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Marcus Richter
Hans-Joachim Wilke
Patrick Kluger
Lutz Claes
Wolfhart Puhl

Load-displacement properties of the normal and injured lower cervical spine in vitro

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M. Richter (✉) · P. Kluger · W. Puhl
Department of Orthopaedics and SCI, University of Ulm, Ulm, Germany
e-mail: marcus.richter@medizin.uni-ulm.de,
Tel.: +49-731-5112, Fax: +49-731-1103

H-J. Wilke · L. Claes
Department of Orthopaedic Research and Biomechanics, University of Ulm, Ulm, Germany

M. Richter
RKU – Orthopädische Klinik mit Querschnittgelähmtenzentrum der Universität Ulm, Oberer Eselsberg 45, 89081 Ulm, Germany

Abstract The objective of this study was to determine which discoligamentous structures of the lower cervical spine provide significant stability with regard to different loading conditions. Accordingly, the load-displacement properties of the normal and injured lower cervical spine were tested in vitro. Four artificially created stages of increasing discoligamentous instability of the segment C5/6 were compared to the normal C5/6 segment. Six fresh human cadaver spine segments C4-C7 were tested in flexion/extension, axial rotation, and lateral bending using pure moments of ± 2.5 Nm without axial preload. Five conditions were investigated consecutively: (1) the intact functional spinal unit (FSU) C5/6; (2) the FSU C5/6 with the anterior longitudinal ligament and the intertransverse ligaments sectioned; (3) the FSU C5/6 with an additional 10-mm-deep incision of the anterior half of the anulus fibrosus and the disc; (4) the FSU C5/6 with additionally sectioned ligamenta flava as well as interspinous and supraspinous ligaments; (5) the FSU C5/6 with additional capsulotomy of the facet joints. In flexion/extension, significant differences were observed concerning range of motion (ROM) and neutral zone (NZ) for all four stages of instability compared to the intact FSU. In axial rotation, only the stage 4 instability showed a significantly increased ROM and NZ compared to the intact FSU. For lateral bending, no significant differences were observed. Based on these data, we conclude that flexion/extension is the most sensitive load-direction for the tested discoligamentous instabilities.

Key words Cervical spine · Biomechanical testing · Discoligamentous structures

Introduction

The discoligamentous structures of the cervical spine are often involved in cervical spine injuries, for example in whiplash injuries. Although standard clinical imaging techniques, especially nuclear magnetic resonance imaging (MRI), allow the detection of discoligamentous injuries [9, 13, 24, 30, 31], few biomechanical data exist concerning the significance of the different discoligamentous structures for the load-displacement properties of the cervical spine under physiological loads. Several studies have been carried out to evaluate the load-displacement properties of the normal lower cervical spine in vitro [6, 15, 17, 19, 25] and in vivo [2, 3, 12, 20], as well as in different types of artificial defect situations [6, 18, 26, 32]. Variations in the study designs with regard to testing protocol and type of artificial defect make comparison between the different studies difficult. Few studies have tested artificial discoligamentous defects in the lower cervical spine under near-physiological loads [25, 26, 32].

The objective of this study was therefore to evaluate the type and amount of instability caused by injury of different discoligamentous structures of the cervical spine in comparison to the intact cervical spine.

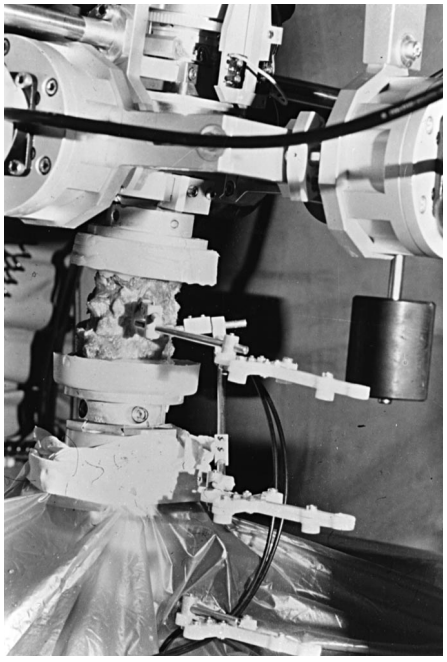

Fig. 1 Cervical human C4–C7 specimen fixed in the three-dimensional spinal loading simulator. Monosegmental motion of the segment C5/6 was measured using a noncontacting ultrasound motion analysis system

Materials and methods

We tested six human cadaveric cervical spine segments (C4-C7) with a mean age of 84.8 ± 11.2 years. The specimens were wrapped in triple-sealed plastic bags and kept frozen at –20 °C prior to preparation and testing. Before testing, the specimens were thawed at room temperature and all musculature was removed, while carefully preserving ligamentous and bony structures.

The cranial vertebra (C4) and the caudal vertebra (C7) were potted in polymethylmethacrylate (Technovit 3040, Heraeus Kulzer GmbH, Wehrheim, Germany). To achieve a better anchorage of the vertebrae in the plastic material, short screws were partially driven into the two embedded vertebrae. The specimens were mounted in a previously described spinal loading simulator (Fig. 1) [28]. C7 was fixed rigidly in the testing device, C4 was fixed in a gimbal containing integrated stepper motors that could introduce pure moments separately around three axes. The other five out of six degrees of freedom were free, enabling the specimen to move unconstrained.

The motion in each single segment was measured simultaneously using a three-dimensional ultrasound-based motion analysis system (Zebris, 50/4, Isny, Germany) with a reported resolution of 0.2 °. Plastic crosses were rigidly fixed with screws to the ventral part of the vertebral body. Each cross has three integrated ultrasound transmitters on one side and three integrated ultrasound receivers on the other side. The transmitter sends pulse ultrasound waves. Each receiver measures the time of the ultrasound signal picked up from each transmitter of the adjacent cross, and uses this information to calculate the relative motion of these adjacent crosses and thus of the vertebrae. The Euler angles are then projected into the principal motion planes to enable imaging of the results, taking into account a certain level of error, which is negligible so long as the coupled motions are not too big.

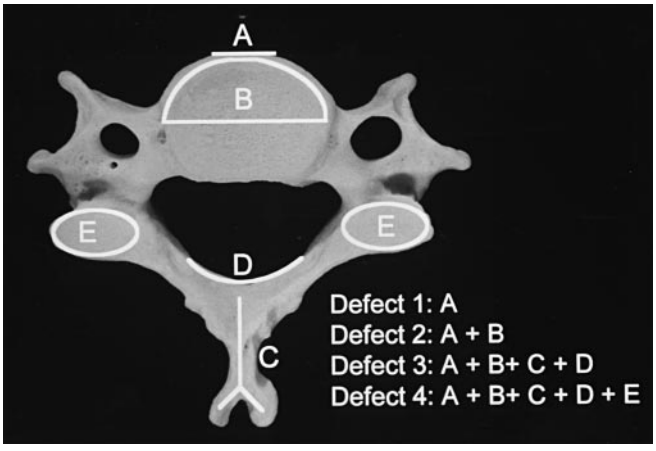

Fig. 2 A–E The four artificial discoligamentous injuries. Sectioned structures: **A** anterior longitudinal ligament, **B** anterior half of the anulus fibrosus and the disc, **C** inter- and supraspinous ligaments, **D** ligamenta flava, **E** facet joint capsules

Alternating sequences of flexion/extension (± M*y*), left/right axial rotation (± M*z*), and right/left lateral bending (± M*x*) moments of 2.5 Nm in each direction were applied at a constant rate of 2 °/s. Two precycles were applied to precondition the construct so as to minimize the viscoelastic effects, and data of the third cycle were recorded.

The range of motion (ROM) and the neutral zone (NZ) of the segment C5/6 were determined for each direction of loading. ROM was defined as the angular deformation at maximum load. NZ was defined as the difference at zero load between the angular positions corresponding to the loading and unloading phases of the test cycle, which corresponds to the range in which only very small moments are needed to flex, rotate, and bend the specimen.

Radiographs were taken of the intact specimen to detect serious degenerative disease as well as neoplastic disease. None of the specimens used in this study showed serious degenerative or neoplastic changes.

Five conditions were investigated consecutively:

1. Intact functional spinal unit (FSU) C5/6
2. The FSU C5/6 with the anterior longitudinal ligament and the intertransverse ligaments sectioned
3. The FSU C5/6 with an additional 10-mm-deep incision of the anterior half of the anulus fibrosus and the disc
4. The FSU C5/6 with additionally sectioned ligamenta flava as well as interspinous and supraspinous ligaments
5. The FSU C5/6 with additional capsulotomy of the facet joints.

The four artificial discoligamentous injuries are shown in Fig. 2.

All testing conditions were adapted to the recommendations for the standardization of in vitro stability testing of spinal implants drawn up by the Study-Group For Pre-Clinical Testing, formed by the German Society for Spinal Surgery [29].

Data are reported as means and standard deviations of the observed ROM and NZ. Because of the small number of specimens, presenting the data in terms of median and range would be more precise from the statistical point of view. However, as all of the biomechanical studies cited in this paper described data in terms of means and standard deviations, we did so too, in order to make the data comparable. We used the ANOVA test to determine whether there were significant differences between the five test conditions. If significant differences were found, we used Fisher's post hoc test at the 5% significance level to determine which conditions were responsible for the differences in the ROM and NZ.

Table 1 Range of motion (ROM) and neutral zone (NZ) of the segment C5/6 for all loading conditions tested with pure moments of ± 2.5 Nm (mean ± SD)

	Flexion/extension		Axial rotation		Lateral bending	
	ROM ext. (°)	NZ (°)	ROM (°)	NZ (°)	ROM (°)	NZ (°)
Intact	13.4 ± 3.1	10.3 ± 2.8	8.6 ± 2.4	1.5 ± 0.9	9.9 ± 2.4	5.4 ± 1.8
Defect stage 1	16.4 ± 2.7	12.7 ± 2.4	9.3 ± 2.4	2.3 ± 1.3	9.9 ± 2.3	5.7 ± 2.2
Defect stage 2	18.4 ± 3.2	15.1 ± 3.4	9.7 ± 2.4	2.3 ± 1.3	10.3 ± 2.4	6.3 ± 2.4
Defect stage 3	19.3 ± 2.8	15.9 ± 3.0	9.9 ± 2.3	2.7 ± 1.1	10.4 ± 2.4	6.5 ± 2.4
Defect stage 4	20.5 ± 1.9	16.5 ± 2.3	12.6 ± 2.7	3.1 ± 0.9	12.3 ± 1.9	8.0 ± 2.9

Table 2 ROM and NZ of the segment C5/6 for all loading conditions tested with pure moments of ± 2.5 Nm (intact = 100%)

	Flexion/extension		Axial rotation		Lateral bending	
	ROM flexion (%)	NZ (%)	ROM (%)	NZ (%)	ROM (%)	NZ (%)
Intact	100	100	100	100	100	100
Defect stage 1	122	123	108	156	100	106
Defect stage 2	137	147	112	182	105	116
Defect stage 3	144	154	115	182	105	121
Defect stage 4	153	160	147	206	124	148

Table 3 Significance levels concerning ROM and NZ of the segment C5/6 for all loading conditions, determined by the ANOVA test with Fisher's PLSD post hoc test

	Flexion/extension		Axial rotation		Lateral bending	
	ROM flexion	NZ	ROM	NZ	ROM	NZ
Defect stage 1	*	NS	NS	NS	NS	NS
Defect stage 2	***	**	NS	NS	NS	NS
Defect stage 3	***	**	NS	NS	NS	NS
Defect stage 4	*** #	** #	* #	*	NS	NS

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ compared to intact C5/6
# $P < 0.05$ compared to stage 1 instability *NS* not significant

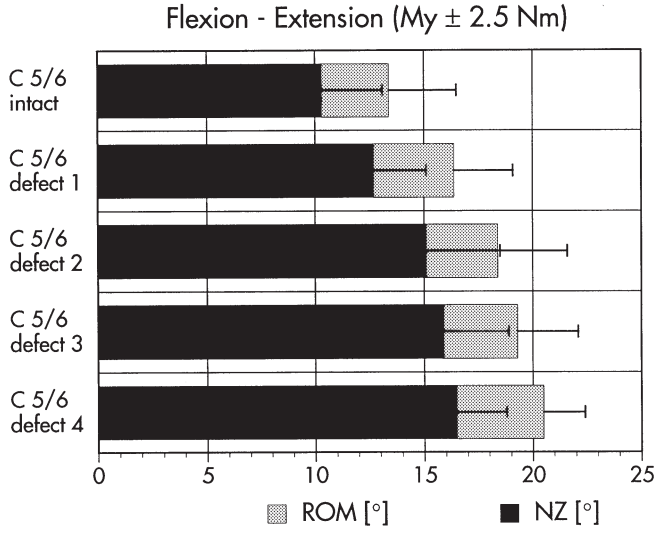

Fig. 3 Mean values and standard deviations for range of motion (ROM) and neutral zone (NZ) of C5/6 for flexion/extension with applied flexion/extension moments of ± 2.5 Nm

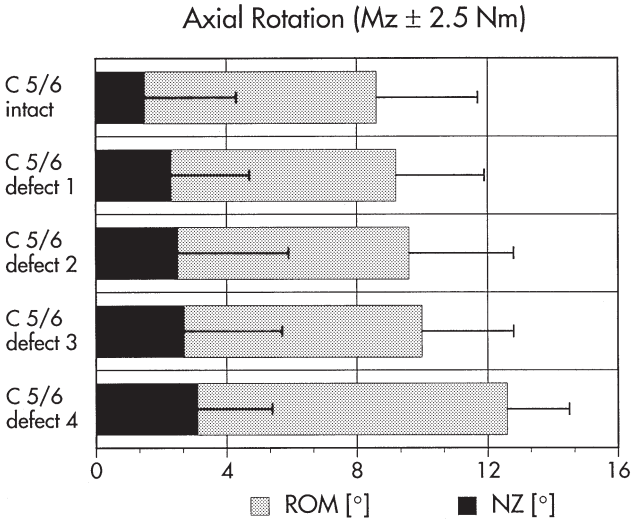

Fig. 4 Mean values and standard deviations for ROM and NZ of C5/6 for left/right axial rotation with applied left/right axial rotation moments of ± 2.5 Nm

Results

In flexion/extension, significant differences were observed concerning ROM and NZ for all four stages of instability compared to the intact FSU C5/6. The ROM and NZ increased gradually with each increasing stage of instability. Even the isolated sectioning of the anterior longitudinal ligament caused significant instability (Tables 1–3, Fig. 3).

In contrast to the results in flexion/extension, in axial rotation, sectioning of the anterior longitudinal ligament plus the intertransverse ligaments, with an additional 10-mm-deep incision of the anterior half of the anulus fibrosus and the disc, sectioning of the ligamenta

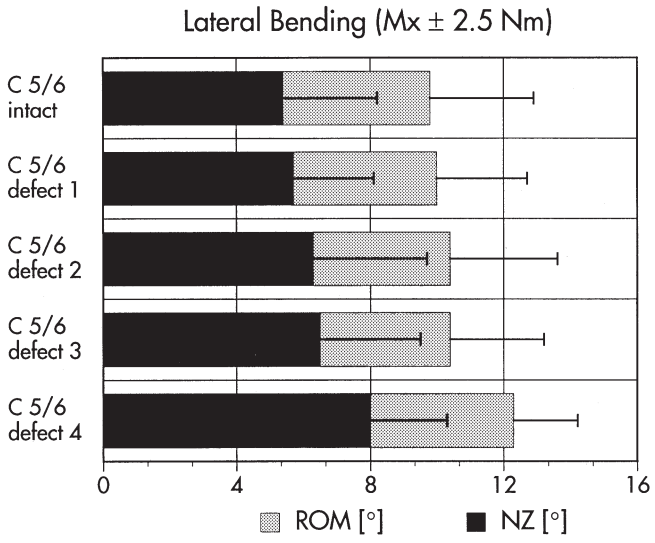

Fig. 5 Mean values and standard deviations for ROM and NZ of C5/6 for right/left lateral bending with applied right/left lateral bending moments of ± 2.5 Nm

flava as well as interspinous and supraspinous ligaments did not lead to a significantly greater ROM and NZ compared to the intact FSU C5/6. Only the stage 4 instability, with additional capsulotomy of the facet joints, caused a significantly increased ROM and NZ (Tables 1–3, Fig. 4).

For lateral bending, no significant differences concerning ROM or NZ were observed, although ROM and NZ increased 24% and 48%, respectively, compared to the intact FSU C5/6 (Tables 1–3, Fig. 5).

Discussion

This study showed that the tested artificial discoligamentous injuries of the lower cervical spine cause significant instabilities for flexion/extension and axial rotation, whereas lateral bending was not significantly influenced.

Our study protocol was defined according to the testing criteria for spinal implants following the recommendations for the standardization of in vitro stability testing of spinal implants drawn up by the Study Group For Pre-Clinical Testing formed by the German Society for Spinal Surgery [29]. The purpose was to allow comparisons of our data with future results from various research groups, although we did not test spinal implants in this study. It is very difficult to compare previously reported in vitro data of research groups, because of variations between the study protocols. For example, the applied moments for in vitro testing of cervical spine specimens vary over a wide range, from ± 0.3 Nm [4, 5] through ± 0.45 Nm [22], ± 2.5 Nm [1, 14], ± 3.0 Nm [11] to ± 4.5 Nm [25, 26].

We tested the FSU C5/6, as most cervical spine injuries occur at this level [8, 10, 23]. The types of artificial discoligamentous injuries we created were based on the findings of biomechanical studies dealing with injury patterns of the discoligamentous structures of the lower cervical spine, especially in whiplash injuries [8, 23].

Our results indicate that for the tested artificial discoligamentous defects, flexion/extension is the most sensitive loading direction, whereas lateral bending is not significantly influenced. Therefore, where conservative therapy is adopted for this type of injury, the orthosis for temporary immobilisation of the cervical spine should especially limit flexion/extension and axial rotation. If operative therapy is chosen, these types of instability can be treated successfully by anterior instrumentation of the cervical spine, which stabilizes especially in the directions of flexion/extension and axial rotation [21].

Clinical instability of the spine has been defined as the loss of ability of the spine to maintain, under physiological loads, its pattern of displacement so that there is no initial or additional neurologic deficit, no major deformity, and no incapacitating pain [27]. According to Panjabi and Grob [7, 16], the NZ is more closely associated with clinical instability than is the ROM. Thus, the significant increases in the NZ for all four stages of injury in flexion/extension and stage 4 injury in axial rotation may explain the long-term complaints in some patients following cervical spine injuries without pathological findings in the clinical and radiological examination. As the NZ can not be measured in vivo, only the detection of injured discoligamentous structures and correlation with biomechanical in vitro data can provide the connection between injury and pain. Although MRI studies can detect discoligamentous injuries much better in the acute phase than in the chronic phase [9, 13, 31], in many cases in the acute phase no MRI study is done. Therefore, significant discoligamentous injuries may not be detected in the late diagnostic course.

Several limitations of our study should be noted. The method of applying pure moments does not truly represent physiological loads, as compressive and shear forces are neglected. Furthermore, no muscle forces were applied, although it is known that muscles will stabilize the cervical spine. However, in vivo motion patterns were well reproduced and loading was consistent, and thus known at every point in the specimen. This has the advantage of reproducible loading from one specimen or one study to the next.

Conclusions

As flexion/extension is the most sensitive load-direction for discoligamentous instabilities, any orthosis for a temporary post-injury immobilization should stabilize espe-

cially for this direction The significant increases in NZ may explain the long-term therapy-resistant complaints following cervical spine injuries in some patients without pathological findings in diagnostic radiographic imaging.

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