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Lag-Screw Osteosynthesis in Thoracolumbar Pincer Fractures

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Abstract

Study Design: Biomechanical.

Objective: This study evaluates the biomechanical properties of lag-screws used in vertebral pincer fractures at the thoracolumbar junction.

Methods: Pincer fractures were created in 18 bisegmental human specimens. The specimens were assigned to three groups depending on their treatment perspective, either bolted, with the thread positioned in the cortical or cancellous bone, or control. The specimens were mounted in a servo-hydraulic testing machine and loaded with a 500 N follower load. They were consecutively tested in 3 different conditions: intact, fractured, and bolted/control. For each condition 10 cycles in extension/flexion, torsion, and lateral bending were applied. After each tested condition, a computed tomography (CT) scan was performed. Finally, an extension/flexion fatigue loading was applied to all specimens.

Results: Biomechanical results revealed a nonsignificant increase in stiffness in extension/flexion of the fractured specimens compared with the intact ones. For lateral bending and torsion, the stiffness was significantly lower. Compared with the fractured specimens, no changes in stiffness due to bolting were discovered. CT scans showed an increasing fracture gap during axial loading both in extension/flexion, torsion, and lateral bending in the control specimens. In bolted specimens, the anterior fragment was approximated, and the fracture gap nullified. This refers to both the cortical and the cancellous thread positions.

Conclusion: The results of this study concerning the effect of lag-screws on pincer fractures appear promising. Though there was little effect on stiffness, CT scans reveal a bony contact in the bolted specimens, which is a requirement for bony healing.

Keywords

spinal fusion, weightbearing, spinal fractures, pincer fracture, lag-screw, biomechanics, human specimen, spine

Introduction

It is agreed that stable vertebral fractures can be safely treated conservatively.[1-4] This essentially refers to A1 fractures according to the classification of the AO Foundation. Likewise, it is agreed that unstable fractures (AO A3-C) need to be treated surgically. With regard to pincer fractures (AO A2) the situation is still unclear. This type of fracture is considered partially stable and is treated conservatively,[3] but clinical experience indicates that pincer fractures regularly end up in nonunion due to intrusion of disc tissue into the fracture gap.[4] Those fractures are frequently treated surgically,[5] which implies that the fracture is considered unstable. However, it is possible that this is driven by safety concerns, but it is also true that an adequate treatment is yet to be found. A variety of treatment options are described in the literature. They range from vertebroplasty[6] and dorsal stabilization to combined dorsoventral procedures,[5,7,8] while each of these procedures has its own disadvantages.

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Either material remains in situ even after vertebral healing, as in vertebroplasties, or the fracture is not addressed directly, as in dorsal spondylodesis. Complete vertebral replacement in combined procedures appears to be disadvantageous, since pincer fractures usually occur in young patients.

This fracture type represents a rare injury. Besides case reports, there are few publications addressing this subject. General suggestions were given by Aebi,[9] who considered pincer fractures as fractures that could end up in a nonunion due to the ruptured disc material. In 1975, Roy-Camille et al[10] reported 3 vertebral fractures with the fracture lines situated in the frontal plane, none of which healed after 10 to12 months due to an increasing fracture gap. Therefore, the authors recommended an operative treatment. De Boeck et al[11] reported 12 patients with coronal vertebral fractures, all treated with an internal fixation and a transpedicular bone grafting. All of those fractures healed without deformity.[11] In 2014, Huwart et al[12] published results of 62 patients with vertebral A2 fractures treated with percutaneous vertebroplasty. In all cases, the cement bridging the fracture gap was stable after 6 months and no adjacent vertebral fractures occurred. Amoretti and Huwart[6] presented a combined percutaneous osteosynthesis and vertebroplasty as an option in the treatment of pincer fractures. Ten consecutive patients were treated this way, all of them ended up in a stable situation after 6 months.[6]

Furthermore, several case reports have been published dealing with pincer fractures. Sasani et al[13] reported on a vertebral pincer fracture following kyphoplasty in an osteoporotic compression fracture. However, the authors did not describe any treatment options in their article.[13] Ladurner et al[5] described the treatment of a vertebral pincer fracture sustained during an epileptic seizure. The treatment in this case was a complete vertebral body replacement.[5] Recently, Velonakis et al[14] found the use of a polyetheretherketone (PEEK) implant beneficial in terms of height restoration and pain reduction in A2 fractures. The use of balloon kyphoplasty was considered effective in a series of 85 patients with various A-type fractures, including pincer fractures.[15]

As there is a lack of clinical or biomechanical evidence, the treatment of vertebral pincer fractures remains inconsistent. Nonetheless, treatment options need to be evaluated, as the possible complication of a vertebral non-union is a condition in which patients regularly suffer from disabling intermittent or permanent back pain.

Lag-screws are successfully used for the treatment of long-bone fractures, but they have borne no relevance in spinal surgery of the thoracic and lumbar spine so far. It is hypothesized that if a pincer fracture's anterior fragment offers a sufficient size to fully introduce a lag-screw's thread, a sufficient compressive force could be applied to the fracture. This procedure can possibly prevent a vertebral nonunion, which is the main threat in pincer fractures. Furthermore, the fracture is addressed directly, the bone stock is preserved, and the complete material can be removed after vertebral healing. Therefore, the aim of this study was to investigate the primary stability of lag-screws used to treat pincer fractures in a biomechanical cadaver model.

Materials and Methods

This study was approved by the Ethics Board of the local University Medical Center. After informed consent was obtained, 18 unembalmed human specimens of the thoracolumbar junction (TLJ) were obtained from the Department of Legal Medicine, University Medical Centerand stored at –20 °C.[16,17] There were 14 male and 4 female donors, the donors' mean age was 63.7 years (range 31-92 years). The TLJ was chosen due to the high incidence of injuries in this spinal section.[17]

Pretest Examination

In phase I (intact) a computed tomography (CT) screening (Brilliance 16, Philips) with a standardized abdominal scan protocol (0.8 mm slice-thickness) was conducted to exclude specimens with preexisting fractures, neoplasm, or morphologic abnormalities. The bone mineral density (BMD) was also determined from the CT images based on a phantom (QRM-BDC 700 mm, QRM GmbH) positioned underneath the specimens during the CT scan. This phantom provided the calibration factor between CT-Hounsfield units and BMD in terms of concentration of calcium hydroxyapatite (mg CaHA/cm^3) equivalent (Structural Insight 3.1.5.2, Section Biomedical Imaging, Department of Diagnostic Radiology, Kiel, Germany). This pretest examination indicated the end of "phase I."

Biomechanical Setup

Approximately 12 hours prior to testing, each specimen was thawed in a humid environment to start phase II (fractured). Sections of 2 functional spinal units (FSU) were chosen at random and isolated from the spines: 9 from Th11 to L1 and 9 from Th12 to L2. All soft tissues except spinal ligaments, intervertebral discs, and facet capsules were dissected. The inferior and superior vertebrae of each specimen were embedded in metal holders using a two component-polyurethane-resin (RenCast FC 52/53 Isocyanate/FC 53 Polyol, Huntsman Advanced Materials) and fixed in an upright position on top of the load cell of a servo-hydraulic testing machine (Bionix 358.2, MTS).

A follower-load frame (100 N) with eight 50 N hanging dead weights was attached to the superior vertebra in order to apply a physiological compression to the specimens with a total load of 500 N.[18-20] A 6-axis load cell followed by an angular actuator for extension/flexion or lateral bending and an x-y table to allow translational movements was mounted on top of the superior vertebra (Figures 1 and 2) and connected to the machine actuator. All specimens were tested at room temperature in a humid environment.

Cyclic Testing

Spinal motions comprise combined movements in three directions: extension/flexion around the transversal axis, torsion

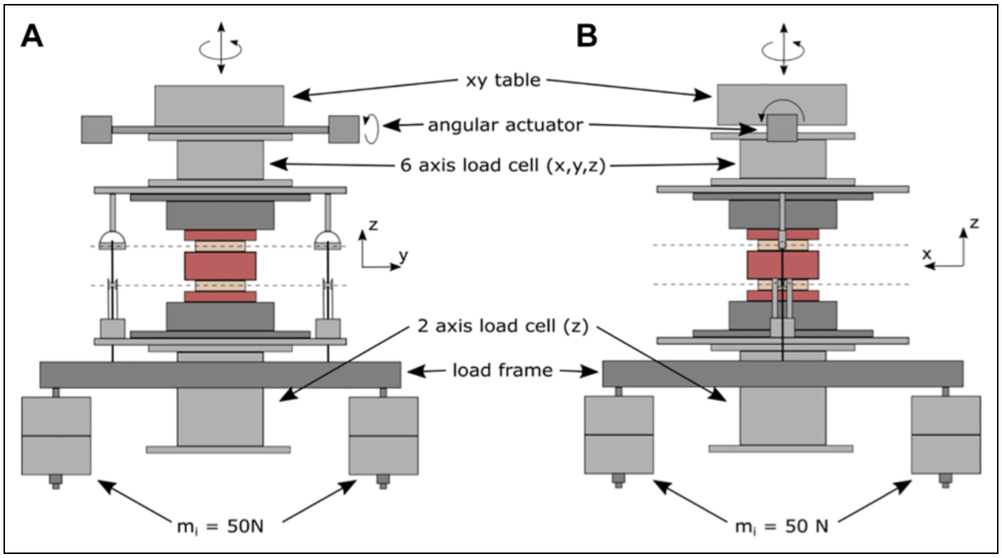

Figure 1. Scheme of the experimental setup. In the frontal view (a), the sideward guides for the cable of the follower load are visible. The lateral view (b) exhibits the position of the angular actuator for extension/flexion and lateral bending of the specimen.

around the longitudinal axis, and lateral bending around the sagittal axis. To mimic this, the intact specimens were initially tested for both extension/flexion and torsion. Then they were rotated by 90° (z-axis)[21] within the loading frame and subsequently tested for lateral bending—10 cycles each. An alternating moment with peak loads of ±7.5 N·m[21] was chosen to determine the maximum range of motion for each specimen's mobility in phase.

The obtained specimen's angles were then maintained as the upper and lower limits for all subsequent extension/flexion and lateral bending tests. The torsion loading in each stage remained at ±7.5 N·m, as reported in comparable studies.[18-20,22,23]

After initial testing in phase I, a pincer fracture was created in the mid-vertebra of the specimen[21] (either Th12 or L1). A wedged, V-shaped metal section (Figure 3) was introduced laterally between the inferior endplate of the upper vertebral body and the intervertebral disc (IVD) until the IVD penetrated the superior endplate of the mid-vertebral body. The same procedure was undertaken at the inferior IVD and the superior endplate of the lower vertebral body. Macroscopically, it was ensured that the IVDs were dissected from the upper and the lower vertebra. This mechanism is considered as a requirement for the formation of this fracture type.[8] Two plain radiographs (BV 212, Philips Medical Systems) were conducted to control for regular fracture morphology (Figure 4).

Subsequently, the fractured specimens were tested with 10 cycles in extension/flexion and lateral bending to achieve a measure of reproducibility in their biomechanical behavior, again using the obtained angles from the initial testing.

Next, all specimens were randomly assigned to three groups with six specimens in each: control, cortical thread position (bolted COT) and cancellous thread position (bolted CAT). It was ensured that each group contained 3 Th11-L1 and 3 Th12-L2 specimens. Vertebrae of the bolted COT and bolted CAT group were treated with transpedicular lag-screws (6.5 mm diameter, 16 mm thread, Axomed GmbH), with the

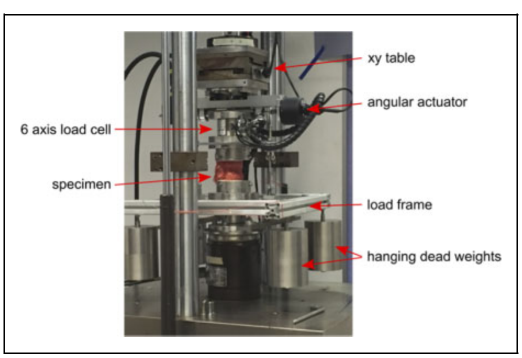

Figure 2. Dissected and embedded specimen fixed to a monoaxial servo hydraulic testing machine.

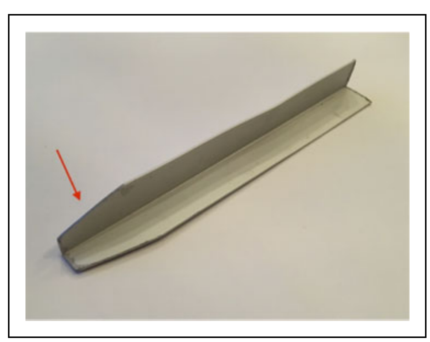

Figure 3. Wedged (left side) V-shaped metal section to induce pincer fractures. The arrow indicates the tip, which was inserted between the endplate and the intervertebral disc.

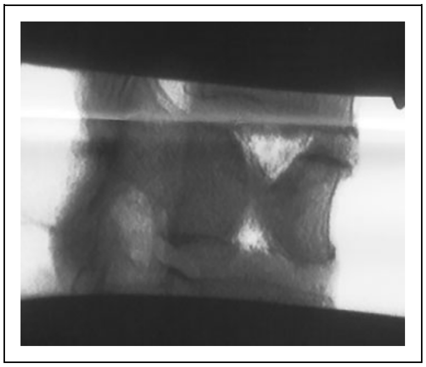

Figure 4. Lateral radiograph of a specimen (Th11 to L1) with an artificially created pincer fracture in the Th12 vertebral body, with parts of the intervertebral disc pushed into the fracture gap.

thread placed either in the fragment's cortical (bolted COT, Figure 5a) or cancellous bone (bolted CAT, Figure 5b). Proper positioning of the screws, centrally in the anterior fragment, was ensured by fluoroscopic imaging (Figure 5a and b). The control group did not receive any stabilization.

The bolted specimens were again tested with 10 cycles in extension/flexion, lateral bending and torsion. Subsequently, a CT scan was conducted to visualize dislocations of the fractured parts or (if applicable) potentially loosened screws. This CT scan indicated the end of phase II.

Finally, in phase III (fatigue), a fatigue test in extension/flexion with the same range of motion (ROM) as before was conducted with all 18 specimens (control, bolted COT, bolted CAT). To this end, the specimens were wrapped in 0.9% saline-soaked gauze to prevent them from drying out. It was aimed to apply 140 000 loading cycles, which is regarded the number of movements of an uninjured lumbar spine within 3 weeks.[24] However, the whole testing procedure was also limited to a maximum duration of 20 hours, as it is assumed that the properties of the specimen will change beyond this period.[21] Since the initial parameter testing required an average of 4 hours, the fatigue test could last for a maximum of 16 hours. With a constant angular velocity of the angular actuator of 2 deg/s to reach the individual ROM of the specimen not every specimen could reach the threshold of 140 000 loading cycles within the given time frame.

Finally, a CT scan was performed to detect morphological changes of the specimen during the fatigue test. This last CT scan indicated the end of phase III.

Outcome Measures

For the 10 cycles testing, the peak moments obtained in extension/flexion, lateral bending and torsion were divided by the respective peak angles to calculate the apparent stiffness (N·m/deg) of the specimens in each phase (I: intact, II: fractured, III: fatigue). A higher stiffness indicates that a similar extent of movement results in a higher loading of the specimen.

The CT scans were interpreted by using the Osiris X Software (Pixmeo SARL). The vertebral body length (cranial endplate, caudal endplate, and mid-vertebra) was measured in the anterior-posterior (AP) midline using a 2-plane view (Figure. 6).

Both intervertebral spaces (IVS) adjacent to the fractured vertebra were measured as well. Measurements were conducted along the vertebra's midline at each of the anterior and posterior ends.

The fracture gap was determined in the same way. The width of the gap after the fatigue test was measured at both endplate levels and the midline of the cranio-caudal extent.

The CT scans after all 3 phases were analyzed.

Statistical Analysis

For statistical analysis, the commercial SPSS 22.0 software (IBM Corp) was used. Statistical evaluation of the dependent

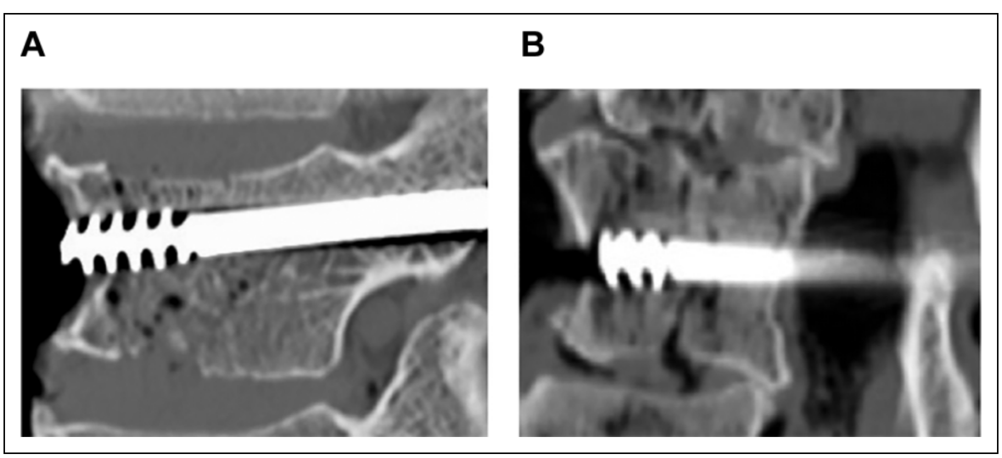

Figure 5. Computed tomography scans. (a) Lateral view of a lag-screw in situ, thread positioned in the specimen's cortical bone. (b) Lateral view of a lag-screw in situ, thread positioned in the specimen's cancellous bone. Specimens with a lag-screw position as shown in (a) are referred to as bolted COT, specimens with a lag-screw position as shown in (b) are referred to as bolted CAT.

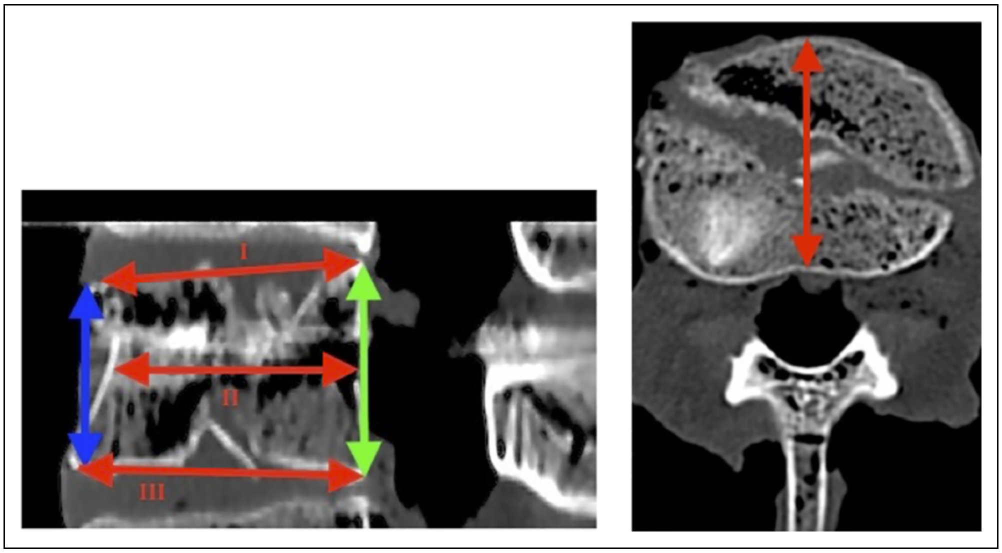

Figure 6. Computed tomography scan of a fractured vertebral body (lateral [left] and coronal [right] view). Red arrows indicate: I: length of cranial endplate, II: length of vertebral midline, III: length of caudal endplate. Green arrow indicates posterior vertebral height; blue arrow indicates anterior vertebral height.

groups (phase I, phase II, phase III) was conducted using the Wilcoxon signed-rank test (WSR) with a Bonferroni correction. Kruskal-Wallis ranks analysis was used to analyze the homogeneity of the independent groups (control, bolted CAT, bolted COT). A type I error level of .05 was used for all tests of significance.

Results

The specimen's BMD ranged from 60.4 to 223.5 mg/cm^3 (mean 102.95 mg/cm^3, SD 31.45 mg/cm^3). No significant differences with regard to age ($P = .604$) or the BMD ($P = .866$) among the groups were exhibited.

Extension/Flexion

The intact specimens (phase I) allowed a mean extension of 6.6° (SD 2.6°) and a mean flexion of 5.2° (SD 1.5°) after applying an alternating moment of 7.5 N·m. The mean ROM was 11.9° (SD 3.5°).

The stiffness of the specimens in extension/flexion after the 10 cycles testing was similar in all 3 groups (control, bolted CAT, bolted COT) regarding phase I ($P = .623$) and phase II ($P = .459$). Independent of the group, a trend toward a higher stiffness of the specimens in phase II was observed, but this difference was not significant ($P = .064$). Furthermore, stiffness in the bolted groups (bolted CAT, bolted COT) did not change significantly during the phases (Table 1).

Lateral Bending

For lateral bending (*x*-axis rotation, Figure 1) a mean angle of 6.6° (SD 2.7°) for counterclockwise (cc) and a mean angle of 4.5° (SD 2.9°) for clockwise (c) rotation was found. The mean ROM was 11.1° (SD 4.5°).

The stiffness in lateral bending was again similar in all 3 groups for phase I ($P = .772$) and phase II ($P = .918$). A significant higher stiffness was observed for the specimens in phase I compared with the specimen's stiffness in phase II ($P < .001$).

Significant differences in the stiffness of the bolted CAT group or the bolted COT in phase III compared with their stiffness in phase I were found ($P = .002$ and $P = .008$, respectively). However, there were no significant differences in both groups in phase III compared with their stiffness in phase II ($P = .51$ and $P = .86$, respectively) (Table 2).

Table 1. Mean Stiffness (N·m/deg) for Extension/Flexion in Phases I, II, and III: First Column Refers to the Specimen's Perspective Treatment (Control, Bolted CAT, Bolted COT).

	Phase I		Phase II		Phase III		Phase III vs phase I	Phase III vs phase II
N·m/deg	Mean	SD	Mean	SD	Mean	SD	Probability value	Probability value
Control	1.06	0.32	1.15	0.42				
Bolted CAT	1.26	0.38	1.20	0.34	1.20	0.31	.766	.946
Bolted COT	1.33	0.39	1.50	0.48	1.48	0.38	.193	.906
Probability value: bolted (CAT and COT) vs control	.623		.459					

Table 2. Mean Stiffness (N·m/deg) for Lateral Bending in Phases I, II, and III: First Column Refers to the Specimen's Perspective Treatment (Control, Bolted CAT, Bolted COT).

N·m/deg	Phase I		Phase II		Phase III		Phase III vs phase I	Phase III vs phase II
	Mean	SD	Mean	SD	Mean	SD	Probability value	Probability value
Control	1.46	0.50	1.15	0.41				
Bolted CAT	1.57	0.31	1.08	0.24	1.09	0.26	.002	.51
Bolted COT	1.59	0.55	1.23	0.49	1.22	0.51	.008	.86
Probability value: bolted (CAT and COT) vs control	.772	.918						

Torsion

Other than extension/flexion or lateral bending, torsional testing was performed using a constant alternating moment ($\pm$7.5 N·m). The stiffness in torsion was found to be similar in all 3 groups for phase I (P = .884) and phase II (P = .557) (Table 3). In all groups, a significantly higher stiffness was observed for the specimens in phase I compared with phase II (P < .001).

A significant lower stiffness of the bolted CAT group in phase III compared with phase I was found (P = .043). However, compared with phase II, there was no significant difference (P = .098). In the bolted COT group, no significant changes appeared between phase III and phase I (P = .054). The comparison between phase III and phase II though, did show significant changes (P = .013). Whereas the stiffness decreased after initiating a fracture (phase II), the stiffness increased after positioning screws in the fragment's cortical bone to stabilize the fracture (phase III).

Each specimen was subjected to a fatigue test in extension/flexion. None of the specimens reached the switch off criterion of 140 000 cycles. After 16 hours, the mean number of cycles was 12 883 (SD 3910). Whereas no significant differences in stiffness before and after the fatigue test were found for the control (P = .080) and bolted COT group (P = .463), the stiffness of the bolted CAT group significantly increased with the fatigue testing (P = .046).

CT Scans

The CT scans of the intact specimens (phase I) showed a mean Daniaux-angle of 3.2° (SD 1.7°) in the perspective fractured vertebrae. This changed to 3.1° (SD 1.1°) after the specimens had been fractured (phase II) and tested in this state (P = 1.000). After the fatigue test (phase III), the mean angle increased significantly to 4.0° (SD 2.1°) (P = .032).

Statistical analysis revealed a comparable initial shape of all specimens (P > .05) prior to testing. However, during testing significant changes both in the length of the cranial endplate of the bolted COT specimens compared with the control group (P = .011) and in the bolted CAT specimens compared with the control group (P = .004) were determined.

The other changes depicted in Table 4 were not significant. In particular, there was no significant shifting of the complete anterior fragment, which would have been depicted in an increasing length of both the cranial and caudal endplate and the mid-vertebra length.

Before the fatigue test the minimal width of the fracture gap in the control specimens was 3.66 mm (SD 2.24). In contrast, the minimal width in all of the bolted specimens was 0 mm. Due to the fracture's morphology (V-shape) the maximal fracture gap width ranged from 3.6 to 16.1 mm, which was measured near the cranial or caudal endplates. There were no differences in maximum width between the bolted specimens and the control group.

A significant widening of the fracture gap in the control specimens during fatigue testing (phase III) was found. However, dependent on where the widening was determined, different levels of significance were found: cranial endplate (CrE) P = .028, caudal endplate (CaE) P = .046, mid-vertebra (M) P = .028 (Figure 7), whereas the fracture gap did not increase in the bolted specimens (P = .116-1.000).

Referring to the IVS, a significant narrowing appeared in the bolted specimens (P < .05). The analysis revealed that during testing, the mean height of the IVS decreased by 47%.

However, the IVS of the control specimens only showed a significant decrease in the ventral and dorsal parts (cranial ventral [CrV]: P = .027, cranial dorsal [CrD]: P = .046, caudal

Table 3. Mean stiffness (N·m/deg) for Torsion in Phases I, II, and III: First Column Refers to the Specimen's Perspective Treatment (Control, Bolted CAT, Bolted COT).

N·m/deg	Phase I		Phase II		Phase III		Phase III vs phase I	Phase III vs phase II
	Mean	SD	Mean	SD	Mean	SD	Probability value	Probability value
Control	3.75	1.19	1.53	0.30				
Bolted CAT	3.69	1.88	1.35	0.11	1.49	0.22	.043	.098
Bolted COT	4.15	2.39	1.52	0.48	1.79	0.44	.054	.013
Probability value: bolted (CAT and COT) vs control	.884		.557					

Table 4. Mean Vertebral Dimensions (mm) of the Grouped Specimens (Control, Bolted COT, Bolted CAT) in Different Phases During Testing: Measurements Were Taken as Depicted in Figure 6.

	Phase I		Phase II		Phase III	
Group	Mean	SD	Mean	SD	Mean	SD
Control						
Length (mm)						
Cranial endplate	34.27	1.79	35.5	2.44	36.22	2.45
Caudal endplate	34.1	1.81	34.97	1.92	36.27	3.81
Mid-vertebra	32.97	2.46	32.67	2.58	34.7	3.1
Height (mm)						
Anterior vertebral body	25.53	2.38	25.2	1.3	25.45	0.99
Posterior vertebral body	29.02	1.86	28.4	1.9	27.77	1.73
Bolted COT						
Length (mm)						
Cranial endplate	32.95	2.48	32.07	2.62	31.2	2.89
Caudal endplate	32.62	2.14	31.47	2.97	33.32	2.78
Mid-vertebra	30.77	1.63	28.93	1.67	30.92	2.29
Height (mm)						
Anterior vertebral body	24.77	1.59	23.63	2.79	19.5	4.63
Posterior vertebral body	27.05	2.41	26.63	2.49	24.7	4.86
Bolted CAT						
Length (mm)						
Cranial endplate	32.57	3.11	30.73	1.77	30.27	2.45
Caudal endplate	32.13	3.57	30.78	4.17	31.22	5.51
Mid-vertebra	30.83	3.11	29.35	3.08	29.87	4.46
Height (mm)						
Anterior vertebral body	23.97	0.71	22.68	2.67	18.17	4.64
Posterior vertebral body	26.05	2.90	25.42	2.72	22.92	5.55

ventral [CaV]: $P = .028$, caudal dorsal [CaD]: $P = .027$), while there were no changes in the central parts (cranial central [CrC]: $P = .08$, caudal central [CaC]: $P = .249$). No differences between the bolted CAT and bolted COT group were detected (Table 5).

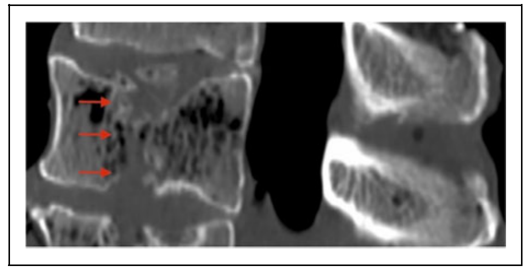

Figure 7. Computed tomography scan: lateral view of a control specimen after fatigue loading, arrows indicating a broad fracture gap with bone debris and intervertebral disc tissue impressed into the fracture gap.

Discussion

Vertebral pincer fractures (AO A2) are rare.[6,10-12] Little is known about their biomechanical behavior and healing ability. So far, other than case reports[5,13,25] there are no scientific publications on this topic. Consequently, there is no consensus about the proper treatment, and both conservative[3,10,11] and partly extensive, surgical treatment regimen are reported.[5,8]

The primary objective of this study was to evaluate the effect of transpedicular lag-screws in vertebral pincer fractures. The lag-screw principle in combination with anti-rotational plates is common in long-bone fractures, as lag-screws reduce the threat of a non-union. However, besides case reports dealing with cervical spine fractures,[26] this principle has no relevance in spine surgery so far. Obviously, a lag-screw osteosynthesis is out of the question in most vertebral fractures; however, keeping in mind the fracture-morphology both split and pincer fractures could benefit from this treatment.

The second objective was to simulate the behavior of vertebral pincer fractures in a biomechanical setting. Both non-union and increasing dislocation of the anterior fragment are feared complications of this fracture type. Therefore, it seemed necessary to test the specimens under a physiological load and with each specimen's physiological ROM.

Although there are studies using axial load applications, a compressive follower load is a standard principle in spinal

Table 5. Mean Intervertebral Disc (IVD) Height of the Specimens in Phases I and III, Dependent of Their Treatment Group (Control, Bolted COT, Bolted CAT), "Probability Value" Indicating the Significance Level of the Changes Between Phases I and III.

	Control			Bolted COT			Bolted CAT		
	Mean IVS height (mm)		Probability value	Mean IVS height (mm)		Probability value	Mean IVS height (mm)		Probability value
	Phase I	Phase III	Phase I vs phase III	Phase I	Phase III	Phase I vs phase III	Phase I	Phase III	Phase I vs phase III
CrV	7.9	5.5	.027	7.2	4.7	.043	7.7	5.0	.028
CrC	9.6	8.1	.08	8.0	5.5	.043	7.4	4.4	.028
CrD	5.1	2.8	.046	4.5	2.1	.028	4.9	2.0	.028
CaV	9.5	6.7	.028	8.4	5.4	.028	9.2	5.9	.027
CaC	10.7	9.0	.249	10.0	7.5	.027	8.9	6.3	.028
CaD	5.8	2.5	.027	5.6	2.2	.027	6.0	1.4	.027

Abbreviations: IVS, intervertebral space; CrV, cranial ventral; CrC, cranial central; CrD, cranial dorsal; CaV, caudal ventral; CaC, caudal central; CaD, caudal dorsal.

testing. Rohlmann et al[27] considered it the only reasonable loading mode simulating standing. Therefore, a compressive follower load of 500 N was chosen.[28-30] Stolworthy et al[22] described a follower load applied to single FSU specimens. Until then, the follower load principle was used only in specimens of bigger dimensions.

Since the fractured vertebra cannot be attached to the follower-load line, the transfer of an ideal follower load path was not possible in this fracture type.[29] Therefore, the loading protocol described by Gonzalez-Blohm et al[23] was chosen after the pretest findings showed instability of the specimens during flexion/extension.

Although 2 preconditioning cycles are common,[23] Stolworthy et al[22] still found "significant residual changes in segmental flexibility" and recommended 20 cycles. These findings appear consistent to the findings in this study. To prevent the IVD from being pressed into the vertebral body during the preconditioning cycles, 10 instead of 20 cycles for preconditioning were conducted, with the follower load applied. During testing, the IVS decreased, while the vertebral body's dimensions rarely changed.

A tendency toward higher moments was found in extension/flexion, with the same ROM, in the fractured specimens (phase II) compared with the intact condition (phase I). This seems to be similar to the findings of Janevic et al,[31] who found an increase in flexion stiffness due to large compressive preloads on single FSU. Patwardhan et al[30] interpreted these findings as a rising stiffening due to an increasing internal pressure of the IVD. The tests used in the presented study show, that these increased moments may be caused by a progressive inward pressure of the IVD into the vertebral body. This proposed mechanism correlates with the findings that the intervertebral space becomes narrower as the test proceeds. With this, the FSU movement changes from a "water cushion" movement of an intact IVD to a rather "tipping" movement caused by the reduced IVS in extension/flexion, which requires higher bending moments.

During the testing the stiffness for both lateral bending and torsion decreased significantly in most of the specimens compared with the intact state (phase I). These findings correspond both to those of Wong et al,[32] who found kyphoplasty as a stand-alone treatment was unable to restore the stiffness of an intact specimen in vertebral burst fractures and to those of Mundis et al,[33] who described an increased motion in lateral bending for expandable cages . Furthermore, the approach in this study appears to show similar results compared to a cement augmentation, which did also not show an improvement in torsional stiffness ($P = .72$).[32]

The minor effect of lag-screws on the stiffness of the specimens in both extension/flexion, lateral bending and torsion emphasizes the necessity of lag-screws being supported by devices, that provide a local immobility. In a clinical setting, this could be induced, for example, by a dorsal spondylodesis.

The minimal morphological changes in the CT scans were partly expected. Referring to Denis's 3-column theory, none of the column's stiffness is damaged in this fracture type, thus there are only minor changes in the Daniaux angle.[34] Additionally, the intact ligamentous complex seems to provide sufficient tension to prevent a fragment dislocation. These findings were similar to those of Li et al,[35] who described a persistent stiffness in specimens with a preserved ligamentous complex.

The most important point that emerged from analyzing the CT scans was the facture gap width. Since clinical experience shows a recurring appearance of nonunions in pincer fractures,[4,36] the increasing fracture gap was expected in the control specimens. As the control specimens correspond to the nonoperative treatment of this fracture type, the increasing fracture gap can be considered as the reason for a nonunion.

In contrast, the bolted specimens showed no increase in the fracture gap with persistent bony contact even after the fatigue test. This, in turn, is the main requirement for fracture healing and is provided by lag-screw implantation.

In conclusion, the results imply a benefit of using lag-screws in vertebral pincer fractures. Compared with the treatment of long-bone fractures, there was no increase in stiffness, although a persistent bony contact, as a premise for bony healing, could be achieved. This study revealed the ability of lag-screws to maintain fragment's contact against a permanent pushing-in of the intervertebral disc into the fracture gap.

This study probably has an influence on the treatment of vertebral pincer fractures.

The main issue in pincer fractures is the vertebral nonunion. By using lag-screws, the main requirement to prevent a nonunion, bony contact, can be achieved as CT scans reveal.

A dorsal spondylodesis is considered as a basic treatment form of any vertebral instability. However, these devices do not address a pincer fracture directly, as lag-screws do. Compared with a vertebral body replacement, saving the bone stock appears conceivable. Additionally, a vertebral replacement is likely to have a higher rate of complications compared with a transpedicular lag-screw implantation.

Also, it is possible to remove the material after vertebral healing, which appears beneficial compared to vertebral body replacement and vertebroplasty. Since this fracture type is typically found in younger patients, this can be considered as a real benefit.

The limitations of this in vitro study have to be kept in mind. Pincer fractures occur due to a complex mechanism, which is difficult to simulate. In fact, there is no accredited fracture model, and the fracture model of this study might be improved.

The mechanical effect of the surrounding soft tissue on vertebral stiffness was not represented since the vertebrae were dissected. A statement about changes in the sagittal alignment of the entire spine is hardly possible based on this bisegmental experiment.

The specimen's mean age of 63 years was slightly different from the typical patients age group, since pincer fractures usually appear in a younger population. This might have biased the biomechanical results.

Because of their high flexibility and by that a long test cycle duration, none of the specimens reached the projected 140 000 testing cycles in the planned time frame. Therefore, statements referring to fatigue failure are restricted in this study.

Lag-screws as a stand-alone treatment are rarely used in long-bone fracture treatment nowadays, as often a loss of reduction is feared. Lag-screws in vertebral pincer fractures and their testing in combination with a pedicle screw fixation system might warrant further scientific investigation.

Screw loosening is a complex topic in osteosynthesis. Since there are multiple factors interfering, further investigations might be reasonable.

Summary

In summary, this study shows encouraging results concerning the effect of lag-screws in vertebral pincer fractures. Although this treatment appeared to have little effect on spinal stiffness, CT scans revealed a persistent bony contact in the bolted specimens in contrast to the control specimens. However, lag-screws as a stand-alone solution do not seem to improve the specimen's stiffness significantly. This corresponds to other studies that have dealt with lag-screws,[37] as well as studies dealing with kyphoplasty[32] or cages[33] as stand-alone treatments in vertebral fractures. Furthermore, a decreasing IVS appeared during the testing, which correlates to a progressive collapse of the IVD into the vertebral body and might be the reason for repeatedly reported vertebral nonunion. In the control specimens an increasing fracture gap was found. This correlates to the clinical finding that vertebral pincer fractures are at risk of developing a vertebral nonunion.

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References

1. Vaccaro AR, Oner C, Kepler CK, et al. AOSpine thoracolumbar spine injury classification system. *Spine (Phila Pa 1976)*. 2013; 38:2028-2037. doi:10.1097/BRS.0b013e3182a8a381
2. Schnake KJ, Schroeder GD, Vaccaro AR, Oner C. AOSpine classification systems (subaxial, thoracolumbar). *J Orthop Trauma*. 2017;31(suppl 4):S14-S23. doi:10.1097/BOT.0000000000000947
3. Schmidt OI, Gahr RH, Gosse A, Heyde CE. ATLS® and damage control in spine trauma. *World J Emerg Surg*. 2009;4:9. doi:10.1186/1749-7922-4-9
4. Kim BG, Dan JM, Shin DE. Treatment of thoracolumbar fracture. *Asian Spine J*. 2015;9:133-146. doi:10.4184/asj.2015.9.1.133
5. Ladurner A, Forster T, Külling FA. Epileptic seizure-induced vertebral body fractures [in German]. *Unfallchirurg*. 2015;118: 1067-1069. doi:10.1007/s00113-015-0040-9
6. Amoretti N, Huwart L. Combination of percutaneous osteosynthesis and vertebroplasty of thoracolumbar split fractures under CT and fluoroscopy guidance: a new technique. *Cardiovasc Intervent Radiol*. 2014;37:1363-1368. doi:10.1007/s00270-014-0849-6
7. Bühren V. Injuries to the thoracic and lumbar spine [in German]. *Unfallchirurg*. 2003;106:55-69. doi:10.1007/s00113-002-0557-6
8. Gonschorek O, Hauck S, Bühren V. Therapiestandards bei verletzungen der BWS/LWS. *Trauma Berufskrankheit*. 2009;11: 117-123. doi:10.1007/s10039-009-1489-y
9. Aebi M. Classification of thoracolumbar fractures and dislocations. *Eur Spine J*. 2010;19(suppl 1):S2-S7. doi:10.1007/s00586-009-1114-6
10. Roy-Camille R, Lelièvre JF. Pseudarthrosis of the dorso-lumbar vertebrae [in French]. *Rev Chir Orthop Reparatrice Appar Mot*. 1975;61:249-257.
11. De Boeck H, Opdecam P. Split coronal fractures of the lumbar spine. Treatment by posterior internal fixation and transpedicular bone grafting. *Int Orthop*. 1999;23:87-90.
12. Huwart L, Foti P, Andreani O, et al. Vertebral split fractures: technical feasibility of percutaneous vertebroplasty. *Eur J Radiol*. 2014;83:173-178. doi:10.1016/j.ejrad.2013.09.020
13. Sasani M, Ozer AF, Kaner T, Ercelen O. Delayed L2 vertebrae split fracture following kyphoplasty. *Pain Pract*. 2009;9:141-144. doi:10.1111/j.1533-2500.2008.00250.x
14. Velonakis G, Filippiadis D, Spiliopoulos S, Brountzos E, Kelekis N, Kelekis A. Evaluation of pain reduction and height restoration post vertebral augmentation using a polyether ether ketone (PEEK) polymer implant for the treatment of split (Magerl A2) vertebral fractures: a prospective, long-term, non-randomized study. *Eur Radiol*. 2019;29:4050-4057. doi:10.1007/s00330-018-5867-3
15. Francaviglia N, Villa A, Maiello M, et al. Reconstruction of vertebral body in thoracolumbar AO type A post-traumatic fractures by balloon kyphoplasty. A series of 85 patients with a long follow-up and review of literature. *J Neurosurg Sci*. Published online April 23, 2019. doi:10.23736/S0390-5616.19.04628-9
16. Sedlin ED, Hirsch C. Factors affecting the determination of the physical properties of femoral cortical bone. *Acta Orthop Scand*. 1966;37:29-48.
17. Medici A, Meccariello L, Falzarano G. Non-operative vs percutaneous stabilization in Magerl's A1 or A2 thoracolumbar spine fracture in adults: is it really advantageous for a good alignment of the spine? Preliminary data from a prospective study. *Eur Spine J*. 2014;23(suppl 6):677-683. doi:10.1007/s00586-014-3557-7
18. Tsitsopoulos PP, Serhan H, Voronov LI, et al. Would an anatomically shaped lumbar interbody cage provide better stability? An in vitro cadaveric biomechanical evaluation. *J Spinal Disord Tech*. 2012;25:E240-E244. doi:10.1097/BSD.0b013e31824c820c
19. Kikkawa J, Cunningham BW, Shirado O, Hu N, McAfee PC, Oda H. Biomechanical evaluation of a posterolateral lumbar disc arthroplasty device: an in vitro human cadaveric model. *Spine*

(Phila Pa 1976). 2010;35:1760-1768. doi:10.1097/BRS.0b013e3181c87692
20. Beaubien BP, Derincek A, Lew WD, Wood KB. In vitro, biomechanical comparison of an anterior lumbar interbody fusion with an anteriorly placed, low-profile lumbar plate and posteriorly placed pedicle screws or translaminar screws. *Spine (Phila Pa 1976)*. 2005;30:1846-1851.
21. Wilke H, Wenger K, Claes L. Testing criteria for spinal implants: recommendations for the standardization of in vitro stability testing of spinal implants. *Eur Spine J*. 1998;7:148-154.
22. Stolworthy DK, Zirbel SA, Howell LL, Samuels M, Bowden AE. Characterization and prediction of rate-dependent flexibility in lumbar spine biomechanics at room and body temperature. *Spine J*. 2014;14:789-798. doi:10.1016/j.spinee.2013.08.043
23. Gonzalez-Blohm SA, Doulgeris JJ, Lee WE, Shea TM, Aghayev K, Vrionis FD. The current testing protocols for biomechanical evaluation of lumbar spinal implants in laboratory setting: a review of the literature. *Biomed Res Int*. 2015;2015:506181. doi:10.1155/2015/506181
24. Rohlmann A, Consmüller T, Dreischarf M, et al. Measurement of the number of lumbar spinal movements in the sagittal plane in a 24-hour period. *Eur Spine J*. 2014;23:2375-2384. doi:10.1007/s00586-014-3588-0
25. Shim CS, Lee S, Maeng DH, Lee SH. Vertical split fracture of the vertebral body following total disc replacement using ProDisc: report of two cases. *J Spinal Disord Tech*. 2005;18:465-469.
26. Keskil S, Göksel M, Yüksel U. Unilateral lag-screw technique for an isolated anterior ¼ atlas fracture. *J Craniovertebr Junction Spine*. 2016;7:50-54. doi:10.4103/0974-8237.176625
27. Rohlmann A, Zander T, Rao M, Bergmann G. Applying a follower load delivers realistic results for simulating standing. *J Biomech*. 2009;42:1520-1526. doi:10.1016/j.jbiomech.2009.03.048
28. Goel VK, Panjabi MM, Patwardhan AG, Dooris AP, Serhan H. Test protocols for evaluation of spinal implants. *J Bone Joint Surg Am*. 2006;88(suppl 2):103-109. doi:10.2106/JBJS.E.01363
29. Patwardhan AG, Havey RM, Meade KP, Lee B, Dunlap B. A follower load increases the load-carrying capacity of the lumbar spine in compression. *Spine (Phila Pa 1976)*. 1999;24:1003-1009.
30. Patwardhan AG, Havey RM, Carandang G, et al. Effect of compressive follower preload on the flexion-extension response of the human lumbar spine. *J Orthop Res*. 2003;21:540-546. doi:10.1016/S0736-0266(02)00202-4
31. Janevic J, Ashton-Miller JA, Schultz AB. Large compressive preloads decrease lumbar motion segment flexibility. *J Orthop Res*. 1991;9:228-236. doi:10.1002/jor.1100090211
32. Wong EKY, Whyne CM, Singh D, Ford M. A biomechanical assessment of kyphoplasty as a stand-alone treatment in a human cadaveric burst fracture model. *Spine (Phila Pa 1976)*. 2015;40:E808-E813. doi:10.1097/BRS.0000000000000967
33. Mundis GM, Eastlack RK, Moazzaz P, Turner AWL, Cornwall GB. Contribution of round vs rectangular expandable cage endcaps to spinal stability in a cadaveric corpectomy model. *Int J spine Surg*. 2015;9:53. doi:10.14444/2053
34. Denis F. The three column spine and its significance in the classification of acute thoracolumbar spinal injuries. *Spine (Phila Pa 1976)*. 1983;8:817-831.
35. Li Y, Shen Z, Huang M, Wang X. Stepwise resection of the posterior ligamentous complex for stability of a thoracolumbar compression fracture. *Medicine (Baltimore)*. 2017;96:e7873. doi:10.1097/MD.0000000000007873
36. Magerl F, Aebi M, Gertzbein SD, Harms J, Nazarian S. A comprehensive classification of thoracic and lumbar injuries. *Eur Spine J*. 1994;3:184-201.
37. Chatzistergos PE, Karaoglanis GC, Kourkoulis SK, Tyllianakis M, Stamatis ED. Supplementary medial locking plate fixation of Ludloff osteotomy versus sole lag screw fixation: A biomechanical evaluation. *Clin Biomech (Bristol, Avon)*. 2017;47:66-72. doi:10.1016/j.clinbiomech.2017.06.003