A geometrical model of vertical translation and alar ligament tension in atlanto-axial rotation

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Abstract

Introduction While allowing the greatest range of axial rotation of the entire spine with 40° to each side, gradual restraint at the extremes of motion by the alar ligaments is of vital importance. In order for the ligaments to facilitate a gradual transition from the neutral to the elastic zone, a complex interaction of axial rotation and vertical translation via the biconvex articular surfaces is essential. The aim of this investigation is to establish a geometrical model of the intricate interaction of the alar ligaments and vertical translatory motion of C1/C2 in axial rotation.

Methods Bilateral alar ligaments including the odontoid process and condylar bony entheses were removed from six adult cadavers aged 65–89 years within 48 h of death. All specimens were judged to be free of abnormalities with the exception of non-specific degenerative changes. Dimensions of the odontoid process and alar ligaments were measured. Graphical multiplanar reconstruction of atlanto-axial rotation was done in the transverse and frontal planes for the neutral position and for rotation to 40° with vertical translation of 3 mm. The necessary fibre elongation of the

alar ligaments in the setting with and without vertical translation of the atlas was calculated.

Results The mean diameter of the odontoid process in the sagittal plane was 10.6 mm (SD 1.1). The longest fibre length was measured from the posterior border of the odontoid enthesis to the posterior border of the condylar enthesis with an average of 13.2 mm (SD 2.5) and the shortest between the lateral (anterior) border odontoid enthesis and the anterior condylar enthesis with an average of 8.2 mm (SD 2.2). In graphical multiplanar reconstruction of atlanto-axial rotation to 40° without vertical translation of C1/C2, theoretical alar fibre elongation reaches 27.1% for the longest fibres, which is incompatible with the collagenous structure of the alar ligaments. Allowing 3 mm caudal translation of C1 on C2 at 40° rotation, as facilitated by the biconvex atlanto-axial joints, reduces alar fibre elongation to 23.3%.

Conclusion The biconvex configuration of the atlanto-axial joints is an integral feature of the functionality of upper cervical spine as it allows gradual vertical translation of the atlas against the axis during axial rotation, with gradual tensing of the alar ligaments. Vertical translation on its own, however, does not explain the tolerance of the alar ligaments towards the maximum of 40° of rotation and is most likely synergistic with the effects of the coupled motion of occipitocervical extension during rotation.

Keywords Alar ligaments · C1/C2 functional anatomy · Atlanto-axial rotation · Craniocervical biomechanics

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Introduction

The range of motion in axial rotation between the atlas and axis is the greatest between any two vertebrae in the

entire spine [6]. The rotation is facilitated by translatory motion of the inferior articular surfaces of the atlas against the lateral articular surfaces of the axis and is restricted by the alar ligaments. The latter provide the definitive restraint of head rotation at the extremes of motion. Despite the alar ligaments being short with a mean length of 9.5 mm (± 2.5 mm) [4], they allow a large range of rotation, typically 40° to each side [9]. The angle of ligament insertion changes markedly during rotation as the alar ligament tenses and wraps around the odontoid peg, thereby gradually and reliably restricting motion. The fibrous composition of the alar ligaments is well suited to resist tensile forces through expression of predominantly collagen type I in the ligament mid-substance and resist shear forces at the enthesis by virtue of the fibrocartilaginous differentiation with predominance of collagen type II, aggrecan and link protein [3]. This adaptive configuration of the extracellular matrix to a combination of combined tensile and shear forces, which is well described for ligaments and fibrocartilaginous entheses [1], renders the alar ligaments relatively resistant to elongation. As there is no apparent laxity of the alar ligaments at rest, the large range of atlanto-axial rotation can only be explained by three-dimensional positional changes of the atlas against the axis.

The anatomy of the atlanto-axial joint shows that it is composed of two convex surfaces resting upon each other with only minimal joint surface contact (Fig. 1). In an axial

rotation of the atlas against the axis, the biconvex joint configuration allows gradual vertical translation with descent of the atlas and skull [19]. While three-dimensional kinematics has been studied using MRI [5, 13] and computerised radiographic analysis [6], the functionality of vertical translation during axial rotation has not received specific attention.

We hypothesise that in an atlanto-axial rotation, vertical translation of the atlas via the biconvex articular surfaces of the atlanto-axial joints is a decisive factor for the function of the alar ligaments—providing a definitive restraint of rotation, but allowing a large range of motion without ligament laxity.

Methods

Anatomical measurements

Six specimens including the occipital condyles, atlas, axis and associated ligaments were removed en-bloc from adult cadavers (5 males and 1 female, aged 65–89 years) within 48 h of death. In none of the cases the cause of death was related to suboccipital pathology. The sagittal diameter of the odontoid process as well as the shortest (anterior) and longest (posterior) length of each alar ligament between the odontoid and condylar entheses was measured with callipers.

Fig. 1 Sagittal section through the atlanto-axial joint revealing the biconvex joint surfaces as demonstrated by Putz and Pomaroli [19]. **a** Inferior articular surface of atlas. **b** Articular surface of axis

Graphical multiplanar reconstruction of atlanto-axial rotation

Details of the method of graphical multiplanar reconstruction (GMR) in axial rotation of the spine have been published previously [2]. Briefly, a scaled metric representation of an object in one plane is graphically reconstructed in another plane, enabling measurements of the object to be taken in the new plane. This technique was used to assess the orientation and theoretical elongation of the alar ligament fibres during axial rotation from neutral to 40° with and without vertical translation of the atlas.

Anatomical dimensions and ranges of motion published in the literature [4, 7, 10–12, 14–16, 18–21], supplemented by our measurements of the alar ligaments and odontoid process were used for the graphical model. As the objective of the multiplanar reconstruction was to determine relative changes of angles and distances, the absolute values in the literature were approximated where necessary to obtain practicable numbers for graphic representation. The base of the skull and the atlas were functionally considered to form a unit in respect to axial rotation, disregarding any motion between C0 and C1. Three fibres were chosen to schematically represent the alar ligament (Fig. 2; neutral position, 0° rotation). The anterior fibre (AF) was chosen to insert perpendicularly at the lateral circumference of the odontoid process, the midregion fibre (MF) was chosen to insert at the 40° mark of the circumference of the odontoid process (measured from the posterior apex) with an insertional angle of 40° and the posterior fibre (PF) was chosen to insert tangentially at the posterior circumference of the odontoid process. The odontoid entheses of the AF was chosen 1 mm cranial to that of the PF and MF to simulate vertical fibre distribution. The condylar point of insertion of all three fibres was placed 3 mm cranial to the level of the odontoid insertion of the PF and MF (Fig. 2; frontal plane, 0°). The lengths of the fibres in the frontal plane in the neutral position were graphically approximated from the obtained measurements with 7.8 mm for the AF, 9.7 mm for the MF and 12.9 mm for the PF. The condylar entheses were constructed 25 mm apart. The odontoid process was considered to be cylindrical with a diameter of 10 mm—approximated from the obtained measurements.

The unilateral range of motion (ROM) of an axial atlanto-axial rotation was limited to 40°. As the process of rotation is principally the same in both directions, rotation of the head to only one side (right side) was considered. In respect to axial rotation, the contralateral alar ligament has been shown to predominantly limit motion [8, 15]. Therefore, measurements were restricted to the representative fibres of the left alar ligament.

Fig. 2 Graphical multiplanar reconstruction of axial C0–C2 rotation. *Upper image* schematic representation of the craniocervical junction in the transverse plane. The neutral position at 0° rotation is superimposed by the position at 40° axial rotation. The right alar ligament shows the position of the alar fibres in the neutral position. The *left side* of the illustration shows the tensed left alar ligament fibres in the 40° rotated position. The typical fibrocartilage distribution FC is shaded into the right alar ligament. *Lower right image* Metrically reconstructed frontal of the craniocervical junction in the neutral position in a view from posterior. *Lower left image* Metrically reconstructed view of the craniocervical junction at 40° axial rotation. The PF crosses the midline of the OP in rotation. The fibre lengths are measured in this position (values depicted above the CE for AF, MF and PF). All fibres are then “dropped” at the CE by 3 mm, simulating vertical translatory motion (not shown). The length of the fibres is redetermined in this position. OP odontoid process, CE condylar entheses, OE odontoid entheses, AF anterior fibre, MF midregion fibre, PF posterior fibre, FC fibrocartilage

A scaled (1:4) schematic view of the C0/C2 complex in the transverse plane was constructed with precision graphical instruments in the neutral position and at 40° rotation to the right. Thereby the occiput and atlas were considered to rotate as one unit about a longitudinal axis through the centre of the odontoid process. Each position was redrawn by multiplanar reconstruction in the frontal plane (the frontal plane of the occiput and atlas). The alar fibre lengths were measured in each position and rounded to one decimal. The part of the PF that wraps around the odontoid process in rotation was considered to remain in the transverse plane and was calculated as a circle sector ($\pi \times r \times \alpha / 180^\circ$; r radius (5 mm of odontoid process), α sector angle (40° of rotation)). At 40° rotation the alar fibre lengths were redetermined with 3 mm vertical translatory motion of the condylar entheses, mimicking the caudal descent of the occiput and atlas in relation to the axis during rotation by virtue of the biconvex atlanto-axial joint surfaces [14, 19].

Results

Anatomical measurements

The mean diameter of the odontoid process in the sagittal plane was 10.6 mm (SD 1.1). The longest fibre length was measured from the posterior border of the odontoid entheses to the posterior border of the condylar entheses with an average of 13.2 mm (SD 2.5) and the shortest between the lateral (anterior) border odontoid entheses and the anterior condylar entheses with an average of 8.2 mm (SD 2.2).

GMR of alar ligaments in atlanto-axial rotation

Atlanto-axial rotation without vertical translation

Rotation to 40° caused a total fibre elongation of the AF to 116.7%, MF to 126.8% and PF to 127.1%.

Atlanto-axial rotation with vertical translation

Descending vertical translation of 3 mm at 40° rotation reduced the maximum fibre elongation by 1.3–115.4% for AF, 4.1–122.7% for MF and 3.8–123.3% for PF.

With 3 mm vertical translation, the effect of fibre shortening is maximal for the MF and the PF as their angle in the frontal plane is reduced to 0°, thereby connecting the opposing entheses by the shortest path. As the AF was given an odontoid insertion only 2 mm below the level of the condylar insertion (instead of 3 mm as for the other fibres), caudal translation of 2 mm would result in maximal shortening, while 3 mm results in a downward slant towards the condylar entheses at an angle of -7° with slight elongation (Table 1).

Discussion

Functional integrity of the transverse and alar ligaments at the molecular level is crucial for maintaining the balance between physiological motion and mechanical stability of the craniocervical junction. For this to be assured, the probable maximal stretch that can be applied to an alar ligament prior to mechanical failure is 6–8% [20].

This gives rise to an apparent conflict, as rotation of the head and atlas about the odontoid process not only changes the angle of insertion of the ligament fibres, but in theory also requires an elongation of the fibres if they are considered to be tense in the neutral position.

Through GMR the schematic elongation for the different fibre positions is determinable. At 40° unilateral rotation, the longest and most posterior fibre required an elongation

Table 1 Elongation of alar fibres in atlanto-axial rotation with and without vertical translation as determined by schematic multiplanar reconstruction

Fibre	0° Rotation	40° Rotation
Anterior fibre		
No vertical translation		
Fibre length (mm)	7.8	9.1
Fibre elongation (%)	100	116.7
Vertical translation	/	3 mm
Fibre length (mm)		9.0
Fibre elongation (%)		115.4
Midregion fibre		
No vertical translation		
Fibre length (mm)	9.7	12.3
Fibre elongation (%)	100	126.8
Vertical translation	/	3 mm
Fibre length (mm)		11.9
Fibre elongation (%)		122.7
Posterior fibre		
No vertical translation		
Fibre length (mm)	12.9	16.4
Fibre elongation (%)	100	127.1
Vertical translation	/	3 mm
Fibre length (mm)		15.9
Fibre elongation (%)		123.3

The length of the fibre at rest (0° rotation) is defined as 100% length. The effect of 3 mm vertical translation at 40° is shown in cursive values

of at least 27%. The MF and AF required an elongation 26.8 and 16.7%, respectively. As discussed by Saldinger et al. [20], these values are far beyond the capabilities of collagen structures, which fail at deformation of 6–8%. The same group calculated a potential of 3% elongation for ligaments with fibres crossing at 30°, when straightened by tensing. Even when the potential of both of these factors are combined, the theoretically required elongation of the almost exclusively collagenous alar ligaments [2, 9] cannot be reached.

Kinematic factors, therefore, are needed to be present that allow gradual tensing of the alar ligaments over a rotation of 40° without ligament laxity at rest. The results from this investigation reveal vertical translatory motion in an atlanto-axial rotation to have a demonstrable effect on reducing the theoretically required fibre elongation by ~4% in the mid- and posterior regions of the ligament. This is only possible due to the biconvex nature of the atlanto-axial joints, which at first glance appear paradoxically unstable, but actually facilitate a gradual tensing of the alar ligaments. This effect on its own, however, is not sufficient to allow for atlanto-axial rotation of 40°. The coupled motions of occipitocervical extension as

demonstrated by Panjabi et al. [15, 17] and more recently by Ishii et al. [13] are most likely intricately linked to the gradual tensing of the alar ligaments through vertical translation, to allow rotation without exceeding the tolerances of the ligament—a relationship which requires further investigation with more sophisticated methodology.

While the model chosen for this investigation is a simplification of the anatomical geometry and excludes coupled motion, it does serve to reveal the fundamental relationship between alar ligament anatomy and the kinematics of the biconvex atlanto-axial joints.

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Conflict of interest None.

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