Original Article

"Soft that molds the hard:" Geometric morphometry of lateral atlantoaxial joints focusing on the role of cartilage in changing the contour of bony articular surfaces

ABSTRACT

Purpose: The existing literature on lateral atlantoaxial joints is predominantly on bony facets and is unable to explain various C1-2 motions observed. Geometric morphometry of facets would help us in understanding the role of cartilages in C1-2 biomechanics/kinematics.

Objective: Anthropometric measurements (bone and cartilage) of the atlantoaxial joint and to assess the role of cartilages in joint biomechanics.

Materials and Methods: The authors studied 10 cadaveric atlantoaxial lateral joints with the articular cartilage *in situ* and after removing it, using three-dimensional laser scanner. The data were compared using geometric morphometry with emphasis on surface contours of articulating surfaces.

Results: The bony inferior articular facet of atlas is concave in both sagittal and coronal plane. The bony superior articular facet of axis is convex in sagittal plane and is concave (laterally) and convex medially in the coronal plane. The bony articulating surfaces were nonconcordant. The articular cartilages of both C1 and C2 are biconvex in both planes and are thicker than the concavities of bony articulating surfaces.

Conclusion: The biconvex structure of cartilage converts the surface morphology of C1-C2 bony facets from concave on concavo-convex to convex on convex. This reduces the contact point making the six degrees of freedom of motion possible and also makes the joint gyroscopic.

Keywords: Articular surface, atlantoaxial joint, atlas, axis, cartilage, three-dimensional morphometry

INTRODUCTION

Craniovertebral junction is a complex area and represents a unique balance between stability and mobility. The atlantoaxial joints are responsible for significant degree of neck movements.[1] Pathology of these joints makes it unstable, compromising the neural structures and often necessitating manipulation of C1-2 joints and fusing them.[2-4] A thorough knowledge of three-dimensional (3D) anatomy is extremely important for surgical approaches and also to understand the biomechanics/kinematics[5] necessary for the development of newer implants.[6,7] Most of the studies have focused on bony anatomy of C1-C2 elucidating the bone available for instrumentation.[8-12] The bony articular surfaces described are concave inferior C1 and convex superior C2 facet.[13] These shapes suggest a sort of ball and socket joint on either side of dens. This cannot explain the range of rotation and degrees of freedom of movement exhibited at the C1-2. Furthermore, the joints on either side may not be symmetrical, and motion in unison of two joints cannot be explained with this asymmetric configuration. Putz had described the articulation (with cartilages *in situ*) as a biconvex one with minimal contact and explained its functions/movements. Boszczyk *et al.* and Putz and Pomaroli further analyzed vertical translation during extremes of rotation in such biconvex articulation and the role of alar ligaments.[14-16] It is not clear if the cartilages itself bring about

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Prashant Kumar Prasad, Pravin Salunke, Daisy Sahni[1], Parveen Kalra[2]

Departments of Neurosurgery and [1]Anatomy, PGIMER, [2]Department of Production and Industrial Engineering, PEC University of Technology, Chandigarh, India

Address for correspondence: Dr. Pravin Salunke, Department of Neurosurgery, PGIMER, Sector 12, Chandigarh - 160 012, India.
E-mail: drpravin_salunke@yahoo.co.uk

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a major change in the dynamics/kinematics by molding the morphometry of the bony facets.

The purpose of this cadaveric study is to analyze the geometric morphometry of the C1-2 articular surfaces with and without the cartilage using a laser 3D scanner and the latest software. The study further explores the role of cartilages in altering the dynamics/biomechanics of lateral C1-2 joints. These details would aid in developing future implants/prosthesis to restore form and function close to the natural one.[6,7]

MATERIALS AND METHODS

A total of five cadavers (10 joints) in four males and one female with the average age being 54 years were studied. The cadavers were embalmed and then subsequently stored in formalin solution for approximately 4–6 weeks. The cadavers were dissected and C1-C2 removed *en bloc* after due approval by the Institutional Ethics Committee. The C1-C2 was disarticulated keeping the articular cartilage over the bony facets intact. Multiple markers were placed on each vertebra; each vertebra was then scanned using 3D scanner with particular emphasis on facets of C1-C2 joint (ATOS CORE 300, GOM mbH, Braunschweig, Germany with following parameters 5 million pixels, measurement area 230 mm × 300 mm). The probing error was +19 μ with a sphere spacing error of 14 μ. The length measurement error of the scanner was <8 μ. The cartilages were then carefully removed from articular surfaces (inferior facet of C1 and superior facet of C2) taking care not to disturb the markers [Figure 1]. The gross anatomy of the cartilage was studied. The same process of 3D scanning was repeated to acquire data without cartilage. The images thus generated were combined to generate a point cloud which was converted into 3D data about the vertebra using each marker as a reference point.[17] The contours of the articular surfaces with and without the cartilages could be obtained from the software. Comparing the data of C1-C2 with and without the cartilages gave us the exact morphometry of the cartilage [Figures 2-4]. The results obtained helped to know the change the cartilages bring about to the bony facets. The data generated was also used to calculate the facetoisthemic angles and bony dimensions.[18,19]

RESULTS

Results have been described in Table 1.

Bony facet

The inferior C1 facet had an oblique lie with oval shape and maximum diameter in anteroposterior (AP) (16.54 ± 1.67) and transverse axis (14.58 ± 0.88) with AP diameter more than transverse in nine joints. The bony articular surface obtained after denuding the articular cartilage was concave both in coronal (depth −0.83 ± 0.59) and sagittal plane (depth −0.47 ± 0.34) [Figure 4]. The thickness of lateral mass underneath the inferior surface of posterior arch of C1 varies from medial to lateral with more bone laterally as compared to medial. The posterior surface of the C1 lateral mass was almost perpendicular (113.3 ± 18.01) to the articular C1 facet. The facet was coronally inclined with mean value of 67.55 ± 3.99. The minimal distance between C1 facets was 14.96 ± 0.76; the surface area of C1 facet was 212.23 mm^2 (165.8–310.2).

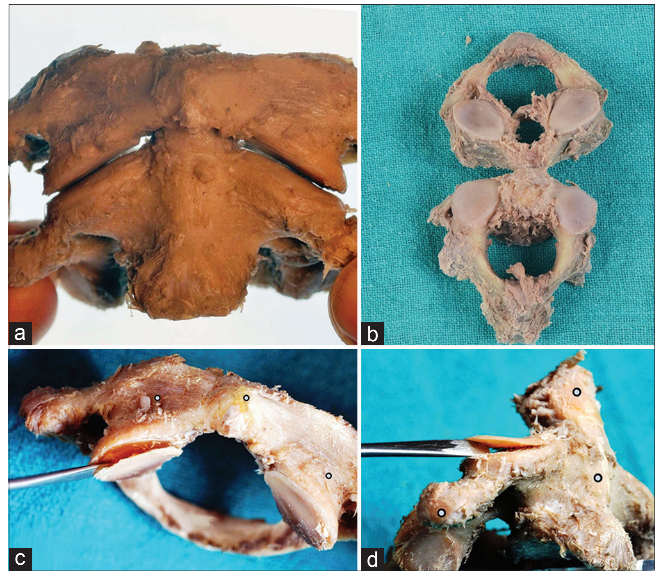

Figure 1: (a) C1-C2 removed *en bloc* and viewed anteriorly after removal of ligaments and capsules. The lateral atlantoaxial joints show convex on convex articulation. (b) Disarticulation of C1-C2 exposing the articular surfaces. (c and d) Denuding the articular cartilage from the inferior articular facet of atlas and from the superior articular facet of axis, respectively. Note the black markers on the bony surface which act as reference points for the three-dimensional scanner

The superior facet joint of C2 is ovoid with AP diameter (16.76 ± 1.99) more than transverse diameter (15.26 ± 1.88) in nine joints. The lie of C2 was more coronally oriented and the area was 220.32 mm^2 (131.5–321.1). The C2 articulating surface unlike the C1 articulating surface was different in coronal and sagittal plane. In the coronal plane, the facet was slightly convex in the medial third and concave in the lateral two third, whereas in the sagittal plane, the C2 articulating surface was convex [Figure 4]. The facets were inclined coronally (63.75 ± 4.35). The posterior surface of the C2 lateral mass/isthmus was angulated at facetoisthemic angle of 161.72 ± 8.71. The C1-C2 articular surfaces formed predominantly concave on concavo-convex surface.

Table 1: Geometric morphometry of C1-C2 (for both bony and cartilages contours)

	C1	C2
Bony facet		
Maximal AP	16.54±1.67	16.76±1.99
Maximal transverse	14.58±0.88	15.26±1.88
Coronal surface geometry	Concave (depth-0.83±0.59)	Medial third convexity (+0.14±0.05), lateral 2/3 concave (depth-0.73±0.46)
Sagittal surface geometry	Concave (depth-0.47±0.34)	Convexity+0.96±0.69
Medial height of facet/isthmus	2.43±1.03	1.23±0.52 (length of isthmus 5.02±0.61)
Lateral height of facet/isthmus	6.77±1.76	1.2±0.52
Width of facet/isthmus	9.33±0.70	6.27±0.45
Minimum distance between facets	14.96±0.76	15.1±2.75
Angle between posterior surface of facet and articulating surface (facetoisthemic angle of C2)	113.3±18.01	161.72±8.71
Coronal angles	67.55±3.99	63.75±4.35
Cartilage		
Maximal AP	16.57±1.67	16.79±1.99
Maximal transverse	14.61±0.89	15.3±1.88
Thickness coronal	1.23±0.44	Biconvex with lateral 2/3 thicker maximal thickness 1.16±0.45
Thickness sagittal	1.18±0.44	Biconvex maximal thickness 1.35±0.56, laterally thin

Concavity is measured as maximum depth and is depicted as negative value. The convexity is maximum thickness above plane denoted as positive value. AP - Anteroposterior

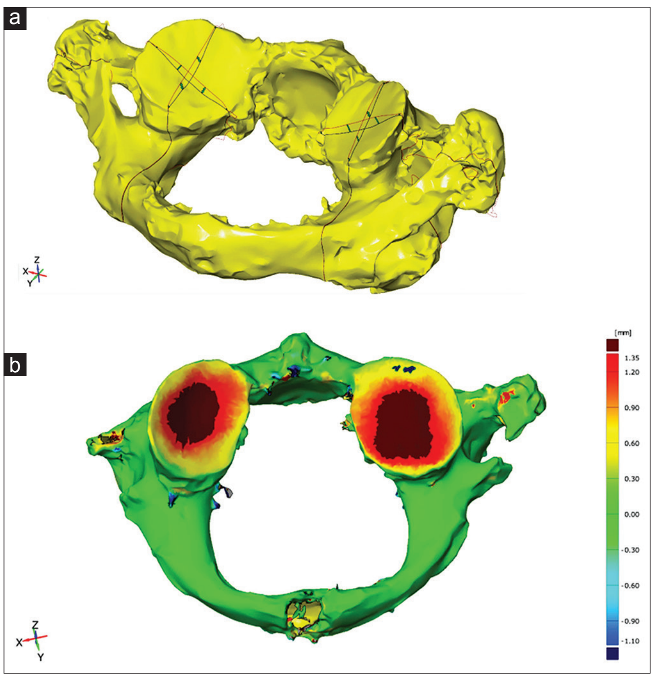

Figure 2: (a) Overlapped three-dimensional image of inferior articular facet of atlas with the black line marking the bony surface of facet and the red line showing the surface of cartilage with the green markers at places depicting the thickness of the cartilage at various levels. (b) Three-dimensional images with and without the cartilage overlapped and analyzed using the color mapping toll resulting in different colors depicting the thickness at various points. The increasing intensity of red depicts increasing convexity of the joint surface (scale attached). This shows a convex articular surface with cartilage *in situ*

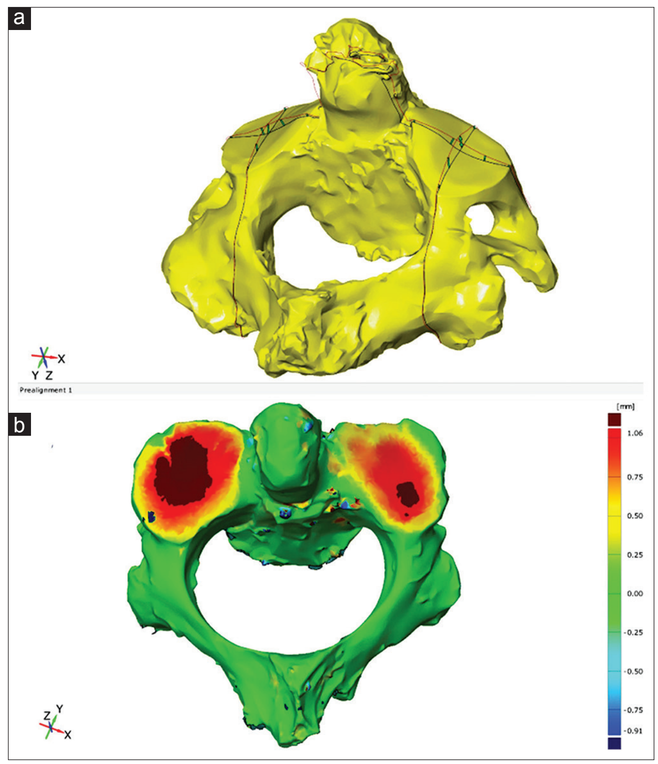

Figure 3: (a) Overlapped three-dimensional image of superior articular facet of axis with the black line marking the bony surface of facet and the red line showing the surface of cartilage with the green markers at places depicting the thickness of the cartilage at various levels. (b) Three-dimensional images with and without the cartilage overlapped and analyzed using color mapping toll resulting in different colors depicting the thickness at various points. The increasing intensity of red depicts increasing convexity of the joint surface (scale attached). This shows a convex articular surface with cartilage *in situ*

Cartilages

The C1 cartilage is oval with a biconvex structure both in sagittal (1.18 ± 0.44) and coronal (1.23 ± 0.44) planes. The AP and transverse diameter was conforming to the dimensions of the bony facet. The minimum thickness was on the lateral aspect of the cartilage and measured 0.1–0.2 mm [Figures 2 and 4].

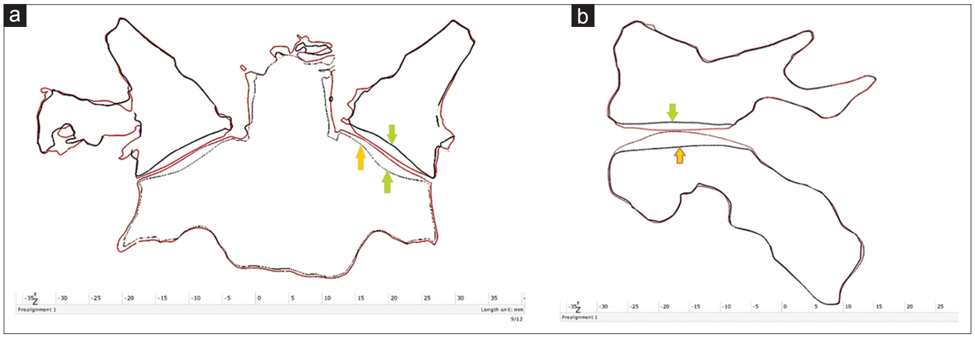

Figure 4: Coronal (a) and sagittal (b) two-dimensional sections passing through the C1-C2 joint of overlapped three-dimensional images with and without the cartilage (soft tissue) with the black line delineating the bone and the red line marks the cartilage (soft tissue). Bony articular surface of C1 is concave both in coronal and sagittal plane (green arrow), whereas for C2, it is concave in sagittal plane (green arrow) and has a medial convexity (orange arrow) with lateral concavity (green arrow) in coronal plane. The cartilages of C1 and C2 are biconvex in both sagittal and coronal planes

The C2 cartilage was biconvex in the lateral two-thirds in both coronal and sagittal plane. The medial third of the cartilage was thin and measured 0.1–0.2 mm in all planes [Figures 3 and 4].

The thickness of both C1 and C2 articular cartilage was more than the depth of bony articular surface. The surfaces with cartilage on the bone were convex in both sagittal and coronal plane for C1 as well as C2. Thus, a bony concavo–concavo-convex surface was converted into a convex on convex surface with the cartilage. The height of the joint with the cartilage increased by 2.39–2.53 in coronal and sagittal axis, respectively.

DISCUSSION

The C1-C2 accounts for nearly 50% of the neck rotation. The dens acts as a central pivot around which the C1 rotates. The atlantodental articulation forms an important part of rotatory mechanics.[1] However, the C1-2 joints on either side of dens have an equally major role to play. The weight of the skull is transmitted along these lateral joints unlike the subaxial spine, where the central body acts as weight-bearing pillar. The C1-2 is unique and exhibits six degrees of freedom of movement.[1] The major movement is of axial rotation (45°). In addition, there is minor translation and rotation in other Cartesian planes (X-Y, Y-Z, and X-Z) in space. There are a few millimeters (2–3 mm) of AP and lateral translation and few degrees of flexion-extension (5°) and lateral bending (2°–3°) possible.[1] It is also noted that during rotation there is vertical translation between C1 and C2. The C1-C2 height is at the summit in neutral position and is minimal in the maximal rotation on either side, phenomenon known as coupling.[1,14,15] There are few degrees of rotation and translation in other axes along with axial rotation, making it very efficient. The bony articular surfaces are predominantly concave to concavo-convex, as described in our study and cannot explain these movements in various planes and coupling. The articular cartilages convert concave on concavo-convex bony surfaces into a convex on convex articulation. Such convex on convex articulation explains the six degrees of freedom of movements as well as coupling. The vertical translation coupled with rotation was explained previously by Putz and Pomaroli and Boszczyk *et al*. They showed a biconvex articulation and tested the elasticity of alar ligaments during such coupled movements.[14-16] Our study shows how the cartilages mold the bony articular surfaces into a biconvex articulation making these coupled movements possible.

The C1-2 joints are coronally inclined and axial rotation of these bony facets around the central dens integrates to form a conical surface.[18] The two lateral C1-2 joints may not be symmetrical and the paths of facets on either side may not be congruous. With the presence of cartilage (convex on convex articulation), the surface contact is reduced. This makes the C1-2 joints gyroscopic and single contact point on either side would lie along a circumference of circle, the center of which is the dens. This gyroscopic articulation also makes axial rotation possible with AP and lateral translation and bending irrespective of any asymmetry in lateral joints on either side.

The cartilages possibly change the bony morphometry in other joints too.[17] This has been demonstrated in the hip joint where the cartilage converts the acetabular cavity into a less spherical one than the femoral head. This allows the cartilage surfaces of femoral head and acetabulum to lose contact with each other so that the cartilage may be exposed to synovial fluid for nutrition and lubrication. The ellipsoid cartilage also functions to optimize the contact stress in the hip joints.

The studies on cartilages of C1-2 lateral joints are few and describe the degenerative changes in them with age.[20,21] A study by Cattrysse *et al*. has suggested that the C1 cartilage makes the articular surface flat and C2 articular surface convex.[20] This would still make the contact point one on either side of dens. They however add that the lateral C1-2 joints are not biconvex. Our results, on the contrary, show that the joint is biconvex with the cartilages.

The abnormal shape and orientation of facets may give rise to atlantoaxial dislocation (AAD).[18] The plane of dislocation depends on the orientation of facets. AAD itself may be multiplanar.[22] The current management focuses on the lateral C1-2 joints by comprehensively drilling them and reducing the dislocation.[3] Further manipulation of these drilled facets realigns the C1-2 joints in all planes.[4] Following reduction, the joints are fused with instrumentation. The cartilages need to be removed and the reduction in height after removal of cartilage and drilling needs to be taken into consideration. The cartilages add to the joint height by approximately 3 mm, and a spacer of at least 3 mm may be required to maintain a normal height after denuding the articular cartilage. However, these measurements were without loading and *in vitro*. It is possible that the thickness of the cartilage would change after axial loading and *in vivo*. Nevertheless, the study gives us a fair idea about the changes the cartilages bring about to the shape of the bony contours allowing the possible movements. The information may aid in developing newer prosthesis.

Limitations

The 3D scanner is used only for *in vitro* measurements which were made in the conditions of unloading. The measurements may be different from normal physiological conditions with loading that may deform the cartilages. Another limitation was lack of fresh cadavers. Furthermore, our cadavers represented the elderly population. The degenerative changes related to the age and preservation techniques were not taken into consideration.

CONCLUSION

The cartilages play a major role in C1-2 articulation. They provide fluidity in movements and convert the bony surface geometric morphometry into a convex on convex making it gyroscopic. This explains the six degrees of freedom of movement even in asymmetric C1-2 joints.

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Conflicts of interest

There are no conflicts of interest.

REFERENCES

1. Dickman CA, Theodore N, Crawford NR. Biomechanics of the craniovertebral junction. In: Bambakidis NC, Dickman CA, Spetzler RF, Sonntag VK, editors. Surgery of the Craniovertebral Junction. 2nd ed. New York, USA: Thieme; 2013. p. 52-62.
2. Goel A, Kulkarni AG, Sharma P. Reduction of fixed atlantoaxial dislocation in 24 cases: Technical note. J Neurosurg Spine 2005;2:505-9.
3. Salunke P, Sahoo SK, Deepak AN, Ghuman MS, Khandelwal NK. Comprehensive drilling of the C1-2 facets to achieve direct posterior reduction in irreducible atlantoaxial dislocation. J Neurosurg Spine 2015;23:294-302.
4. Salunke P, Sahoo S, Khandelwal NK, Ghuman MS. Technique for direct posterior reduction in irreducible atlantoaxial dislocation: Multi-planar realignment of C1-2. Clin Neurol Neurosurg 2015;131:47-53.
5. Goel A. Treatment of basilar invagination by atlantoaxial joint distraction and direct lateral mass fixation. J Neurosurg Spine 2004;1:281-6.
6. Robertson PA, Tsitsopoulos PP, Voronov LI, Havey RM, Patwardhan AG. Biomechanical investigation of a novel integrated device for intra-articular stabilization of the C1-C2 (atlantoaxial) joint. Spine J 2012;12:136-42.
7. Salunke P. Artificial atlanto-axial joints: On the "move". Neurol India 2016;64:275-8.
8. Gupta S, Goel A. Quantitative anatomy of the lateral masses of the atlas and axis vertebrae. Neurol India 2000;48:120-5.
9. Christensen DM, Eastlack RK, Lynch JJ, Yaszemski MJ, Currier BL. C1 anatomy and dimensions relative to lateral mass screw placement. Spine (Phila Pa 1976) 2007;32:844-8.
10. Rocha R, Safavi-Abbasi S, Reis C, Theodore N, Bambakidis N, de Oliveira E, *et al.* Working area, safety zones, and angles of approach for posterior C-1 lateral mass screw placement: A quantitative anatomical and morphometric evaluation. J Neurosurg Spine 2007;6:247-54.
11. Mandel IM, Kambach BJ, Petersilge CA, Johnstone B, Yoo JU. Morphologic considerations of C2 isthmus dimensions for the placement of transarticular screws. Spine (Phila Pa 1976) 2000;25:1542-7.
12. Cacciola F, Phalke U, Goel A. Vertebral artery in relationship to C1-C2 vertebrae: An anatomical study. Neurol India 2004;52:178-84.
13. Baron EM, Tunstall R. Back. In: Standing S, editors. Gray's Anatomy: The Anatomical Basis of Clinical Practice. 41st ed. Spain: Elsevier; 2016. p. 710-50.
14. Putz R, Pomaroli A. Form and function of the lateral atlanto-axial articulation. Acta Anat (Basel) 1972;83:333-45.
15. Boszczyk AA, Boszczyk BM, Putz R, Benjamin M, Milz S. Expression of a wide range of fibrocartilage molecules at the entheses of the alar ligaments-possible antigenic targets for rheumatoid arthritis? J Rheumatol 2003;30:1420-5.
16. Boszczyk BM, Littlewood AP, Putz R. A geometrical model of vertical translation and alar ligament tension in atlanto-axial rotation. Eur Spine J 2012;21:1575-9.
17. Gu D, Chen Y, Dai K, Zhang S, Yuan J. The shape of the acetabular cartilage surface: A geometric morphometric study using three-dimensional scanning. Med Eng Phys 2008;30:1024-31.
18. Salunke P, Sharma M, Sodhi HB, Mukherjee KK, Khandelwal NK. Congenital atlantoaxial dislocation: A dynamic process and role of facets in irreducibility. J Neurosurg Spine 2011;15:678-85.
19. Salunke P, Futane S, Sharma M, Sahoo S, Kovilapu U, Khandelwal NK. 'Pseudofacets' or 'supernumerary facets' in congenital atlanto-axial dislocation: Boon or bane? Eur Spine J 2015;24:80-7.
20. Cattrysse E, Provyn S, Gagey O, Kool P, Clarys JP, Van Roy P. *In vitro* three dimensional morphometry of the lateral atlantoaxial articular surfaces. Spine (Phila Pa 1976) 2008;33:1503-8.
21. König SA, Goldammer A, Vitzthum HE. Anatomical data on the craniocervical junction and their correlation with degenerative changes in 30 cadaveric specimens. J Neurosurg Spine 2005;3:379-85.
22. Salunke P, Sahoo SK, Deepak AN, Khandelwal NK. Redefining congenital atlantoaxial dislocation: Objective assessment in each plane before and after operation. World Neurosurg 2016;95:156-64.