Acta of Bioengineering and Biomechanics
Vol. 12, No. 4, 2010

Original paper

Migration of the instantaneous axis of motion during axial rotation in lumbar segments and role of the zygapophysial joints

MARTIN MICHAEL WACHOWSKI[a]*, THELONIUS HAWELLEK[b], JAN HUBERT[b], ANDREA LEHMANN[b],
MICHAEL MANSOUR[b], CLEMENS DUMONT[a], JOCHEN DÖRNER[c], BJÖRN WERNER RAAB[d],
DIETMAR KUBEIN-MEESENBURG[b], HANS NÄGERL[b]

[a] Department of Trauma Surgery, Plastic and Reconstructive Surgery, Georg-August-University, Germany.
[b] Department of Orthodontics, Georg-August-University, Germany.
[c] Orthopaedic Clinic, Northeim, Germany.
[d] Department of Diagnostic Radiology, Georg-August-University, Germany.

The biomechanical role of the zygapophysial joints was investigated for axial rotations of lumbar segments by recording the positions of the instantaneous helical axis (IHA) against the axial rotational angle and by relating these IHA-positions to anatomical landmarks. Cyclically varying pure axial moments were applied to 3 L1/L2, 7 L3/L4 and 3 L4/L5 segments. There were 800 segment positions per cycle taken by a custom-made high precision 3D-position measuring system.

In intact segments IHA-migration reached from one zygapophysial joint to the other IHA-paths came up to 10–60 mm within small angular intervals (±1 deg). After removing the right joints, IHA-migration remained comparable with that of intact segments only for segment positions rotated to the right. Rotation to the left, however, approximately yielded stationary IHA-positions as found after resection of both joints. Hence, IHA-migration is determined by the joints already for small rotational angles. Each type of segment showed a typical pattern of IHA-migration.

Key words: *kinematics, zygapophysial joints, preload, spine, IHA, axis of rotation*

1. Introduction

In investigating mechanical properties of lumbar segments, a common approach has been to record rotational angle-torque characteristics, which have been assessed in terms of range of motion (ROM), neutral zone (NZ), stiffness, etc. [1]–[13]. These data, however, did not refer to segment *kinematics*. Therefore, a segmentally fixed axis has often been assumed around which the upper segment would helically rotate in relation to the lower segment because ROM seemed to be small covering only few degrees [14]–[20]. The position and direction of this fixed helical axis of motion (HAM) were calculated from two positions of the moved vertebrae, which almost differ by ROM. This calculation is geometrically possible [21]. But, there is a problem since HAM must not have kinematic significance. It is only a geometric construct. In reality, the vertebral body does not rotate around a simple HAM when moving from one axial position to another, but instead, there is a kinematically more complex transfer. ROUSSEAU et al. [22] have already shown that a single HAM is not sufficient to describe kinematically the motion of L5/S1 segments in flexion/extension. Four calculated finite helical axes (FHA) were clearly separated from one another, proving that real movement could not be described by a single HAM. KETTLER et al.

---

* Corresponding author: Martin Wachowski, Department of Trauma Surgery, Plastic and Reconstructive Surgery, Georg-August-University, Robert-Koch-Strasse 40, 37075 Göttingen. Phone: +49551396114, e-mail: martin.wachowski@web.de

Received: September 24th, 2010
Accepted for publication: December 4th, 2010

[23] also calculated separated FHA. Both studies therefore indicated the necessity of tracking the migration of the instantaneous helical axis (IHA) with high space resolution, in order to describe segment motions reliably as shown by WACHOWSKI et al. [24], [25].

According to the laws of kinematics, IHA would be reliably calculated if and only if the two measured positions of the mobile vertebra were approximately *differentially close-by* [21], [26]. In order to measure differentially close-by positions in approximation, we have developed a measuring method with sufficient precision and resolution [24], [25], [27] and illustrated by applying this method that each type of motion segment is characterized by specific shapes of its centrodes [24], [25], [28], [29].

Here, we address the following question: Which anatomical structures are responsible for segment kinematics?

To answer this question we clarify the role of the zygapophysial joints for axial rotation (a) by recording IHA-migration, IHA-direction, and IHA-screw-pitch under variation of the degree of pre-flexion/extension in intact lumbar segments and after removal of one zygapophysial joint as well as after removal of both joints and (b) by relating IHA-migration to anatomical landmarks of the segments.

2. Material and methods

2.1. Material

The 3 L1/L2, 7 L3/L4 and 3 L4/L5 human segments used (median: 58 years; range: 45–86 years) were stabilized with a solution that hardly altered the solid structure or the shape of the osseous and cartilaginous structures [30], [31]. Therefore, the bony parts of the joints remained substantially hard as compared to the intervertebral disc and ligaments. Thus, the possible predominance of the joints in guiding the segment was not affected by the preservation technique. Abnormalities were excluded using X-ray images and CT scans. The segments were also tested after resection of the right zygapophysial joint and of both joints.

2.2. Measurement of IHA-migration in close approximation

Onto the upper vertebra a pure axial torque was applied following a triangular time function. The spatial position of the upper vertebra was monitored in relation to the lower vertebra. A 6D measuring device used (see MANSOUR et al. [27]) consisted of six inductive linear displacement sensors (type 1310 Mahr, Germany), which had a resolution of 0.01–2.4 μm depending on gain. Their mounts were rigidly attached to the lower vertebra. The tips of the sensors touched three glass plates, which were firmly attached to the upper vertebra and formed a cube. The sensors were arranged in a 3-2-1 configuration so that the positions of their tips defined the momentary position of the cube or rather that of the upper vertebra. The precision of the device has been enhanced so that an approximately close description of IHA-migration during a motion cycle could be achieved. The entire ROM was segmented into about 800 successive intervals. For each of these small intervals (≈ ROM/800), the location of the respective helical axis was calculated (for calculation routine, see [24], [25], [27]).

2.3. Validation

The apparatus was re-validated before each measurement series using a precision screw and a circular polymer disc. Sets of IHA-positions were determined for subsequent tiny angular intervals (<0.1°). The IHA-positions were found within an interval of ±1 mm around the expected position.

2.4. Measuring procedure

Both vertebrae were embedded in Combipress® (Methacrylat-Copolymer). The lower vertebra was securely screwed to the frame of the apparatus. The upper vertebra was fixed to the mobile device generating torque and preload. Each segment was arranged so that the x-y-plane was almost parallel to the “plane” of the intervertebral disc. The x-axis ran in the segmental sagittal mirror plane. For the L3/L4 segments the origin of the coordinate system was set in the center of the spinal canal. For the other segments it was experimentally adjusted by shifting a preload F_z along the x-axis. When the segment no longer bent or tilted, the F_z-line met the z-axis of the chosen coordinate system and the x- and y-positions of the origin were set at the transition from flexion to extension. Its z-position was set in the middle of the dorsal margin of the vertebral disc. In this way the origin gained functional significance and was no longer set at an anatomical landmark. The lower vertebra served as reference.

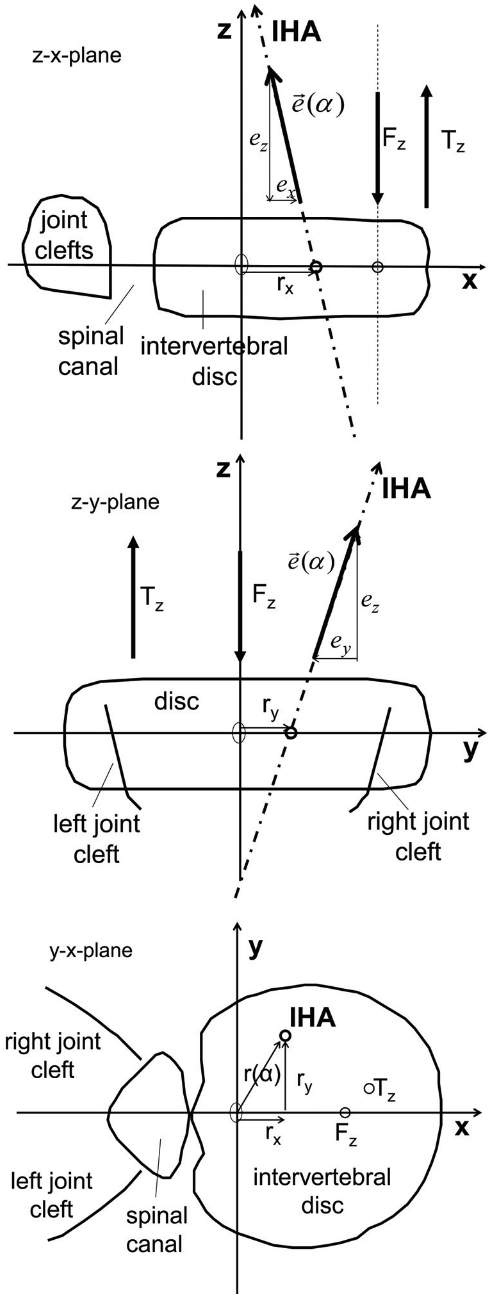

Fig. 1. IHA-line position: z-x-plane has components e_z and e_x and z-y-plane e_z and e_y of the unit vector $\vec{e}(\alpha)$. The position vector $\vec{r}(\alpha)$ is defined by the intersection of the IHA-line with the y-x-plane: r_x and r_y. Preload F_z is shifted along the x-axis. The application point of axial torque T_z is arbitrary

Following this predefinition of the coordinate system the segment was subjected to a stationary axially directed preload F_z in a non-constraining and non-reactive manner. In the test series, its value was varied in 100 N steps between 0 N and 400 N. The F_z-line initially ran through the origin of the coordinate system of the apparatus. In further runs of tests the x-y-position of this F_z-line served as parameter. The accuracy of the line setting was ±0.5 mm. This preload produced a retarding compressive strain. When it was finally stationary, the axially directed pure torque ($T_z(t)$) was applied independently of preload F_z. The parameters of triangular time function $T_z(t)$ included: amplitude 3240 Ncm (3 L1/L2, 5 L3/L4, 3 L4/L5) or 2500 Ncm (2 L3/L4); period ≈1 min.

In the courses of segment motion the following kinematical quantities were determined (figure 1): position vector $(\vec{r}(\alpha)=\vec{r}_x(\alpha)+\vec{r}_y(\alpha)+\vec{r}_z(\alpha))$ (accuracy ±1.0 mm), unit vector $(\vec{e}(\alpha)=\vec{e}_x(\alpha)+\vec{e}_y(\alpha)+\vec{e}_z(\alpha)$, with $|\vec{e}(\alpha)=1|$) of IHA-line (accuracy of its main component ≤0.2%), and the instantaneous screw pitch $\tau(\alpha)$ (≤5%) as functions of the rotational angle $\alpha(t)$, and also the rotational angle-torque characteristics.

3. Results

3.1. Common kinematic features of all segments investigated

I. In all intact segments IHA migrated over several centimetres (up to 8 cm).

a. Its path depended greatly on the degree of pre-flexion/-extension (figure 2).

b. The unit vector of IHA (direction) was not precisely parallel to the axial torque vector $T_z(t)$: IHA tilted laterally by some degrees from the left/right to the right/left side, with axial rotation increasing to the left/right, and was constantly slightly inclined to the dorsal.

c. The major part of IHA-migration was routinely seen within a small angular range between –1° and +1°, especially in the pre-flexed segments (figure 2, table 1).

d. The instantaneous screw pitches were mainly proportional to the rotational angle: $\tau(\alpha)\propto\alpha$. Hence, the vertebrae moved away from one another, with the absolute rotational angle increasing up to about ≈ 100 µm.

II. Removal of one/both vertebral joints altered the paths of IHA-migration dramatically.

a. After removal of one vertebral joint, IHA-migrations were almost identical for parts of the rotational cycles, while other parts were changed radically.

b. Removal of both vertebral joints resulted in IHA-migrations to a minor extent, within the intervertebral disc (figure 3). IHA-locations were then hardly influenced by pre-flexion/-extension.

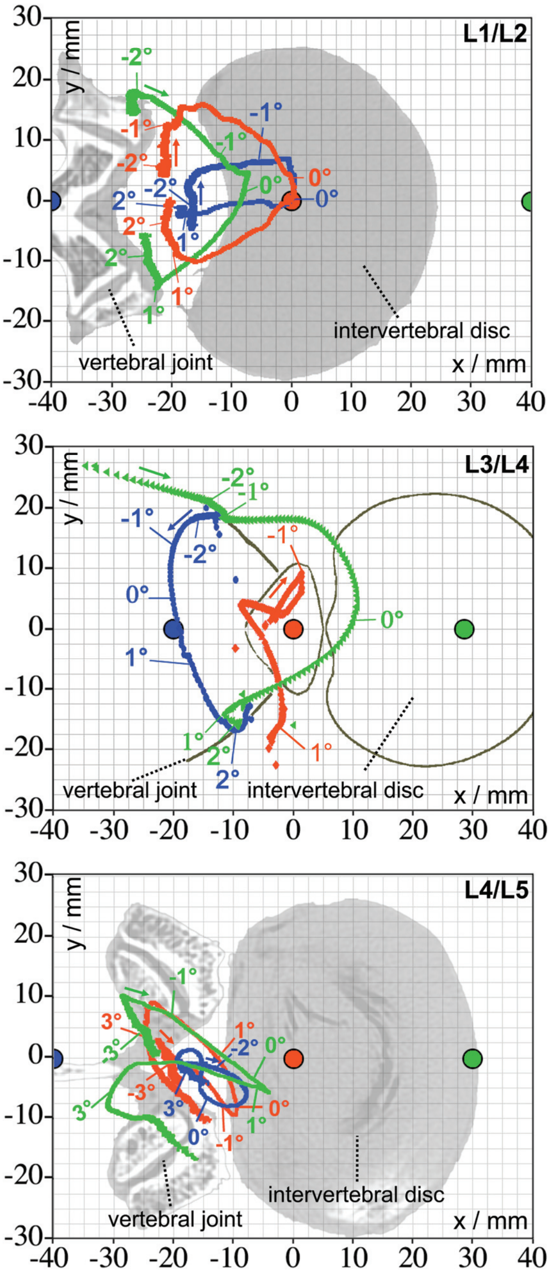

Fig. 2. Comparison of IHA-migration in axial segment rotations to the left from the maximal rotated position to the right. Centrodes for the pre-extended (blue), pre-flexed (green) and neutral (red) state produced by the position of axial preload (●: flexing, ●: neutral, ●: extending). Same features of IHA-migration in the same segment types. The major part of IHA-migration was seen between –1° and +1° axial rotation

Table 1a–c. IHA-path lengths between +1° and –1° axial rotation measured in cm for the flexed or extended segments, for the L1/L2 and L4/L5 segments in neutral flexion/extension. l = path lengths in the intact segments. l_w = path lengths in the segments after removal of both joints but with still-preserved ligaments. Exception: In the segments L3/L4A,B also the ligaments were removed. In removing the joint segment L3/L4G was destroyed. The data prove without doubt that the IHA-migration is dominated by the guidance of the joints

a. L1/L2-segments

Segment	State of flexion–extension	IHA-path lengths between +1° and –1° axial rotation in cm		
		l	l_w	$l–l_w$
L1/L2A	flexed	3.20	0.73	2.47
	neutral	5.61		4.88
	extended	3.34		2.61
L1/L2B	flexed	1.10	0.24	0.86
	neutral	2.06		1.82
	extended	1.72		1.48
L1/L2C	flexed	3.49	1.64	1.85
	neutral	4.45		2.81
	extended	3.11		1.47
L1/L2 means (SD)	flexed	2.60 (1.30)	0.87 (0.71)	1.73 (0.81)
	neutral	4.04 (1.81)		3.05 (1.72)
	extended	2.72 (0.88)		1.85 (0.66)

b. L4/L5-segments

L4/L5A	flexed	2.73	1.11	1.62
	neutral	2.94		1.83
	extended	2.30		1.19
L4/L5B	flexed	1.83	0.73	1.10
	neutral	1,48		0.75
	extended	2.30		1.57
L4/L5C	flexed	2.41	0.53	1.88
	neutral	1.34		0.81
	extended	1.28		0.75
L4/L5 means (SD)	flexed	2.32 (0. 46)	0.79 (0.29)	1.53 (0.40)
	neutral	1.92 (0.89)		1.13 (0.61)
	extended	1.96 (0.59)		1.17 (0.41)

c. L3/L4-segments

L3/L4A	flexed	6.28	0.2	6.08
	extended	2.06		1.86
L3/L4B	flexed	5.26	0.2	5.06
	extended	4.44		4.24
L3/L4$_{A,B}$ means	flexed	5.77	0.2	5.57
	extended	3.25		3.25
L3/L4C	flexed	1,20	0.61	0.59
	extended	1.09		0.48
L3/L4D	flexed	2.96	0.98	1.98
	extended	3.36		2.38
L3/L4E	flexed	1.96	0.44	1.52
	extended	1.81		1.37
L3/L4F	flexed	1.43	0.33	1.10
	extended	0.82		0.82
L3/L4G	flexed	0.98		
	extended	0.58		
L3/L4 means	flexed	1.89 (0.79)	0.59 (0.28)	1.30 (0.59)
	extended	1.77 (1,14)		1.26 (1.12)

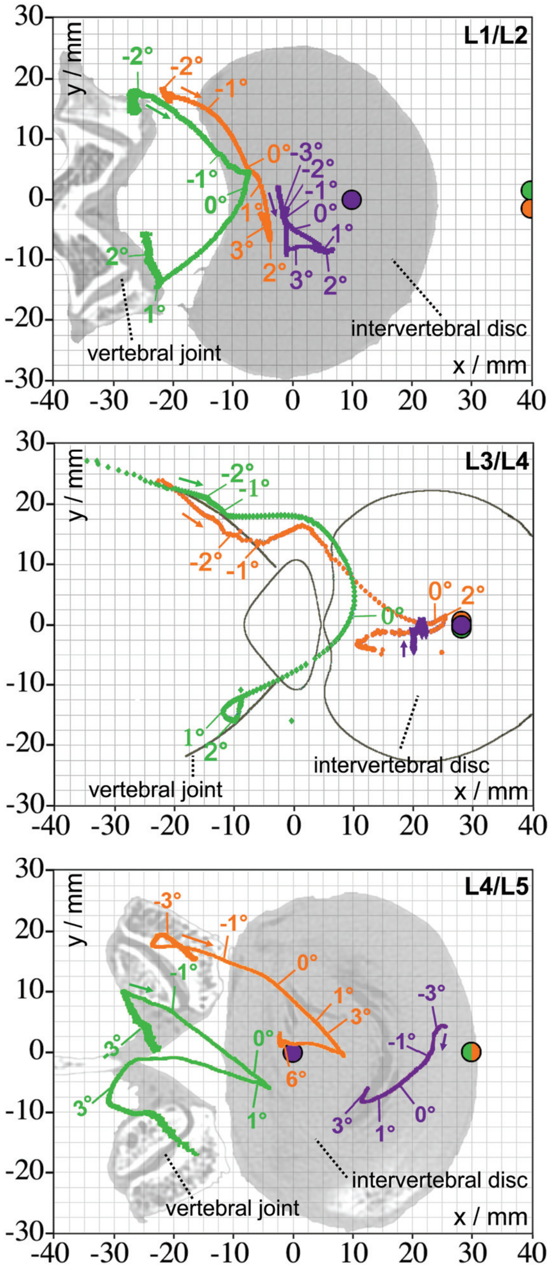

Fig. 3. Axial IHA-migration in segment rotations to the left from the maximal rotated position to the right in pre-flexion: intact segment (●), after resection of the right joint (●), after subsequent resection of both joints (for L3/L4 additionally all ligaments) (●). After resection of the right joint, IHA migrated from positions near the left joint along a centrode close to the centrode of the intact segment. Approaching neutral rotation, further IHA-migration broke down (further IHA-position comparable with the status after resection of both joints)

3.2. Intact segments

L1/L2-segments: The intersections of IHA with the *x*-*y*-plane demonstrated wide IHA-migrations whose paths (lengths >40 mm) represent the corresponding centrodes, which matched up for both senses of rotation. In the largest rotated position of the upper vertebra to the right/left, IHA was always found near the left/right joint. An increase in the preload F_z from 200 N to 300 N and 400 N did not alter the shape of these centrodes, but ventral or dorsal shifting of the line of the preload F_z did (figure 2).

L3/L4-segments: In L3/L4 segments, the shape of the centrodes greatly depended on the state of pre-flexion/-extension (figure 2): under pre-flexion IHA-migration along wide ventral bows from one joint to the other and vice versa and under pre-extension within the dorsal part of the spinal canal. The lengths of the centrodes amounted to about 60 mm (under flexion) and 30 mm (under extension). In maximum rotation to the left/right, IHA was located at the right/left joint.

L4/L5-segments: In neutral pre-flexion/-extension of the segments IHA-migration following the axial torque $T_z(t)$ was limited to the spinal canal: the centrodes were formed like loops. This special IHA-migration was seen in all three segments (figure 2). Again, the shapes of the centrodes greatly depended on the pre-flexion/-extension. A further restricted concentration of IHA-migrations within the spinal canal under extension could be seen, but modulated ventral bows (lengths ≈ 40 mm) were found under flexion. Then, IHA was near the right/left joint at maximum rotation to the right/left.

3.3. Segments after resection of the right joint

L1/L2-segments: With maximal rotation to the right, IHA was located close to the left joint for each segment (figure 3). In subsequent rotation to the left IHA migrated along the centrode as it was measured for the corresponding intact segment up to neutral axial rotation. From there the centrode of the intact segment was left in further rotation to the left. IHA no longer migrated towards the right joint but remained thereabouts within the disc where it was then after resection of both joints (figure 3). In the reversal rotation to the right, IHA ran along almost the same path back to the left joint with maximum rotation to the right. These features were found with each degree of pre-flexion/-extension.

L3/L4-segments: Under pre-flexion, IHA was at maximum rotation to the right within the left joint. Following rotation to the left, IHA initially ran on the centrode of the intact segment (figure 3). On reaching neutral axial rotation, IHA then migrated along the centrode, which was seen when all joints were removed (figure 3) and IHA-migration hardly depended on pre-flexion/-extension.

L4/L5-segments: In neutral pre-flexion/-extension or under extension, IHA moved around within a small region near the intact left joint for the entire ROM. Under pre-flexion, IHA was near the intact left joint in the maximally rotated segment to the right and initially migrated during subsequent rotation to the left along centrodes that were very similar to those of the intact segments. But when neutral axial rotation was reached, IHA-migration stopped (figure 3).

L3/L4B-segment without ligamentous apparatus, but with intact joints: After removal of all ligamentous structures (ligaments, articular capsules), IHA-migration could hardly be distinguished from that of the intact specimen (figure 4).

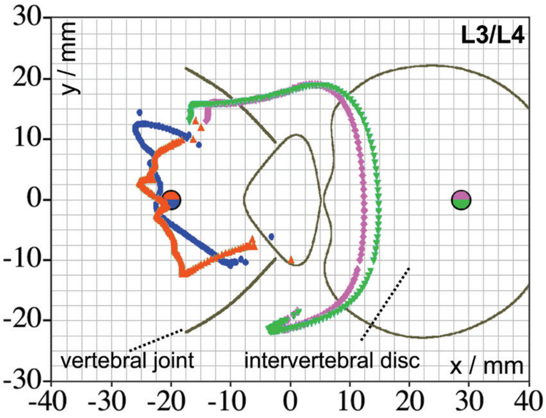

Fig. 4. The centrodes of axial rotation in the flexed or extended L3/L4 segment after resection of all ligamentous structures in comparison with the intact segment. blue/green: intact segment in pre-extension/-flexion red/purple: segment after resection of all ligaments in pre-extension/-flexion. There are still ventrally/dorsally open bows depending on pre-flexion/-extension status known from the intact segments

3.4. Summary of the most important findings

– The shapes of the axial centrodes depend greatly on the degree of pre-flexion/-extension.

– IHA-migration within a small angular interval of ±1° can extend as far as 60 mm.

– Different types of segments show different patterns of IHA-migration but, within the same type, IHA-migration is very similar.

4. Discussion

Our analysis of the biomechanics of lumbar segments showed that IHA migrates several centimetres during axial rotation, which is caused by joint guidance.

The resolution of 0.1 mm of the 3-D-WinJaw/WinBiomechanics ultrasound motion analysis system and 3-D-video-measurements were not sufficient [23], [32], [33] to record IHA-centrodes. Just enhancing the resolution of our 6D position-measuring system at a 0.5 μm level ensured that IHA-migration could be reliably observed. The preloads applied were non-constraining to prevent artifacts especially in axial rotation [34].

Comparison of the results before and after resection of the facet joints proves that the joints are responsible for IHA-position, IHA-alignment and IHA-migration during axial rotations in all segments investigated.

1. In the intact segments the degree of pre-flexion/-extension sets the positions of contact between the articulating surfaces and thus triggers the shape of the centrodes. Hence, after resection of both joints and absent joint guidance pre-flexion/-extension hardly influenced IHA-migration.

2. Under joint-guidance IHA migrated over long distances up to almost 60 mm within the small physiological interval (≈±1.0°) of axial rotation [35], especially in the flexed segments (figure 2, table 1). After joint resection the IHA was practically stationary in this interval (≈ ±1.0°).

3. The resection of the right joint in the segments alone tested our hypothesis. As long as the intact left joint remaining was made functional by a sufficiently large axial rotation to the right and its articulating surfaces came into contact, IHA approximately followed the corresponding centrode of the intact segment (figure 3). With rotations to the left, the intact joint lost contact between its articulating surfaces and consequently its guiding function by exposing a visible cleft: IHA-migration was now limited to a small region as seen after resection of both joints (figure 5).

We expected that IHA should slightly migrate after resection of both joints (figure 3), since some ligamentous fibres became alternately slack or tightened in the course of axial rotation. On the other hand, exclusive resection of all ligaments hardly influenced the shape of IHA-migration (figure 4) confirming the dominance of the joints in guiding axial segment kinematics.

For all three types of segments, IHA was located near to or in the left/right joint (especially in the

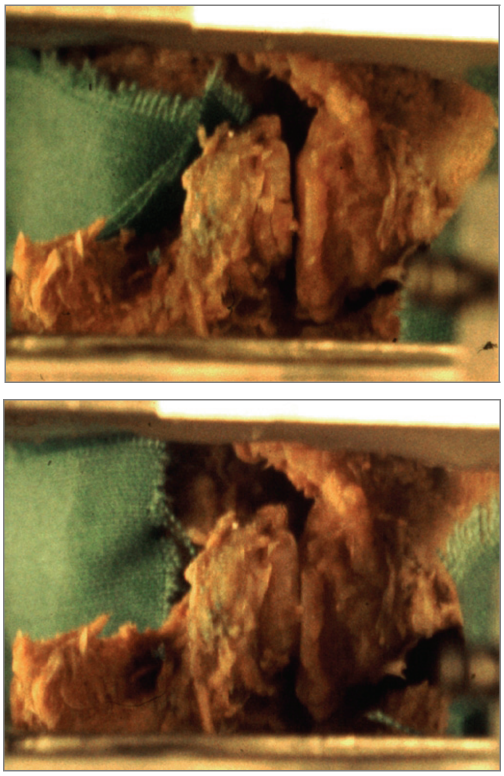

Fig. 5. Segment L3/L4A after resection of the right joint. Photos of the remaining intact left joint. In maximal rotation to the left, a joint space is visible (upper photo). In maximal rotation to the right, the joint space is closed (lower photo). Conclusion in synopsis with the IHA-migration: In rotation to the right, the left joint is made functional. In rotation to the left it is not

flexed segment) when the respective axial rotation to the right/left approached its maximum (figure 2). This location of the IHA implicated that the articulating surfaces must now roll to a substantial extent [36]–[39]. Simultaneously, the left/right joint was exposed to a compressive joint force. Hence, in the loaded joint, *sliding* friction is replaced by considerably smaller *rolling* friction. By this mechanism the problem of friction, as soon as the joint is loaded, is solved kinematically like in the knee joint [36].

Similarities and differences in IHA-migration: In all segments under pre-flexion, the ventrally bent centrodes indicated that only one joint guided axial rotation (figure 6).

In pre-flexed L3/L4-segments the joints alternated in guiding axial rotation, whereas under pre-extension the dorsally concentrated centrodes indicated that both joints provided simultaneous guidance.

For the pre-flexed L1/L2-segments, the ventrally bent axial centrodes also indicated that the joints alternated in providing guidance. Our rationale is: the centrodes of the intact segments and the respective segments with the removed right joint nearly coincided out of maximal axial rotation to the right (figure 3).

The L4/L5-segments provided alternating guidance of the joints only in the pre-flexed condition. In pre-extension and neutral flexion/extension simultaneous guidance placed the axial IHA in the area of the spinal canal.

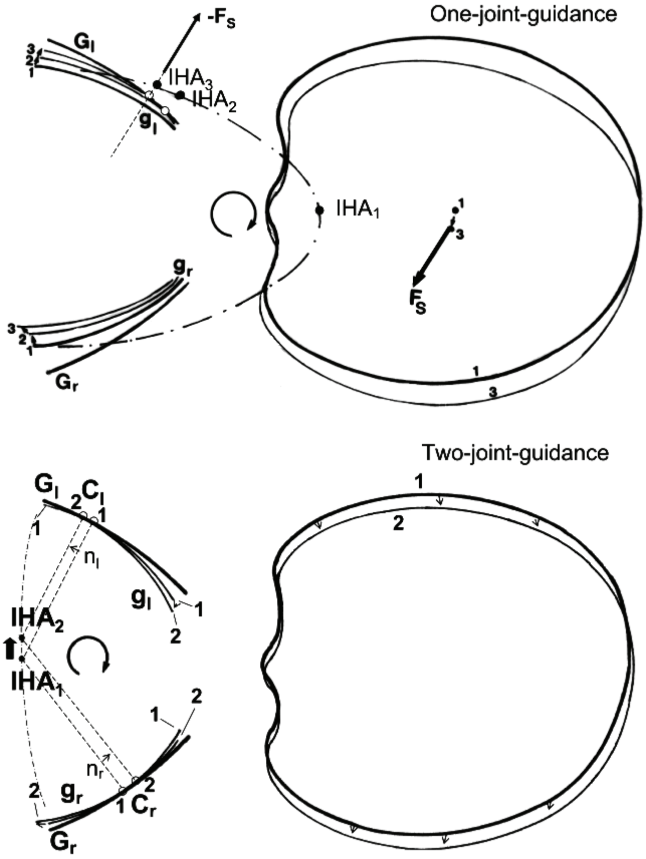

Fig. 6. Simple geometric models.
One-joint guidance: In flexion, upper facets g_r, $g_l(1)$ may not come into contact with the lower facets G_r, G_l: Neutral position of IHA_1. In rotations to the right, $g_l(2)$ contacts G_l: dorsal IHA-migration along the left joint: IHA_3, $g_l(3)$. The result of alternating one-joint guidance is a ventrally bent centrode.
Two-joint guidance: In extension, contacts in both joints. Normal n_r or n_l in contact C_r or C_l meets IHA_1.
In rotations to the right, C_l migrates to the dorsal and C_r to the ventral: IHA migrates towards the left joint.
The result of two-joint guidance is a dorsally bent centrode

The kinematic properties of the three types of segments were substantially different for axial rotation (figures 2, 3). Hence, the curvatures of their articulating surfaces must differ morphologically. Therefore, the precise recording of the differential geometry of the joint facets is an important aspect to be considered in future anatomical research.

Material and methods: A cursory consideration might suggest a weak point in our measurements because only preserved and not fresh segments were available. No doubt the preservation technique influenced the visco-elastic properties of the soft structures and thus the segment stiffness [8]. The segment kinematics, however, would not be altered provided that the hardness of the bony structures of the joints remained higher by a magnitude of some powers of ten more than that of the soft structures, and so the guidance of the segment would be further dominated by the vertebral joints as the measurements clearly revealed.

5. Conclusions

Based on the measurements of axial rotation we can draw the following conclusions:

1. In each and every case axial segment kinematics is guided by a minimum of one zygapophysial joint.
2. Segment motion in axial rotation, in particular within the small angular interval of ±1°, is alternately or simultaneously guided by the zygapophysial joints.
3. Axial segment kinematics is parametrically controlled by the position of axial directed forces adjusting the contact positions in the joints.

These conclusions have the following consequences:

a. The design of non-fusion spine implants (e.g. TDA, TFA, all dynamic stabilization systems) has to take joint guidance into account.

b. FE-calculations of segment motions primarily have to take joint guidance into account, especially within the angular interval of ±1° and the apparent wide IHA-migration.

c. The just roughly known curvature morphology of the articulating surfaces and the unknown alignments of the surfaces in diverse lumbar segments must be clarified using high-precision anatomical measurements.

References

[1] CUNNINGHAM B.W., GORDON J.D., DMITRIEV A.E., HU N., MCAFEE P.C., *Biomechanical evaluation of total disc replacement arthroplasty: an in vitro human cadaveric model*, Spine, 2003, 28(20), 110–117.

[2] GALBUSERA F., BELLINI C.M., ZWEIG T., FERGUSON S., RAIMONDI M.T., LAMARTINA C., BRAYDA-BRUNO M., FORNARI M., *Design concepts in lumbar total disc arthroplasty*, Eur. Spine J., 2008, 17(12), 1635–1650.

[3] MCAFEE P.C., CUNNINGHAM B.W., HAYES V., SIDIQI F., DABBAH M., SEFTER J.C., HU N., BEATSON H., *Biomechanical analysis of rotational motions after disc arthroplasty: implications for patients with adult deformities*, Spine, 2006, 31(19 Suppl.), 152–160.

[4] PANJABI M.M., *Biomechanical evaluation of spinal fixation devices:* I. *A conceptual framework*, Spine, 1988, 13(10), 1129–1134.

[5] PANJABI M.M., ABUMI K., DURANCEAU J., CRISCO J.J., *Biomechanical evaluation of spinal fixation devices:* II. *Stability provided by eight internal fixation devices*, Spine, 1988, 13(10), 1135–1140.

[6] PANJABI M.M., OXLAND T.R., YAMAMOTO I., CRISCO J.J., *Mechanical behavior of the human lumbar and lumbosacral spine as shown by three-dimensional load-displacement curves*, JBJS Am., 1994, 76(3), 413–424.

[7] SCHMIDT H., HEUER F., CLAES L., WILKE H.J., *The relation between the instantaneous center of rotation and facet joint forces – A finite element analysis*, Clin. Biomech., 2008, 23(3), 270–278.

[8] WILKE H.J., KRISCHAK S., CLAES L.E., *Formalin fixation strongly influences biomechanical properties of the spine*, J. Biomech., 1996, 29(12), 1629–1631.

[9] GZIK M., WOLAŃSKI W., TEJSZERSKA D., *Experimental determination of cervical spine mechanical properties*, Acta Bioeng. Biomech., 2008, 10(4), 49–54.

[10] CZYŻ M., ŚCIGAŁA K., JARMUNDOWICZ W., BĘDZIŃSKI R., *The biomechanical analysis of the traumatic cervical spinal cord injury using finite element approach*, Acta Bioeng. Biomech., 2008, 10(1), 43–54.

[11] PAWŁOWSKI P., ARASZKIEWICZ M., TOPOLIŃSKI T., MATEWSKI D., *Impact of injury on changes in biomechanical loads in human lumbar spine*, Acta Bioeng. Biomech., 2009, 11(4), 9–14.

[12] PEZOWICZ C., FILIPIAK J., *Influence of loading history on the cervical screw pullout strength value*, Acta Bioeng. Biomech., 2009, 11(3), 35–40.

[13] TYNDYKA M.A., BARRON V., MCHUGH P.E., O'MAHONEY D., *Generation of a finite element model of the thoracolumbar spine*, Acta Bioeng. Biomech., 2007, 9(1), 35–46.

[14] COSSETTE J.W., FARFAN H.F., ROBERTSON G.H., WELLS R.V., *The instantaneous center of rotation of the third lumbar intervertebral joint*, J. Biomech., 1971, 4(2), 149–153.

[15] HABERL H., CRIPTON P.A., ORR T.E., BEUTLER T., FREI H., LANKSCH W.R., NOLTE L.P., *Kinematic response of lumbar functional spinal units to axial torsion with and without superimposed compression and flexion/extension*, Eur. Spine J., 2004, 13(6), 560–566.

[16] NIOSI C.A., ZHU Q.A., WILSON D.C., KEYNAN O., WILSON D.R., OXLAND T.R., *Biomechanical characterization of the three-dimensional kinematic behaviour of the Dynesys dynamic stabilization system: an in vitro study*, Eur. Spine J., 2006, 15(6), 913–922.

[17] OXLAND T.R., PANJABI M.M., LIN R.M., *Axes of motion of thoracolumbar burst fractures*, J. Spinal Disord., 1994, 7(2), 130–138.

[18] PANJABI M.M., KRAG M.H., GOEL V.K., *A technique for measurement and description of three-dimensional six degree-of-freedom motion of a body joint with an application to the human spine*, J. Biomech., 1981, 14(7), 447–460.

[19] WHITE A.A. 3rd, PANJABI M.M., *The basic kinematics of the human spine. A review of past and current knowledge*, Spine, 1978, 3(1), 12–20.

[20] ZHU Q., LARSON C.R., SJOVOLD S.G., ROSLER D.M., KEYNAN O., WILSON D.R., CRIPTON P.A., OXLAND T.R., *Biomechanical evaluation of the Total Facet Arthroplasty System: 3-dimensional kinematics*, Spine, 2007, 32(1), 55–62.

[21] BEATTY M.F., *Kinematics of finite rigid-body displacements*, J. Physics. Am., 1966, 34, 949–955.

[22] ROUSSEAU M.A., BRADFORD D.S., HADI T.M., PEDERSEN K.L., LOTZ J.C., *The instant axis of rotation influences facet forces at L5/S1 during flexion/extension and lateral bending*, Eur. Spine J., 2006, 15(3), 299–307.

[23] KETTLER A., MARIN F., SATTELMAYER G., MOHR M., MANNEL H., DURSELEN L., CLAES L., WILKE H.J., *Finite helical axes of motion are a useful tool to describe the three-dimensional in vitro kinematics of the intact, injured and stabilised spine*, Eur. Spine J., 2004, 13(6), 553–559.

[24] WACHOWSKI M.M., MANSOUR M., HAWELLEK T., KUBEIN-MEESENBURG D., HUBERT J., NÄGERL H., *Parametric Control of the Stiffness of Lumbar Segments,* Strain, 2009, doi: 10.1111/j.1475-1305.2009.00686.x.

[25] WACHOWSKI M.M., MANSOUR M., LEE C., ACKENHAUSEN A., SPIERING S., FANGHÄNEL J., DUMONT C., KUBEIN-MEESENBURG D., NÄGERL H., *How do spinal segments move?*, J. Biomech., 2009, 42(14), 2286–2293.

[26] WOLF K., *Lehrbuch der technischen Mechanik starrer Systeme*, Springer, Wien, 1947.

[27] MANSOUR M., SPIERING S., LEE C., DATHE H., KALSCHEUER A.K., KUBEIN-MEESENBURG D., NÄGERL H., *Evidence for IHA migration during axial rotation of a lumbar spine segment by using a novel high-resolution 6D kinematic tracking system*, J. Biomech., 2004, 37(4), 583–592.

[28] WACHOWSKI M.M., ACKENHAUSEN A., DUMONT C., FANGHÄNEL J., KUBEIN-MEESENBURG D., NÄGERL H., *Mechanical properties of cervical motion segments*, Arch. Mech. Eng., 2007, LIV (1), 5–15.

[29] WACHOWSKI M.M., HUBERT J., HAWELLEK T., MANSOUR M., DORNER J., KUBEIN-MEESENBURG D., FANGHÄNEL J., RAAB B.W., DUMONT B.C., NÄGERL H., *Axial rotation in the lumbar spine following axial force wrench*, J. Physiol. Pharmacol., 2009, 60 Suppl. 8, 61–64.

[30] FANGHÄNEL J., *Ingredients of the preserving solution: Aqua dest, alcohol, glycerine, formalin, thymol, salicylic acid*, Personal Communication, 2009.

[31] FANGHÄNEL J., SCHULTZ F., *Mitteilung über eine Konservierungsflüssigkeit für anatomisches Präpariermaterial*, Z Med. Labortech, 1962, 3, 329–332.

[32] WOLTRING H.J., *3-D attitude representation of human joints: a standardization proposal*, J. Biomech., 1994, 27(12), 1399–1414.

[33] WOLTRING H.J., LONG K., OSTERBAUER P.J., FUHR A.W., *Instantaneous helical axis estimation from 3-D video data in neck kinematics for whiplash diagnostics*, J. Biomech., 1994, 27(12), 1415–1432.

[34] CRIPTON P.A., BRUEHLMANN S.B., ORR T.E., OXLAND T.R., NOLTE L.P., *In vitro axial preload application during spine flexibility testing: towards reduced apparatus-related artefacts*, J. Biomech., 2000, 33(12), 1559–1568.

[35] GREGERSEN G.G., LUCAS D.B., *An in vivo study of the axial rotation of the human thoracolumbar spine*, JBJS Am., 1967, 49(2), 247–262.

[36] FROSCH K.H., FLOERKEMEIER T., ABICHT C., ADAM P., DATHE H., FANGHÄNEL J., STURMER K.M., KUBEIN-MEESENBURG D., NÄGERL H., *A novel knee endoprosthesis with a physiological joint shape.* Part 1: *Biomechanical basics and tribological studies*, Unfallchirurg, 2009, 112(2), 168–175.

[37] KUBEIN-MEESENBURG D., NÄGERL H., FANGHÄNEL J., *Elements of a general theory of joints*. 1. *Basic kinematic and static function of diarthrosis*, Anat. Anz., 1990, 170(3–4), 301–308.

[38] NÄGERL H., KUBEIN-MEESENBURG D., COTTA H., FANGHÄNEL J., *Biomechanical principles of diarthroses and synarthroses.* III: *Mechanical aspects of the tibiofemoral joint and role of the cruciate ligaments*, Z Orthop. ihre Grenzgeb., 1993, 131(5), 385–396.

[39] NÄGERL H., KUBEIN-MEESENBURG D., COTTA H., FANGHÄNEL J., ROSSOW A., SPIERING S., *Biomechanical principles in diarthroses and synarthroses*. IV: *The mechanics of lumbar vertebrae*, A pilot study, Z Orthop. ihre Grenzgeb., 1995, 133(6), 481–491.