The C1-2 joint is unique and is responsible for more than 50% of the neck rotation. The joints have an ergonomic design that allows maximum motion without getting dislocated. It provides six degrees of freedom, the maximum being axial rotation, and is a marvel of nature’s engineering. The morphometry of lateral masses of C1 and C2 joints was analyzed to explain the possible movements despite minor variations. The normal morphometry was compared with the joints of individuals with congenital atlantoaxial dislocation. The structural flaws were assessed to understand the forces leading to dislocation in various planes. The surgical correction of such flaws and engineering involved has been discussed. The joints of patients with congenital atlantoaxial dislocation are deformed and the lateral masses are trapezoidal as compared to the cuboidal lateral masses of normal individuals. The orientation of joints decides the direction and rate of slip of C1 over C2. Surgical correction of the joints is possible by drilling them, aiding in reduction, and preventing redislocation. The construct needs to be as close to the C1-2 joints as possible. Studying the engineering in naturally occurring joints gives us a chance to understand the dynamics of the abnormal ones. Correcting the deformed joints to near-normal ones makes realignment possible in all planes and helps in understanding the best construct to fuse them. Mimicking the naturally occurring joints can help us in developing prosthesis for C1-2 arthroplasty.

**Keywords:** Abnormal joints, C1-2 joints, congenital atlantoaxial joints, constructs, engineering, normal joints

**Introduction**

Evolution over millions of years has resulted in the best designs and functions. Nature’s engineering is a perfect combination of form and function. The C1-2 joint is an example of the marvel of such engineering. However, occasional flaws result in abnormalities. The minor ones are taken care of by nature’s compensatory mechanism. The major ones lead to disabilities and problems, often in pediatric age group. The congenital atlantoaxial dislocation (CAAD) is a consequence of one such anomaly in nature’s engineering.

Treatement of such abnormalities require an understanding of the evolved normal anatomy and functioning. The laws of physics hold true for normal as well as abnormal joints. However, the resultant kinematics and dynamics for the two are different. This article delineates how changes in geometric morphology of C1-2 joints because of congenital abnormalities result in dislocation with same forces needed for normal movements. This understanding would provide us with valuable insights into effectively treating such disorders.

**Nature’s Engineering**

The C1-2 joints like other parts have evolved over millions of years to provide smooth movements.

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Majority of the neck rotation is provided by C1-2 joints. The C1 anterior arch acts like a spoke and the odontoid process acts as the center around which the spoke rotates. The lateral C1-2 joints have an equally important role to play. They provide the much-needed support required to hold the skull upright as well as to aid the smooth C1-2 rotation. These lateral masses can be imagined as blocks or cuboidal structures. A three-dimensional structure cannot be analyzed in a single dimension. It can be objectively measured in two planes. The hard palate can be used as the reference in the sagittal plane and the foramen magnum can be used as a reference in the coronal plane.[1] The articular surfaces of C1-2 are flat in the sagittal plane and inclined in the coronal plane (165° to foramen magnum).[1]

The normal C1-2 joints are unique and are extremely mobile. The joints exhibit six degrees of freedom of movement, the most important being axial rotation.[2] However, the movements in other planes make the rotation extremely efficient. These movements include lateral translation of 3 mm, the lateral tilt of about 5°, anteroposterior translation of 3 mm, flexion–extension of 5°–10°, and few millimeters of vertical movement of C2 within C1 coupled with rotation [Figure 1].[3] For simple axial rotation, the joints would have been flat in sagittal as well as in coronal plane. However, this would require large surface areas of the C1-2 facets along the perimeter of the path it traces. This would compromise the canal. Besides, it would not be possible to rotate the head in laterally tilted or flexed position. Coronal inclination widens the canal without altering the area of joints or its range of rotation. The lateral movements are easier with coronally inclined joints; however, such coronal inclination has its own problems. Too much of it would lead to vertical instability between C1 and C2. Besides, the rotation of coronally inclined facets creates a cone or frustum, which overlies the convex articular surface of C2 lateral masses or another frustum [Figure 2]. This would make it impossible for movements in other planes. Nature’s solution to this was cartilage that converts the articular surfaces into convex on convex, making all these movements possible. The evolution is an example of adaptation over millions of years. Wider C1-2 joints are seen in
herbivores, where the animal has to bend neck down and turn neck to graze. The range of neck movements in these animals is incredibly wider than humans. In the chain of evolution, the range of neck movements has reduced in the predators and humans.

The C1-2 stability is maintained by the strong ligaments and capsules and to some extent by the unique bony architecture itself. The anterior movement of dens is prevented by the intact C1 anterior arch, whereas the posterior movement is checked by the transverse ligament. The intactness of dens and C2 body is equally important. Strong capsule and ligaments prevent excessive rotation, angulation, or translation beyond ordinary. Any laxity of ligaments can lead to abnormal mobility.

**Minor flaws and how nature rectifies it**

For rotation to occur, the joints should be a mirror image of each other. However, this may not be true in many individuals [Figure 3]. Yet the movements in most of these remain smooth. Cartilages make these joints gyroscopic, allowing rotation even with asymmetric joints. Cartilages take care of minor asymmetry.

**Major flaw in structural engineering**

The OC1 and the C1-2 joints form the lateral pillars that transmit the weight of skull on to the subaxial spine. Below the C2 joint, the vertebral bodies play a major role in weight bearing. The OC1 and C1-2 joints also provide significant movements of the neck. The OC1 joint is like a ball-and-socket joint and is relatively stable. However, the C1-2 joint provides rotational movement and is less stable. The C1-2 joints in patients with CAAD are grossly deformed as compared to normal [Figure 4]. The morphometry of C1 lateral masses in these patients is trapezoidal compared to cuboidal in normal individuals. The deformity can be objectively measured in sagittal and coronal planes. The sagittal inclination of joint leads to anterior and inferior slip of C1 over C2. Increased coronal inclination adds further to vertical slipping of C2 within C1. The inclination often exists in both coronal and sagittal plane, which leads to a combination of anteroposterior and vertical dislocation of C1 over C2 [Figure 5]. The degree of deformity of lateral masses and C1-2 joints decides the rate of dislocation. The rate of vertical or anterior slip is decided by the extent of coronal or sagittal inclination of joint, respectively. Assimilated C1 and fused C2-3 is often associated with such deformed joints. It increases the stress at deformed C1-2 joints precipitating the dislocation.

The deformity on either side may be symmetrical or asymmetrical. If the deformity is mirrored on the other side, the dislocation is anteroinferior and/or vertical. However, if the two sides are asymmetrical, the more inclined joint would dislocate faster and to a greater
Figure 4: (A) C1-2 joints of a normal individual using 3D reconstructed CT as seen from lateral aspect. Notice the flat orientation. (B) C1-2 joints of individual with congenital atlantoaxial dislocation. Notice the obliquity or deformity. The C1 would tend to slip anteriorly and inferiorly with this kind of oblique orientation.

Figure 5: (A and B) Normal C1-2 as seen laterally and from front. (C and D) Deformed C1-2 joints in a patient with CAAD. The lateral masses are trapezoidal unlike the cuboidal ones in normal joints. The normal forces (blue arrows) now cause anteroposterior slip as well as vertical slip of C1 over C2. (E and F) Dislocation progresses to a point where the patient becomes symptomatic and neck maneuvers cannot reduce the dislocation in both planes.
Salunke: Congenital AAD: failed nature’s engineering

If there is coronal asymmetry, the more vertical joint dislocates and the dens tilt to the opposite side leading to lateral angular dislocation.[4,5] This is further exaggerated by the presence of bifid C1 that splays and allows further angular dislocation. Asymmetry of sagittal inclination leads to the anterior dislocation of one joint more as compared to the other. This adds to the rotational component to the dislocation.[4] Torticollis commonly seen in these patients is a result of such bony deformities leading to dislocation.

The dislocation can be prevented initially by the muscles and ligaments that hold the C1-2 in position. The constant muscle spasm causes neck pain. The progress of dislocation with inclined joints is a glacial phenomenon (dynamic process) that continues to a point where muscles and ligaments cannot hold it any longer and closed reduction may not be possible. The canal is compromised and the patient usually presents with progressive signs of myelopathy.

Occasionally, for reasons not clear, the odontoid process does not fuse to the C2 body. This is known as os odontoideum. The C1 and os along with an intact transverse ligament act as a unit and can move in relation to the remaining C2. Often, the C1-2 joints are normal in such cases and dislocation reduces with neck extension.[8] Hyperextension may lead to retrolisthesis in the canal. Multiple trauma due to repeated reduction and dislocation leads to deficits.

Os odontoideum may coexist with deformed C1-2 joints, and the dislocation in such cases may be more complex.[6] The anteroposterior and vertical dislocation progresses and the os is seen anterior to the C2 body. The lax capsules may lead to excessive lateral translation in the presence of os odontoideum.[7]

The C1 arch may not be intact at times, which is known as bifid C1. This leads to splaying of C1 and progressive invagination of C2 within C1.[8]

**Engineering Solutions: Surgical Correction**

The surgical management of CAAD has undergone a significant change in the past two decades. Previously, the focus was on removing the compressing component, i.e., the odontoid process. With a better understanding of pathophysiology, the management has now shifted to the C1-2 joints. These joints are usually approached posteriorly and opened. This is followed by distraction and manipulation of joints to reduce the dislocation, and finally, fuse it as described by Goel et al.[9]

As described earlier, the C1-2 joints are deformed in many cases of CAAD. Deformity correction is likely to aid reduction in all planes as well as to prevent redslocation. The C2 nerve root can be cut, thus exposing the joint. The C1-2 joints are opened and drilled comprehensively in both coronal and sagittal planes to make it near-normal [Figure 6]. In the sagittal plane, the posterosuperior wedge of C2 and the anteroinferior wedge of C1 are drilled.[10] In the coronal plane, the medial wedge of C2 and the lateral wedge of C1 are drilled.[10] This corrects the deformity.[10] This converts a deformed trapezoid lateral mass to a near-normal cuboidal structure. Such drilling, however, leads to bone loss that needs to be compensated with metallic spacers.

Further manipulation can be achieved using the facet screws by holding them together with a loosely fastened rod and then manipulating them using a long stout rod holder. The long rod holder acts as a lever.[11] Anteroposterior correction can be achieved by turning the rod holder caudally, whereas lateral tilt and translation can be corrected by turning the lever clockwise or anticlockwise [Figure 6]. Thus, multiplanar alignment can be achieved.[11] Finally, the tulips need to be compressed a bit to jam the spacers in the realigned position to prevent any movement.

Alternatively, the same can be achieved using an osteotome insinuated in the joint, which acts as a lever, as described by Goel and Shah.[12] Using the Goel's plate, the anteroposterior dislocation can be corrected and the lateral masses can be compressed together. Whatever the technique, the final goal is to achieve multiplanar realignment and to avoid redislocation till the joints fuse [Figure 7].

**Engineering in constructs**

Fusing the C1-2 joints requires a construct that can avoid any translation and rotation in any axis. Fusing the C1-2 joints close to the articular surfaces provides excellent stability. Transarticular screws on both sides, anterior or posterior, are a good alternative.[13] Transarticular screws and C1 lateral mass with C2 pedicle screws provide similar stiffness.[14]

**Shortcomings**

Fusing the occipital squama to the C2-3 lateral masses is not a good alternative and does not follow the engineering principals. The forces act at C1-2 joint, and fusing the occipital squama to the C2 takes the construct away from the point of forces. This is likely to fail, unless a long segment fusion is done, which, of course, is not desirable as it compromises the neck movements further.[15] Even in the presence of assimilated arch of the atlas, anomalous vertebral artery, or pseudofacets, C1-2 facet fusion/transarticular fusion should be attempted before resorting to fusing the occipital squama to C2-3.[16,17]
Figure 6: (A and B) Comprehensive drilling of anteroinferior wedge of C1, posterosuperior wedge of C2 (shaded area) as seen in sagittal plane and medial wedge of C2, lateral wedge of C1 in coronal plane. (C–F) Realignment using the long rod holder and the loosely fastened rod onto C1-2 screws. The long rod holder acts as lever and caudal force realigns the C1-2 in anteroposterior plane whereas clockwise or anticlockwise force corrects the lateral translation/tilt.

Figure 7: (A–E) Preoperative imaging of a patient with C1-2 dislocation in all planes; anteroposterior, significant vertical, and rotational (minimal). The yellow lines mark the extent of dislocation. Note the oblique deformed joints (yellow lines) marking facets. (D) Surgical correction of lateral masses by drilling comprehensively in all planes (yellow lines: G-J) and multiplanar realignment of C1-2 (F, G, K and L).
Future engineering: biomimicry
Arthrodesis of the C1-2 joint is not the best way of treating its instability as it compromises the neck movements significantly, thus adversely affecting the person’s quality of life. An artificial joint or C1-2 arthroplasty, if feasible, would be better than arthrodesis. Naturally occurring joints can be considered as the most evolved and efficient ones. The most effective way would be to mimic natural joints, both the design and the material. Attempts have been made to copy the design of the naturally occurring joints.[18] It is likely to provide an almost similar range of movements as of the naturally occurring C1-2 joints. In addition, the convex-on-convex articulation makes the joints gyroscopic adapting to varying anatomy.[18]

Conclusions
Normal C1-2 joints are ergonomically designed to provide maximum axial rotation without dislocating. The deformed joints are prone to dislocation. The plane of dislocation and the rate of slip are decided by the direction of deformity. Realigning is possible by deformity correction. Though not the best treatment, C1-2 realignment and arthrodesis is the best option currently available.

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Conflicts of interest
There are no conflicts of interest.

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