THE ARCHIVE OF MECHANICAL ENGINEERING

VOL. LIV 2007 Number 1

DOI: 10.24425/ame.2007.131541

Key words: biomechanics, cervical segment, segmental kinematics and stiffness

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MECHANICAL PROPERTIES OF CERVICAL MOTION SEGMENTS

Dedicated to HR Prof. Dr. Rudolf Beer for his 80th birthday

Using a highly sensitive and precise apparatus, series of spatial movements of human cervical segments (C3/C4) were measured. They followed cyclic varied pure torques for axial rotation, lateral flexion, and flexion-extension in the presence of axially directed preloads as running parameter, whose force lines were shifted over the segments. By successive resections of the uncovertebral and zygapophysial joints as well as ligamental structures, the reach of these guiding structures for segmental kinematics and stiffness could be evaluated. For the first time, the biomechanical significance of the uncovertebral joints could be substantiated. In axial rotation and in lateral bending, the instantaneous helical axis (IHA) was found to be not stationary. Its position depended on the size of the rotational angle. The ensemble of the skew IHA formed a ruled surface with a waist. Torque and unit vector of the IHA were found to be parallel only for flexion-extension. In this case, all four joints were in guiding function, whereas in axial rotation and lateral flexion the joints alternated with each other. IHA included with torque $T_z(t)$ for axial rotation $\approx$+30deg, and with torque $T_x(t)$ $\approx$−30deg: These motions were coupled. Resection of all ligaments did hardly influence the kinematical structure.

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1. Preliminary note

The high lifetime prevalence of about 70% makes neck pain a very common disease [1], and also chronic neck pain is widespread. It has an overall frequency of still 14% [2]. One of its possible pathogenesis is the arthrosis of the uncovertebral joints. As a reason for cervical radiculopathy, it is even more common than disc prolapses [3]. Therapeutic alternatives are: open discetomy [4], [5], spondylodesis, anterior or dorsal foraminotomy. Some authors recommended broad resection of the uncovertebral joints, some suggested preservation of these structures. Despite of these open points, and despite of the high significance of the uncovertebral joints in cervical spine mechanics, valid analyses of their biomechanical role were not carried out hitherto.

2. Introduction

In the lumbar and thoracic spine, the adjacent vertebrae are flexibly connected by the intervertebral disc and the two vertebral joints (VJ). But in the cervical spine, between the vertebrae C2 and C7, two joints are additionally fitted in, the so-called uncovertebral joints (UJ). They are developed during the postnatal growth (e.g. [6]) and finally shaped in the age of puberty, when the two unci corporis at the dorsal lateral sides of the respective lower vertebra reached their final heights. Morphologically they represent diarthroses (e.g. [7], [8]). Curiously, they are not mentioned in some anatomical or even neuro-anatomical textbooks (e.g. [9], [10], and [11]) although they undoubtedly must play an important kinematic role, since according to the laws of spatial kinematics [12] every diarthrosis reduces the number of the kinematical degrees of freedom (DOF) at least by one, as soon as the joint is put in function.

Panjabi et al. [13] presented a morphologic investigation which was confined to the spatial alignment and the survey of size of the articulating surfaces of the uncovertebral joints. An investigation of the curvature morphology of the articulating surfaces which determines the joint guidance has not been carried out yet. Comprehensive measurements of the spatial kinematics of cervical motion segments are lacking, too, by which the changing position of the instantaneous helical axis (IHA) is recorded depending on the rotational angle of a segment. Previous papers (e.g. [14]) only yielded rough data about range of motion (ROM) or segment stiffness, but did not describe the actual instantaneous segment motion since resolution and precision of the used measuring devices were not sufficient to observe the spatial IHA migration. Thus, kinematical structure of the spatial cervical segment motion has hitherto not been subject of evaluation.

The purpose of our study was to start on filling this gap and to evaluate structures of the spatial kinematics of C3/C4-segments. Axially, laterally, and anterior-posteriorly directed time periodic torques were applied under simultaneously axially directed stationary preloads of varying size and position. By stepwise resections of the uncovertebral and vertebral joints their mechanical significance was specified. Variables of criterion were: 1) Differential stiffness, 2) Rotational angle – torque characteristics, 3) Location and direction of the migrating IHA, 4) Differential screw pitch.

3. Material and methods

Material

One fresh and two autopsy C3/C4-segments could be obtained. Abnormities could be excluded by x-ray and CT recordings. The autopsy segments were preserved by a special method [15] which did hardly influence the proportion of the rigidities of the bony and ligamentous structures. Additionally, an artificial segment was used to verify the validity of the method. It consisted of two cylinders of a rigid polymer which were connected by a circular, 5mm thick layer out of the same but softened up polymer simulating the vertebral disc.

Measuring method

Previously Mansour et al. [16] and Nägerl et al. [17] presented a measuring method, by which in vitro the migrating IHA could be resolved in lumbar motion segments. Adapting this method to the features of the smaller vertebrae and the less segment stiffness, we performed the analysis of C3/C4-segment motion. The measuring procedure is summarized in the following, for further details see [16]: Pure torques and preloads could be independently exerted on the C3/C4-segments. When the upper vertebra was following the specific periodic, triangularly varying torque component (axial $T_z(t)$, lateral $T_y(t)$, or anterior-posterior $T_x(t)$), we recorded a series of more than 200 "snap shots" of spatial positions of the moving upper vertebra (C3) in relation to the lower vertebra (C4, reference) for each period of motion. The resolutions of the position changing of the upper vertebral body were: 2.4 μm for the translation and 1mdeg for the rotation. Thus, the migration of the IHA could be tracked by successive C3 positions, which only differed by rotational angles of about 0.01deg. We determined i) the position vector $\vec{r}(\alpha)$ of the IHA in the reference system (accuracy of the magnitude: ±1.0mm), ii) the unit vector $\vec{e}(\alpha)$ (accuracy of its main component: ≤0.2%) of the IHA line, and iii) the instantaneous screw pitch $tau(\alpha)$ (≤5%) with $\tau(\alpha) = ds/d\alpha$.

The quantities are illustrated by figure 1. The running parameters were the position and the size of the axially directed static preload F_z. The force line was set with an accuracy ±0.5mm for the magnitude of the position vector and ≤0.2% for the main component of the unit vector.

Execution of measurements

Definition of the coordinate system: The C3/C4-segment was put into the apparatus, so that the spinal channel was in parallel with the line of gravity (z-direction). To keep comparisons between the C3/C4 segments as simple as possible, the “centre of resistance” for axial preloads was determined experimentally. An axially directed load F_z (20N) was shifted in x-y-plane as far as the upper vertebra (C3) tilted neither laterally, nor anterior-posteriorly. The intersection of this adjusted force line of F_z with the x-y-plane running through the posterior middle of the intervertebral disc was taken as the centre of resistance C_R, and used as the origin of the coordinate system (Fig. 1). C_R lied at the anterior margin of the spinal channel. The x-axis ran in the sagittal mirror plane of the segment.

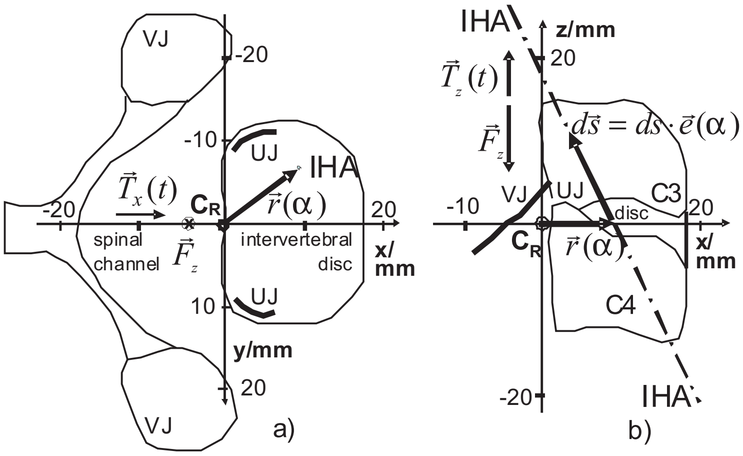

Fig. 1. Coordinate system, measured kinematic quantities, and segmental dimensions (radiographic tracings). C_R = origin of the coordinate system. C3, C4 vertebral bodies, VJ = projections or clefts of the vertebral joints, UJ = clefts or projections of the uncovertebral joints. IHA = instantaneous helical axis.

a) x-y-plane: $\vec{r}(\alpha)$ = position vector of the IHA, $\vec{T}_x(t)$ = applied pure torque for lateral flexion. $\vec{F}_z$ = axial preload.

b) z-x-plane: $\vec{r}(\alpha)$ = position vector of the IHA, $\vec{e}(\alpha)$ = unit vector of the IHA-line: $|\vec{e}(\alpha)| = 1$, $d\vec{s} = ds \cdot \vec{e}(\alpha)$ = increment of screw displacement belonging to the rotation increment $d\vec{\alpha} = d\alpha \cdot \vec{e}(\alpha)$, screw pitch $\tau(\alpha) = ds/d\alpha$.

Application of the torques: After applying the preload F_z, we loaded the segment by a periodic torque $T_i(t)$. As expected, the subsequent rotational angle-time-functions $\alpha(t)$ showed a marked transient phenomenon. The $\alpha(t)$-functions became not stationary in shape until after some cycles.

Parameters of the measurements: By means of the artificial segment, we checked the measuring and analyzing procedure of the IHA, since the round elastic layer had to show a stationary IHA through its centre. For the measuring series of the intact C3/C4-segments, the size and (x,y)-position of the preload F_z served as parameters. The same extensive measuring program was always executed after stepwise resections of joints and ligamentous structures.

In the fresh segment we firstly removed the right uncovertebral joint, then the left one, then the left and finally the right vertebral joint. The resections of the uncovertebral joints were done because they have often been carried out in neurosurgery. In one segment of the autopsy material, however, the complete ligamentous apparatus was removed at first to evaluate its significance for the kinematics of the segmental movement. The following simultaneous resection both vertebral joints showed their role in guiding the segment. The second autopsy segment was only measured in the intact state. Since its kinematical structure did not differ from the others, we renounced further executions of the extensive measuring programs.

Evaluation of the measurements and presentation mechanical properties of the segments

The rotational angle-torque-characteristics $\alpha(T_i$ were computed from the measured rotational angle-time function $\alpha(t)$ and the applied torque-time function $T_i(t)$ for the running parameters: size and position of the preload F_z. It allowed analysing the stiffness for each differential position and angle (α). As mentioned above, for the first time we analysed the kinematical structure of cervical movements by precise recording of the spatial location of the IHA line. Position and direction of the IHA strongly depended on the size of rotational angle α.

4. Some important results

The artificial segment showed the stationary IHA in the centre of the elastic layer, as expected.

Intact fresh C_3/C_4

Axial torque $T_z(t)$: a) Symmetric sigmoid $\alpha(T_z$ – characteristics with hystereses. The initial stiffness $D_z(0) = dT_z/d\alpha$ (at $\alpha = 0$) strongly depended not only on the size $|F_z|$, but also on the location of F_z-line (Fig. 2): Shifting to the dorsal by 15 mm made the stiffness $D_z(0)$ to increase by 2.5-fold! After each reversal point, $\alpha(T_z)$ mirrored the transient motion of $\alpha(t)$, which followed $T_z(t)$ with its constant slope dT_z/dt: $\alpha(t)$ followed $T_z(t)$ temporally delayed and afterwards in a slight non-linear fashion. b) The position of the

IHA depended on the rotational angle α. The IHA belonging to different α were skew. Therefore, the set of all IHA formed a ruled surface which showed a waisting in the central region of the segment (Fig. 3a). c) After the reversals of $T_z(t)$, the unit vector $\underline{e}(\alpha)$ of the IHA showed a small temporary component to the left or right (e_y) and a short time increase of e_x which quickly decayed in the course of motion (Fig. 3b). That means: During the transient phenomenon, the direction of the IHA altered significantly and afterwards it was constant lying in parallel to the sagittal plane, but *not in parallel* to the applied torque vector $T_z(t)$. The angle between unit vector $\underline{e}(\alpha)$ and torque T_z was about 30 deg (Fig. 3a,b). Hence, the axial rotation was found to be coupled with lateral flexion showing an e_x – component! d) The ruled surface (defined by the family of the IHA-lines) had sharp edges (Fig. 4). e) The screw pitch $\tau(\alpha)$ was found to be an odd function so that the distance between the two intervertebral bodies increased with increasing rotational angle α independently of the sign of rotation.

Lateral flexion $T_x(t)$: a) The $\alpha(T_x)$-curves were shaped like the $\alpha(T_z)$. b) After the transient phenomenon, the unit vector $\underline{e}(\alpha)$ lied also in a sagittal plane, and was in comparison with $T_x(t)$ clockwise rotated by ≈30 deg (hence: coupling with axial rotation!). c) Again the ruled surface of the IHA revealed sharp edges (Fig. 5).

Flexion-extension $T_y(t)$: The IHA was found to be nearly stationary and in parallel to the torque $T_y(t)$.

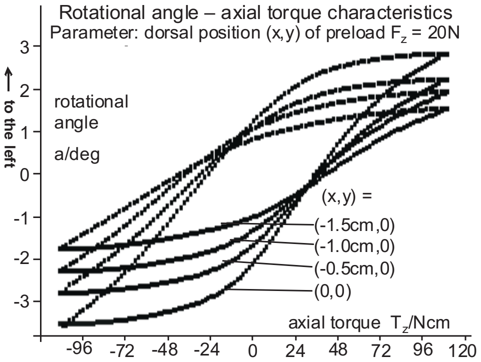

Fig. 2. Stationary $\alpha(T_z)$ – characteristics after building-up in axial rotation. Fresh segment. Dorsal displacement of the line of the axial preload $\vec{F}_z$ led to a considerable increase of segmental stiffness.

Removal of the right UJ: Altogether the stiffness of the segment was reduced dramatically (35%). But the unit vector $\underline{e}(\alpha)$ of the IHA was hardly altered. The axial stiffness $D_z(0)$ did no longer depend on preload position: Shifting of the preload to the dorsal did no longer affect the segment stiffness as done

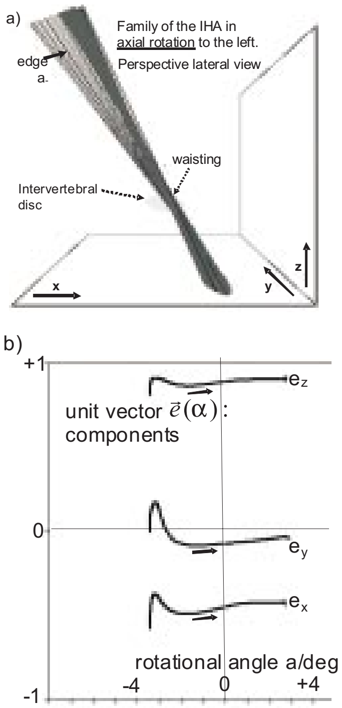

Fig. 3. Instantaneous helical axis (IHA) in axial rotation to the left.
Preload F_z = 20N running through the centre of resistance C_R.
a) The family of the IHA-lines defined a ruled surface with a distinct waisting under the intervertebral disc. Perspective lateral view. The arrow marks the edge a_- of the ruled surface.
b) Components of the unit vector of the IHA-line family depended on the rotational angle α. Since the component e_y was small the IHA-lines were found to be almost parallel to the sagittal plane. After reversal of motion (at $\alpha = -4$ deg) the IHA-line swiveled in the lateral plane in the transient process. For rotation to the right the graphs of the components were found to be almost point symmetrical. The angle between the IHA and the stimulating torque T_z was found to be about 30 deg in all segments.

in the intact segment by 2.5-fold. A sharp edge of the IHA ruled surface disappeared in large rotations to the left.

Following removal of the left UJ: Further reduction of stiffness, but the unit vector $\underline{e}(\alpha)$ *of the IHA* still remained unaltered. The second edge in rotations to the right disappeared (Fig. 5b).

Additional removal of the left VJ: Asymmetric $\alpha(T_z)$- and $\alpha(T_x)$-curves mirroring that the contact in the right VJ was suspended in rotations to the left. The segment showed an increase in stiffness only under lateral position of preload. The IHA at the diverse positions were still skew. But the angles between the unit vector $\underline{e}(\alpha)$ and $T_z(t)$ or $T_x(t)$, respectively, were only ≈17 deg or »19 deg now. A further sharp edge in the ruled surfaces disappeared. Only one of the original four sharp edges was left. $\underline{e}(\alpha)$ was no longer parallel

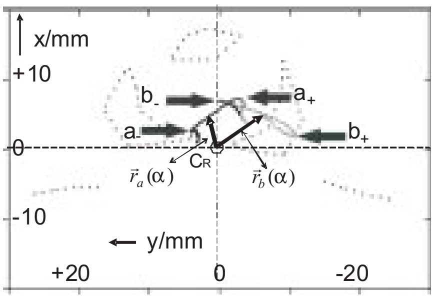

Fig. 4. Positions vector $\vec{r}_a(\alpha)$ of the IHA in axial rotation to the left. $\vec{r}_b(\alpha)$ = corresponding position vector in rotation to the right. The tips of the vectors moved along curves with lengths of 10–20mm! Both curves showed sharp edges: a_- and a_+ in rotation to the left, b_- and b_+ in rotation to the right. a- is the marked edge in figure 3a. Parameter: Preload F_z = 20 N through C_R. Dotted lines: Tracings of an x-ray picture. Below: vertebral joints; middle: both unci corporis; above: anterior segmental region.

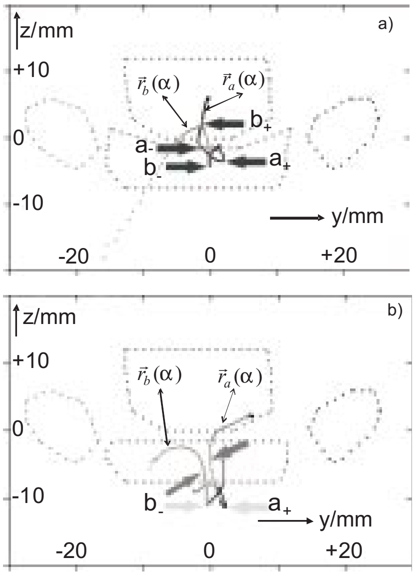

Fig. 5. Lateral flexion: Position vectors of the IHA in the y-z-plane of the coordinate system. Preload F_z = 20N through C_R.
a) Intact segment. In flexion to the left the course of the position vector $\vec{r}_a(\alpha)$ showed the two edges: a_- and a_+, in rotation to the right course $\vec{r}_b(\alpha)$ had the edges b_- and b_+.
b) Segment after excision of the two uncovertebral joint. The edges b_+ and a_- (dark arrows) were disappeared.
Dotted lines: Tracings of the corresponding X-ray pictures, frontal view. On both sides outside: the vertebral joints. a) Intact segment: With both unci corporis. b) Both unci corporis removed.

to $T_y(t)$, but now nearly parallel to the articulating surfaces of the remained left joint.

Removal of all joints: Apart from thixotropic effects, the fresh intervertebral disc revealed the kinematical properties of the measured visco-elastic layer like the disc of the autopsy material did, too.

Intact autopsy C_3/C_4

Axial rotation, lateral flexion and flexion-extension: The hystereses of the characteristics were smaller and the initial stiffness higher than those of the fresh segment. By shifting the axial preload to the dorsal, the axial stiffness increased to the same extent as for the fresh segment. The kinematic structures were hardly altered: They corresponded to those of the fresh segment.

Sole removal of all ligaments and preserved joints and intervertebral disc: Apart from a reduction of segmental stiffness, the kinematical structures closely corresponded to those of the intact segment. Especially, the stiffness again increased when the axial preload was shifted to the dorsal.

Removal of all ligaments and the two VJ, but preserved UJ and intervertebral disc: Almost parallelism of nearly stationary IHA and the torques. But the guidance of the UJ produced positions of the IHA lines which did not meet the centre of resistance as found in the disc alone or the visco-elastic layer.

5. Discussion & conclusions

The structure of segmental motion and even the stiffness were found to be dominated by the joint's guidance and not by the intervertebral disc. Generally, geometric parameters like alignment and curvature morphology of the articulating surfaces play the first role as we already found in the lumbar region [18]. This point of view is supported by the following line of reasoning: A segmental centre of rotation (as existing in the artificial intervertebral disc modelled by a visco-elastic layer) did not exist, and the directions of rotation and of applied torque did not lie in parallel (Figs. 3). The manifolds of motions were enabled by altering number and combination of the guiding joints. The edges in the IHA ruled surfaces indicated exchanges of the guiding joints. This thesis was supported by the observation that simultaneously with the successive removals of the UJ and the VJ certain edges of the IHA ruled surface disappeared. After removal of the two UJ and the left VJ the experiments showed a simpler procedure of guidance change: The sole right VJ lost its guiding in rotation to the left.

Altogether, in the intact segment, the state of guidance depended on the instantaneous position and inclination of the IHA and on the location of the static preload F_z, by which the centres of contact in the joints are set. Like in the lumbar region, the neuro-muscular apparatus is able to alter the axial segmental stiffness without any variation of preload size $|F_z|$. For solely by specified geometrical configurations of the muscle forces which produce shifts of the F_z-line to the dorsal, the segmental stiffness should be considerably heightened. This phenomenon seemed to have a general significance, since it was found in the same degree in the fresh, in both autopsy segments, and in the autopsy segment after excision of the ligaments. The only common feature of these four segments was the remained intact guidance of the joints. However, this *mechanism of rotational stiffness control by adjustment of preload position failed to take place when only one UJ in the fresh segment or the VJ was removed in the autopsy material, when so the joint guidance was no longer intact*. Additionally, the removal of one UJ or the two VJ in the autopsy segment resulted in a large decrease of the segmental stability for any type of rotation (More details in [19]).

We suggest that the postnatal UJ development (which comes along with a cleavage of parts of the intervertebral disc) involves segment stiffening and the stiffening control in axial rotation by a jamming of the UJ with the VJ. This jamming can be produced by the reactive forces of the joints and intervertebral disc, which together yield a counteracting torque because the respective force lines are skew. Sacrificing of an uncovertebral joint, as partially clinically being done, should be not undertaken, as mechanical instability would inevitably be generated.

Manuscript received by Editorial Board, February 22, 2006;
final version, October 19, 2006.

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Właściwości mechaniczne segmentów ruchowych kręgosłupa szyjnego

Streszczenie

Za pomocą czułej i precyzyjnej aparatury zmierzono serię ruchów przestrzennych odcinków szyjnych (C3/C4) kręgosłupa ludzkiego. Obrót osiowy następował pod działaniem czystego, okresowo zmiennego momentu obrotowego, a zgięcie i zgięcie-ekstensja w obecności skierowanych osiowo obciążeń wstępnych, traktowanych jako parametr zmienny, których linie sił przebiegały przez badane odcinki. Wykonując kolejno resekcje stawów międzykręgowych hakowych (Luschki) i stawów wyrostków kręgowych, a także struktur więzadłowych, dokonano oceny wpływu tych elementów na właściwości kinematyczne i sztywność odcinka szyjnego. Po raz pierwszy udało się potwierdzić biomechaniczne znaczenie stawów hakowych (Luschki). Przy rotacji osiowej i przy zgięciu bocznym chwilowa oś spiralna (IHA) okazała się niestacjonarna. Jej położenie zależało od wartości kąta obrotu. Rodzina nachylonych osi IHA utworzyła powierzchnię rozwijaną z przewężeniem. Stwierdzono, że moment obrotowy i wektor jednostkowy osi IHA są wzajemnie równoległe tylko dla ruchu zginania-ekstensji. W tym ruchu brały udział wszystkie cztery stawy, podczas gdy przy ruchu obrotowym i zgięciu bocznym stawy działały naprzemiennie. Oś IHA miała kąt $\approx +30^\circ$ przy obrocie osiowym dla momentu $T_z(t)$, oraz $\approx -30^\circ$ dla momentu $T_x(t)$. Ruchy te były sprzężone. Usunięcie wszystkich więzadeł wpłynęło w niewielkim stopniu na strukturę kinematyczną.