The specific arrangement of ligaments at the craniocervical junction utilizes the atlas as a washer or base for a coupled, multiplanar motion. The ligamentous anchors of this arrangement extend from the bony elements surrounding the foramen magnum to the odontoid.

Pathologic Conditions

The combination of a high degree of motility on the basis of relatively delicate ligamentous and bony structures makes the upper cervical spine susceptible to injury from indirect high-energy trauma. This circumstance was used around the world for judicial hanging in the hope of achieving instant and painless death. Postmortem studies have shown fracture-dislocations of the craniocervical junction to also be the leading cause of death of motor vehicle crashes (5,18). The rate of loading, direction of force vectors, and anatomic factors account for the high degree of variability of injuries seen in this anatomic region.

The atlas is the most fragile vertebral segment in humans, since it will fracture with as little as 1 to 2 mm of deformation. It is especially susceptible to bursting-type fractures with relatively low axial loads. Transverse ligament integrity played no significant factor in the amount of load to failure tolerated by the atlas ring in a cadaveric study (9). Due to its propensity for fractures, the atlas ring has an indicator function as a red flag for the presence of spine injury elsewhere. The two most vulnerable bony structures of the axis are the pars interarticularis and the odontoid waist. Forced hyperextension can lead to failure of either structure. Flexion is believed to be causative in 80% of odontoid fractures by forcing the transverse ligament against the odontoid (23).

Ligamentous instability of the craniocervical junction can be subtle; however, it can lead to grave consequences if left undetected. Intact atlanto-occipitocervical ligamentous structures usually allow not more than 5 degrees of rotation and not more than 1 to 2 mm diastasis (35). The alar ligaments are at highest risk for traumatic rupture with the head in a flexed and rotated position. Atlantoaxial rotation of more than 50 degrees in either direction as measured by CT scan is suspicious for alar ligament insufficiency; more than 56 degrees is diagnostic of disruption (34). An intact transverse ligament limits anterior subluxation of the atlas relative to the axis to 3 mm in adults and 5 mm in children (36). Similarly, more than 5 degrees of atlantoaxial flexion is highly indicative of transverse ligament insufficiency (36). If atlantoaxial translation exceeds 9 mm in adults, comprehensive failure of all key craniocervical ligaments has to be assumed.