


Original Article

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The Effect of Rod Pattern, Outrigger, and Multiple Screw-Rod Constructs for Surgical Stabilization of the 3-Column Destabilized Cervical Spine - A Biomechanical Analysis and Introduction of a Novel Technique

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Objective: Anterior-only reconstructions for cervical multilevel corpectomies are prone to fail under continuous mechanical loading. This study sought to define the mechanical characteristics of different constructs in reducing a range of motion (ROM) of the 3-column destabilized cervical spine, including posterior cobalt-chromium (CoCr)-rods, outrigger-rods (OGR), and a novel triple rod construct using lamina screws (6S3R). The clinical implications of biomechanical findings are discussed in depth from the perspective of the challenges surgeons face cervical deformity correction.

Methods: Three-column deficient cervical spinal models were produced based on reconstructed computed tomography scans. The corpectomy defect between C3 and C7 end-level vertebrae was restored with anterior titanium (Ti) mesh-cage. The ROM was evaluated in a customized 6-degree of freedom spine tester. Tests were performed with different rod materials (Ti vs. CoCr), varying diameter rods (3.5 mm vs. 4.0 mm), with and without anterior plating, and using different construct patterns: bilateral rod fixation (standard-group), OGR-group, and 6S3R-Group. Construct stability was expressed in changes and differences of ROM (°).

Results: The largest reduction of ROM was noticed in the 6S3R-group compared to the standard- and the OGR-group. All differences observed were emphasized with an increasing number of corpectomy levels and if anterior plating was not added. For all simulated 1-, 2-, and 3-level corpectomy constructs, the OGR-group revealed decreased ROM for all motion directions compared to the standard-group. An increase of construct stiffness was also recorded for increased rod diameter (4.0 mm) and stiffer rod material (CoCr), though these effects lacked behind the more advanced construct pattern.

Conclusion: A novel reconstructive technique, the 6S3R-construct, was shown to outperform all other constructs and might resemble a new standard of reference for advanced posterior fixation.

Keywords: Biomechanical study, Cervical spine, Construct testing, Instrumentation patterns, Multilevel constructs, Three-column instability



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INTRODUCTION

Cervical corpectomy and multilevel reconstruction is indicated in patients with degenerative disorders and stenosis, spinal column destruction from fracture, infection, or neoplastic disease, and for the treatment of cervical deformity.¹⁻¹⁴

The ideal construct pattern to be selected for each patient is difficult to define because spinal construct stability is the sum of instrumentation pattern, bone quality, number of fixation points used, anterior column support, and posterior tension band integrity, as well as spinal alignment and cervical balance.^{4,15-22} Likewise, anterior-only reconstruction of multilevel corpectomies using a cage and anterior cervical plate only is prone to failure.²⁻⁷ The anterior stabilization with cage and plate in combination with posterior screw-rod instrumentation using 3.5-mm titanium (Ti)-rods has already been established as a standard of reference (SOR) both, biomechanically and clinically.^{2,4,6-8,23}

The 360°-construct outperforms all anterior-only or posterior-only constructs in its ability to resist fatigue testing in flexion-extension (FE), axial rotation (AR), and lateral bending (LB).^{8,24-29} Nevertheless, augmentation of anterior constructs with anterior transpedicular screw fixation or using cement augmentation was shown to increase primary construct stability compared to the SOR significantly.^{6,20,21,30,31}

In some patients, anterior reconstruction or plating is either not possible in case of destructive osseous characteristics, or it is intentionally avoided in preference for a posterior-only construct to enable screw-rod based posterior correction after an anterior release.¹⁵ In the treatment of cervical deformities, a posterior-only construct in combination with posterior osteotomies was used in 55% of patients in one large multicenter study.³² A 3-column osteotomy at the cervicothoracic junction results in 3-dimensional spinal destabilization and renders the osteotomy sites highly unstable. However, the biomechanical influence of various posterior-only instrumentation patterns and rod characteristics on construct stability is not fully understood yet.

For the lumbar and thoracic spine, the use of CoCr-rods and multiple-rods bridging 3-column osteotomies was shown to increase the reduction in range of motion (ROM) at zones of high instability in biomechanical studies and decrease the risk of rod fractures and pseudoarthrosis in clinical studies.³³⁻³⁸ These out-rigger-rods (OGR) and satellite rod constructs are easily applied using lateral off-set connectors attached to a standard bilateral screw-rod construct. In the cervical spine, no study has ana-

lyzed the biomechanical impact of multiple-rod constructs.

Recently, Koller and Robinson¹⁵ have published their technique using a triple rod construct using lamina screws (6S3R) construct for augmentation of construct strength in posterior-only constructs for the reconstruction of the 3-column destabilized cervical spine. With this technique, in addition to a standard posterior construct using bilateral rods, a third in the midline is connected to 2 lamina screws inserted in the upper and lower end-vertebrae. This results in each of the 6 screws being connected to the end-vertebrae. The triple rod construct using lamina screws were shown clinically effective but demanded biomechanical analysis and benchmark to standard instrumentations.

Therefore, the objectives of the current study were to analyze construct stability of the 3-column destabilized cervical spine using different instrumentation patterns, rod characteristics, and the novel triple rod construct using lamina screws.

The selected study setup provides comparable test conditions to identify mechanical differences among varying construct patterns to serve basic data for future investigations of long-term fatigue and resistance to failure.

MATERIALS AND METHODS

1. Biomechanical Laboratory Study

Using polyamide models, this study compared the construct stiffness in terms of ROM reduction of different constructs bridging a 1-, 2-, and 3-level corpectomy defect (Fig. 1). Complete anterior and posterior column destabilization was simulated by removing all anterior and posterior elements.

2. Spine Models

The spinal models and vertebrae were produced based on the reconstructed computed tomography (CT) scan of a healthy 43-year-old female patient without cervical disorders (Figs. 1, 2). The C3 and C7 vertebrae were used as the proximal and distal end-vertebrae of the corpectomy models tested.

Using computer-aided design software, the upper osseous elements of C3 and the lower elements of C7 were linked to a socket, which could be affixed to the testing apparatus to ensure stability (Fig. 1). The models were printed on a Formiga P110 (EOS GmbH Electro Optical Systems, Munich, Germany) using selective laser sintering technology. The material was polyamide 2200 (Tensile modulus 1650 Mpa, density 930 kg/m³).

The vertical dimensions of a 1-, 2-, and 3-level corpectomy defect were calculated based on the dimensions measured on

the sagittal CT scans. A distance of 20 mm between the proximal and the distal end-vertebra resembled a 1-level corpectomy, 40-mm distance a 2-level corpectomy and 60-mm distance

a 3-level corpectomy. The corpectomy distance was reconstructed with a cut titanium mesh-cage to provide structural anterior column support (Fig. 2).



Fig. 1. The spine simulator with a 3-dimensional motion analysis system.

3. Instrumentation Patterns

The 3-column destabilized spinal models were instrumented using an anterior mesh-cage and combinations of different posterior rod materials (Ti vs. CoCr), rod diameters (3.5 mm vs. 4.0 mm), rod patterns (2 vs. multiple-rods), an anterior cervical plate, and with a triple rod construct using lamina screws.

The test-setup with the 3-column destabilized spine was realized by simulating a 1-, 2-, and 3-level corpectomy. The end-vertebrae were instrumented with posterior pedicle screws (Fig. 2).

In general, 3 different constructs were tested with the aforementioned modifications:

- (1) Bilateral posterior screw-rod instrumentation. This instrumentation included 2 rods and 2 pedicle screws in each end-vertebra and resembled the standard-group (Figs. 2A1, 3).
- (2) Bilateral posterior screw-rod instrumentation with addition of bilateral 3.5-mm Ti OGR attached by lateral connectors to the lateral side of the standard bilateral rods (OGR-group; Figs. 2A2, 3).
- (3) Bilateral posterior screw-rod instrumentation with addition of one lamina screw inserted in the upper and the lower end-vertebra and connected by a midline 3.5-mm Ti-rod (6S3R-group; Figs. 2A3, 3).

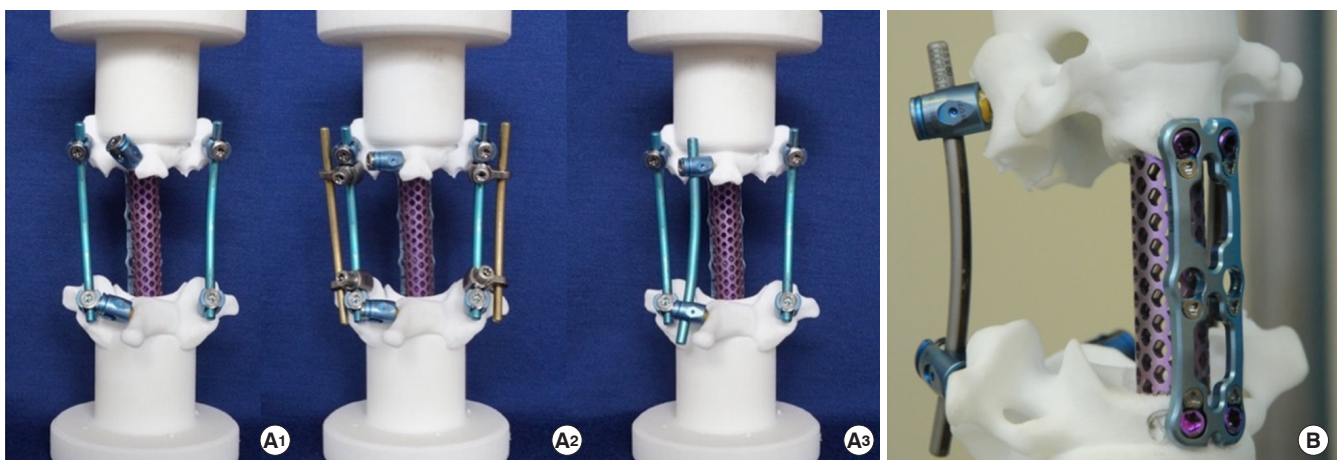


Fig. 2. Test-setup with an instrumented 3-column destabilized spine model. (A1) Bilateral posterior screw-rod instrumentation with 2 rods and 2 pedicle screws in each end-vertebra (standard-group); (A2) bilateral posterior screw-rod instrumentation with the addition of bilateral 3.5-mm titanium outrigger-rods attached by lateral connectors to the standard bilateral rods (OGR-group); (A3) bilateral posterior screw-rod instrumentation with addition of a lamina screw inserted in the upper and the lower end-vertebra connected by a midline 3.5-mm titanium-rod (6S3R-group). (B) A 2-level model with posterior instrumentation according to the standard-group within the spine tester.

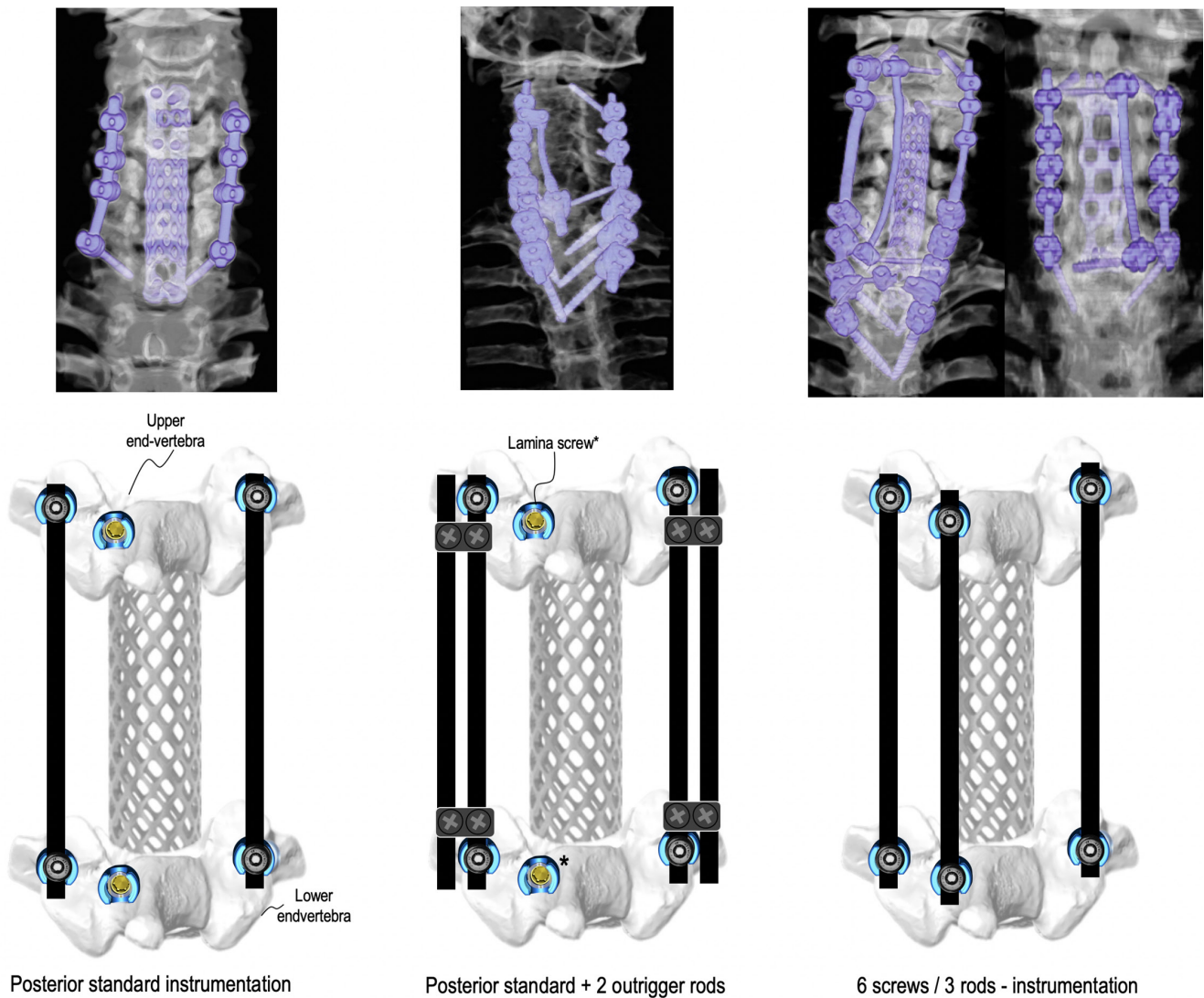


Fig. 3. Artist’s illustration of instrumentation patterns tested (lower row) and clinical rationale and examples (upper row).

These 3 basic set-ups were modified by rod diameter and rod material, as well as the addition of an anterior plate.

4. Spinal Implants

For the posterior screw-rod instrumentation, the Symphony System was used (Depuy Synthes Co., Raynham, MA, USA). Pedicle screw fixation was done using 3.5-mm diameter Ti screws with 30-mm length. For lamina screw fixation, the authors used 3.5-mm diameter screws with 24-mm length.

Anterior structural support was supplied by a SynMesh-Cage system (Synthes Spine Inc., West Chester, PA, USA). For anterior plate fixation, the Skyline Anterior Cervical Plate System (Synthes, Oberdorf, Switzerland) was applied using 4.0-mm diameter screws with 14-mm length. The screws were connected to

the plate to form a constrained construct by a cam-lock mechanism.

5. Flexibility Testing

The spinal tests were carried out in a customized 6 degrees of freedom spine simulator. The specimen was loaded with pure moments of 2.0 Nm in FE, AR, and LB. The moments were applied by a stepper motor, a 6-component load cell attached to the cranial end of the spine was used for feedback control of the applied bending moments. Three load cycles were performed for each motion direction, only the third load cycle was used for data evaluation. The biomechanical testing of the models was carried out following the recommendations for testing of spinal implants.³⁹ An intersegmental motion was measured us-

ing an ultrasound-based motion analysis system (Winbiomechanics, Zebris, Isny, Germany). The proximal and distal end-vertebrae were connected with their socket to the spine tester. The length of the proximal socket was 60 mm, the distal socket 70 mm. This rigid connection to the end-vertebrae prevented movement of the end-vertebrae during testing. The 3-dimensional motion analysis system was fixed to the polyamide sockets of the end-vertebrae (Fig. 1).

All flexibility tests were performed with the same polyamide model to enable comparability. The models were instrumented in the customized spine tester with an axial preload of approximately 2 kg. This ensured a standardized stable preloaded cage fixation in the anterior part of the 3-column destabilized spine model. Additionally, in case of rod material or rod diameter change, one rod was left in place to ensure construct stability

while the rod on the contralateral side was replaced. Afterward, the remaining rod was replaced too. The same was done for application and removal of the anterior plate. All locking screws were placed with the use of the 2 Nm torque limiting handle.

Construct stiffness was assessed using flexibility tests (ROM) with pure moment testing, and the differences were expressed as percentage ROM (%ROM) normalized to the performance of the SOR.

6. Statistical Analysis

Data storage and descriptive statistical analyses were performed with the use of Microsoft Excel (ver. 15.36 for Mac OS X, Microsoft Corp., Redmond, WA, USA).

The ROM results for each construct tested were recorded, and the calculated percentage ROM (%ROM) normalized to

Table 1. Results of mechanical testing of construct stiffness in axial rotation

Model	Diameter (mm)	With anterior plate				Without anterior plate			
		Ti °ROM	Ti %ROM	CoCr °ROM	CoCr %ROM	Ti °ROM	Ti %ROM	CoCr °ROM	CoCr %ROM
1-Level model									
Standard-group	3.5	1.72	100	1.35	78	4.19	244	3.22	187
Standard-group	4.0	1.74	101	1.4	81	4.03	234	3.86	224
OGR-group	3.5	1.58	92	1.44	84	3.4	198	3.47	202
OGR-group	4.0	1.29	75	1.2	70	3.85	224	3.79	220
6S3R-group	3.5	1.12	65	1.07	62	2.79	162	2.34	136
6S3R-group	4.0	0.62	36	0.57	33	2.7	157	2.54	148
2-Level model									
Standard-group	3.5	3.54	100	2.57	73	8.99	254	6.32	179
Standard-group	4.0	3.07	87	2.89	82	7.54	213	6.70	189
OGR-group	3.5	3.22	91	2.42	68	7.74	219	6.02	170
OGR-group	4.0	2.73	77	2.86	81	6.75	191	6.67	188
6S3R-group	3.5	1.68	47	1.58	45	5.48	155	3.70	105
6S3R-group	4.0	1.58	45	1.31	37	4.62	131	4.15	117
3-Level model									
Standard-group	3.5	6.06	100	4.94	82	14.66	242	9.29	153
Standard-group	4.0	3.73	62	4.34	72	11.49	190	9.10	150
OGR-group	3.5	5.27	87	4.78	79	13.02	215	7.30	120
OGR-group	4.0	3.75	62	4.12	68	11.10	183	7.98	132
6S3R-group	3.5	4.14	68	3.51	58	8.96	148	5.93	98
6S3R-group	4.0	2.53	42	2.20	36	7.55	125	4.95	82

Presented data resembles raw data (°) of the ROM analysis and normalized values expressed as %ROM, normalized to the performance of the SOR (standard-group with bilateral 3.5-mm titanium-rods) in axial rotation.

ROM, range of motion; CoCr, cobalt-chromium; OGR, outrigger-rods; SOR, standard of reference; Ti °ROM, ROM (°) results with testing titanium-rods; Ti%ROM, normalized results; CoCr °ROM, ROM (°) results with testing cobalt chromium rods; CoCr%ROM, normalized results.

the performance of the SOR was outlined. The bilateral posterior screw-rod instrumentation using 3.5-mm Ti-rods in combination with an anterior cervical plate resembled the SOR (Fig. 2A1). In the current study, all constructs were benchmarked to the ROM results of the SOR. A difference larger than 30% between the ROM of the SOR and calculated %ROM of the other constructs tested was defined as a significant difference in our model.

RESULTS

The study design resulted in a total of 432 test configurations. Descriptive analysis of the models did not show any screw loosening or implant breakage due to the nondestructive test-setup. Results of ROM testing for AR and FE are summarized in Ta-

bles 1, 2 and Figs. 4, 5. The results for LB are summarized in Table 3 and Fig. 6 and are available as an electronic supplement.

Among all constructs tested, the largest change was seen with the addition of an anterior plate and with a triple rod construct using lamina screws (6S3R-construct).

1. Effect of Number of Corpectomy Levels on ROM

An increased destabilization from the instrumented 1- to the 3-level model was observed regardless of the posterior instrumentation pattern and anterior plate, particularly in AR-testing. In AR-testing, approximately a 2-fold increase of ROM from the 1- to the 2-level model could be observed as well as a 0.5-fold increase of ROM from the 2- to the 3-level model (Table 1). The smallest increase of ROM among the 1- to 3-level models was observed within the 6S3R-group and with the addition of

Table 2. Results of mechanical testing of construct stiffness in flexion/extension

Model	Diameter (mm)	With anterior plate				Without anterior plate			
		Ti °ROM	Ti %ROM	CoCr °ROM	CoCr %ROM	Ti °ROM	Ti %ROM	CoCr °ROM	CoCr %ROM
1-Level model									
Standard-group	3.5	0.57	100	0.50	88	7.94	1,393	6.32	1,109
Standard-group	4.0	0.47	82	0.43	75	8.12	1,425	6.27	1,100
OGR-group	3.5	0.49	86	0.51	89	6.76	1,186	5.80	1,018
OGR-group	4.0	0.52	91	0.50	88	7.31	1,282	6.28	1,102
6S3R-group	3.5	0.38	67	0.32	56	2.13	374	1.73	304
6S3R-group	4.0	0.36	63	0.31	54	2.42	425	2.03	356
2-Level model									
Standard-group	3.5	0.58	100	0.50	86	7.94	1,369	5.58	962
Standard-group	4.0	0.60	103	0.48	83	10.01	1,726	9.21	1,588
OGR-group	3.5	0.55	95	0.53	91	8.24	1,421	6.10	1,052
OGR-group	4.0	0.52	90	0.58	100	8.37	1,443	9.51	1,640
6S3R-group	3.5	0.28	48	0.30	52	3.34	576	1.82	314
6S3R-group	4.0	0.32	55	0.30	52	2.74	472	2.17	374
3-Level model									
Standard-group	3.5	0.56	100	0.55	98	13.96	2,493	9.45	1,688
Standard-group	4.0	0.66	118	0.59	105	12.78	2,282	8.56	1,529
OGR-group	3.5	0.54	96	0.50	89	10.90	1,946	6.10	1,089
OGR-group	4.0	0.73	130	0.65	116	10.09	1,802	5.95	1,063
6S3R-group	3.5	0.32	57	0.31	55	4.34	775	3.32	593
6S3R-group	4.0	0.44	79	0.31	55	4.20	750	3.20	571

Presented data resembles raw data (°) of the ROM analysis and normalized values expressed as %ROM, normalized to the performance of the SOR (standard-group with bilateral 3.5-mm titanium-rods) in flexion/extension.

ROM, range of motion; CoCr, cobalt-chromium; OGR, outrigger-rods; SOR, standard of reference; Ti °ROM, ROM (°) results with testing titanium-rods; Ti%ROM, normalized results; CoCr °ROM, ROM (°) results with testing cobalt chromium rods; CoCr%ROM, normalized results.

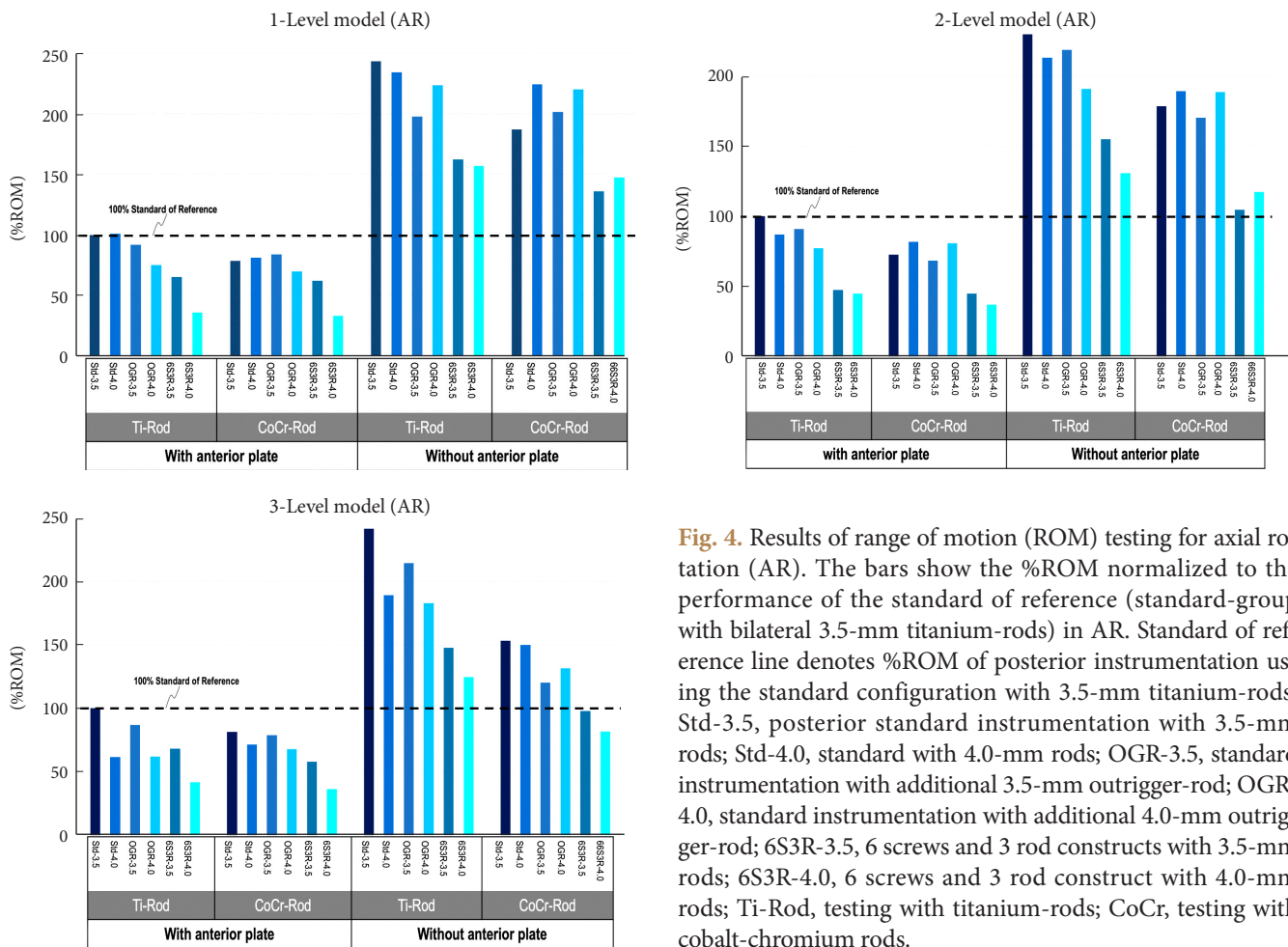


Fig. 4. Results of range of motion (ROM) testing for axial rotation (AR). The bars show the %ROM normalized to the performance of the standard of reference (standard-group with bilateral 3.5-mm titanium-rods) in AR. Standard of reference line denotes %ROM of posterior instrumentation using the standard configuration with 3.5-mm titanium-rods. Std-3.5, posterior standard instrumentation with 3.5-mm rods; Std-4.0, standard with 4.0-mm rods; OGR-3.5, standard instrumentation with additional 3.5-mm outrigger-rod; OGR-4.0, standard instrumentation with additional 4.0-mm outrigger-rod; 6S3R-3.5, 6 screws and 3 rod constructs with 3.5-mm rods; 6S3R-4.0, 6 screws and 3 rod construct with 4.0-mm rods; Ti-Rod, testing with titanium-rods; CoCr, testing with cobalt-chromium rods.

an anterior plate. This effect was observed particularly in AR and FE (Tables 1, 2).

2. Effect of Rod Material and Rod Diameter on ROM

In FE, the use of different rod materials and rod diameter had no significant influence on ROM reduction in neither the 1-level, 2-level, nor 3-level models. This was generally true whether an anterior plate was added or not.

In FE without anterior plate, a significantly improved reduction of ROM was noted for the use of CoCr-rods instead of Ti-rods for all corpectomy models (Table 2, Fig. 5).

In AR without an anterior plating, the diameter of the Ti-rod showed a significant influence on ROM reduction in the 2-level and the 3-level models, as well as the use of a 3.5-mm CoCr-rod compared to a 3.5-mm Ti-rod in the 1-, 2-, and 3-level group. For the 4.0 mm Ti-rod compared to the 3.5-mm Ti-rod, a colinear trend existed for the 2- and 3-level model (Table 1, Fig. 4).

In FE with additional anterior plating, rod diameter and rod

material showed no significant influence on ROM reduction.

For AR with an anterior plate, the use of CoCr-rods instead of Ti-rods showed a general trend towards improved %ROM reduction in 1-, 2-, and 3-level models, but differences did not yield significance. The same was true in AR with the use of 4.0-mm Ti-rods compared to 3.5-mm Ti-rods in 2- and 3-level models. However, this trend was eliminated when using 3.5 mm or 4.0 mm CoCr-rods instead of Ti-rods (Table 1, Fig. 4).

For LB without anterior plating, significantly improved reduction of ROM was shown for 4.0-mm vs. 3.5-mm diameter Ti-rods in the 2- and 3-level model and for the use of a CoCr-rod instead of Ti-rod in the 1-, 2- and 3-level model regardless the rod diameter. With anterior plating, the nuances mentioned above in reduction of ROM were eliminated in LB (Table 3, Fig. 6).

Summarizing, comparison of Ti- and CoCr-rods in standard posterior instrumentation without anterior plating showed a significant %ROM reduction in favor for the CoCr-rod in FE and AR for all models, and LB for the 2- and 3-level model. The diameter of the CoCr-rod did not have a significant influence

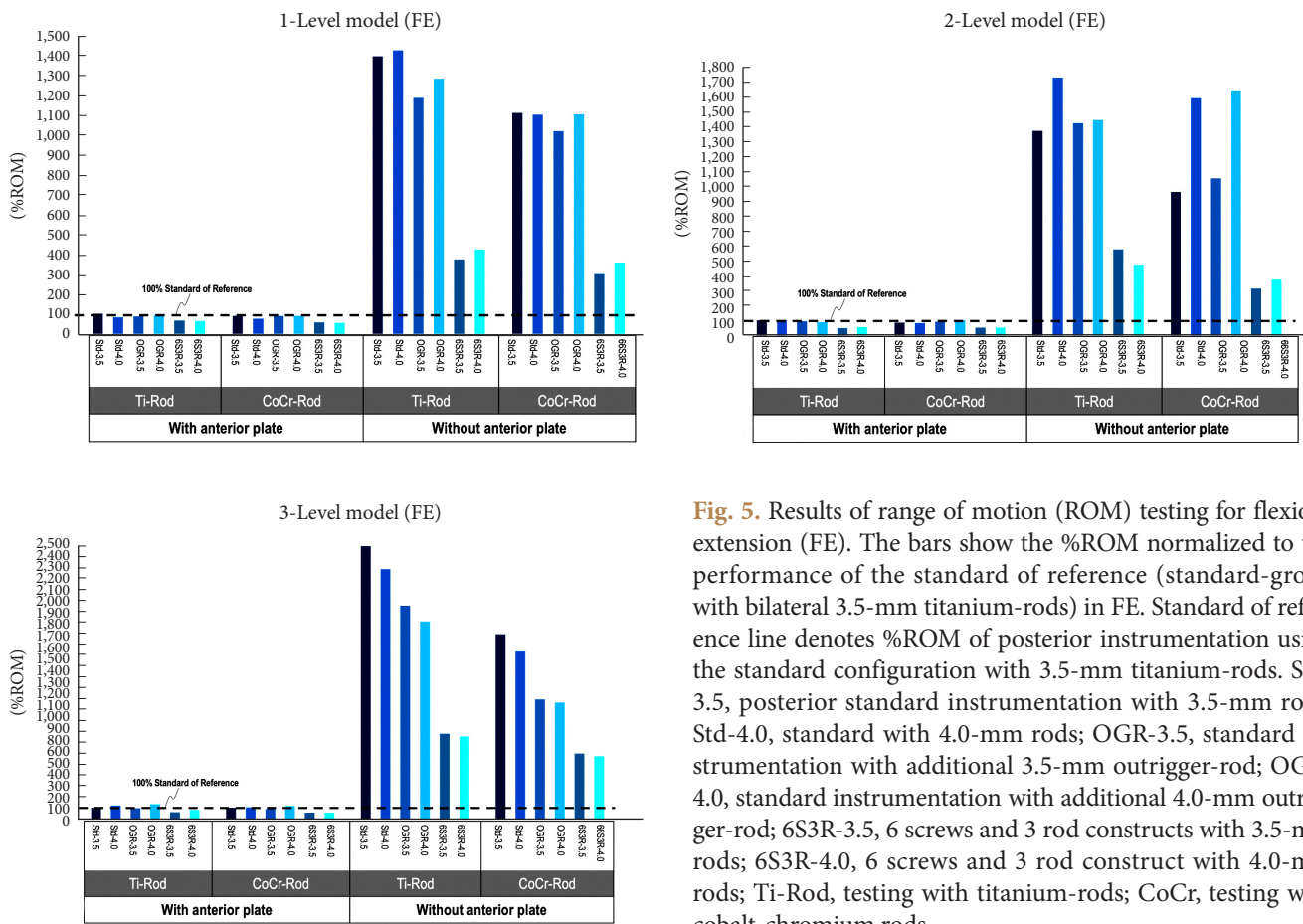


Fig. 5. Results of range of motion (ROM) testing for flexion-extension (FE). The bars show the %ROM normalized to the performance of the standard of reference (standard-group with bilateral 3.5-mm titanium-rods) in FE. Standard of reference line denotes %ROM of posterior instrumentation using the standard configuration with 3.5-mm titanium-rods. Std-3.5, posterior standard instrumentation with 3.5-mm rods; Std-4.0, standard with 4.0-mm rods; OGR-3.5, standard instrumentation with additional 3.5-mm outrigger-rod; OGR-4.0, standard instrumentation with additional 4.0-mm outrigger-rod; 6S3R-3.5, 6 screws and 3 rod constructs with 3.5-mm rods; 6S3R-4.0, 6 screws and 3 rod construct with 4.0-mm rods; Ti-Rod, testing with titanium-rods; CoCr, testing with cobalt-chromium rods.

on ROM reduction.

The use of different rod diameters did not affect in models tested within the OGR-group and 6S3R-group. However, in AR a significant difference for the use of CoCr-rods instead of Ti-rods were seen for both groups in the 2-level and 3-level model without anterior plate (Table 1, Fig. 4).

3. Effect of Posterior Construct Patterns on ROM

The posterior-only instrumentation with 3.5-mm Ti-rods provided the smallest construct stability among all constructs tested. The 360°-construct (SOR) outperformed all other constructs in FE, AR, and LB among all models tested. However, only the 6S3R-construct without an anterior plate but with CoCr-rods were able to achieve a similar reduction of ROM in AR for 2- and 3-level models (Table 1) and in FE for the 1-level construct (Table 2) compared to the SOR.

With an anterior plate in FE, the 6S3R-construct did further improve stability for the 1-, 2-, and 3-level model (Table 2). In AR, the addition of a 6S3R-construct significantly improved construct stability for all models tested, while in LB of the 2-level

el model, a significant gain in stability was achieved. The stiffest posterior construct was revealed to be the 6S3R-construct with the use of CoCr-rods.

Notably, the OGR-group did not perform as well as expected. Without anterior plating, it showed a nonsignificant ROM reduction compared to the posterior standard-group and the SOR regardless of the motion direction. In AR, a significant difference to a standard posterior instrumentation was achieved for the 2- and the 3-level model if 4.0-mm Ti-rods or CoCr-rods of any size were used in the OGR-group without an anterior plate (Table 1). However, in AR, the OGR-group with Ti-rods did not perform significantly better than the posterior standard-group with 4.0-mm Ti-rods (Table 1). Likewise, in AR, the OGR-group with CoCr-rods did not perform significantly better than the posterior standard-group with either 3.5- or 4.0-mm CoCr-rods regardless of plate usage.

In FE, a significant difference between the OGR-group and the standard-group was only noted with CoCr-rods in the 1- and the 3-level corpectomy group without an anterior plate (Table 2). Contrastingly, the standard posterior instrumentation with

Table 3. Results of mechanical testing of construct stiffness in lateral bending

Model	Diameter (mm)	With anterior plate				Without anterior plate			
		Ti °ROM	Ti %ROM	CoCr °ROM	CoCr %ROM	Ti °ROM	Ti %ROM	CoCr °ROM	CoCr %ROM
1-Level model									
Standard-group	3.5	0.45	100	0.40	89	0.82	182	0.64	142
Standard-group	4.0	0.47	104	0.47	104	0.88	196	0.70	156
OGR-group	3.5	0.43	96	0.37	82	0.76	169	0.61	136
OGR-group	4.0	0.48	107	0.35	78	0.72	160	0.62	138
6S3R-group	3.5	0.42	93	0.34	76	0.72	160	0.60	133
6S3R-group	4.0	0.45	100	0.40	89	0.76	169	0.60	133
2-Level model									
Standard-group	3.5	0.50	100	0.42	84	0.81	188	0.59	118
Standard-group	4.0	0.48	96	0.52	104	0.59	137	0.56	112
OGR-group	3.5	0.48	96	0.41	82	0.71	165	0.61	122
OGR-group	4.0	0.36	72	0.41	82	0.57	133	0.50	100
6S3R-group	3.5	0.35	70	0.32	64	0.67	156	0.50	100
6S3R-group	4.0	0.33	66	0.39	78	0.53	123	0.47	94
3-Level model									
Standard-group	3.5	0.38	100	0.35	92	1.18	311	0.67	176
Standard-group	4.0	0.55	145	0.39	103	0.93	245	0.72	189
OGR-group	3.5	0.46	121	0.38	100	0.85	224	0.70	184
OGR-group	4.0	0.42	111	0.40	105	0.76	200	0.64	168
6S3R-group	3.5	0.47	124	0.47	124	0.70	184	0.59	155
6S3R-group	4.0	0.42	111	0.44	116	0.63	166	0.57	150

Presented data resembles raw data (°) of the ROM analysis and normalized values expressed as %ROM, normalized to the performance of the SOR (standard-group with bilateral 3.5-mm titanium-rods) in lateral bending.

ROM, range of motion; CoCr, cobalt-chromium; OGR, outrigger-rods; SOR, standard of reference; Ti °ROM, ROM (°) results with testing titanium-rods; Ti%ROM, normalized results; CoCr °ROM, ROM (°) results with testing cobalt chromium rods; CoCr%ROM, normalized results.

a 3.5- or 4.0 mm CoCr-rod instead of 3.5-mm Ti-rods performed similarly to the OGR-construct in FE among all models.

The same characteristics were true in LB for all models tested. The standard posterior instrumentation with 3.5- or 4.0-mm CoCr-rods instead of 3.5-mm Ti-rods performed similarly to the OGR-construct in LB regardless of the use of an anterior plate.

With anterior plating, the OGR-group showed nonsignificant improvement in %ROM reduction among all models tested except a significant difference in AR for the 3-level models using 4.0-mm Ti-rods or 4.0-mm CoCr-rods (Table 1). In general, the lowest impact of the OGR-construct was noted in FE, where it did not influence %ROM reduction.

4. Effect of an Anterior Plate on ROM

Compared to the posterior standard-group without an ante-

rior plate, the SOR with anterior plating and standard posterior instrumentation showed a significant increase of ROM reduction among all instrumentation patterns regardless of the models tested, and the motion direction applied. Without anterior plating, an up to a 6-fold increase of ROM could be noted among groups with the use of the standard posterior instrumentation. The largest absolute difference was shown in FE, followed by AR, the smallest absolute ROM reduction was observed in LB (Tables 1–3, Figs. 4–6). None of the posterior constructs could fully outweigh the effect of additional anterior plating.

The same was true for the OGR-construct. Only with 3.5-mm CoCr-rods, the OGR-construct without anterior plate performed similarly to the SOR in AR of the 3-level model and LB of the 2-level model (regardless of the used rod diameter).

Notably, in AR-testing without anterior plating, the 6S3R-

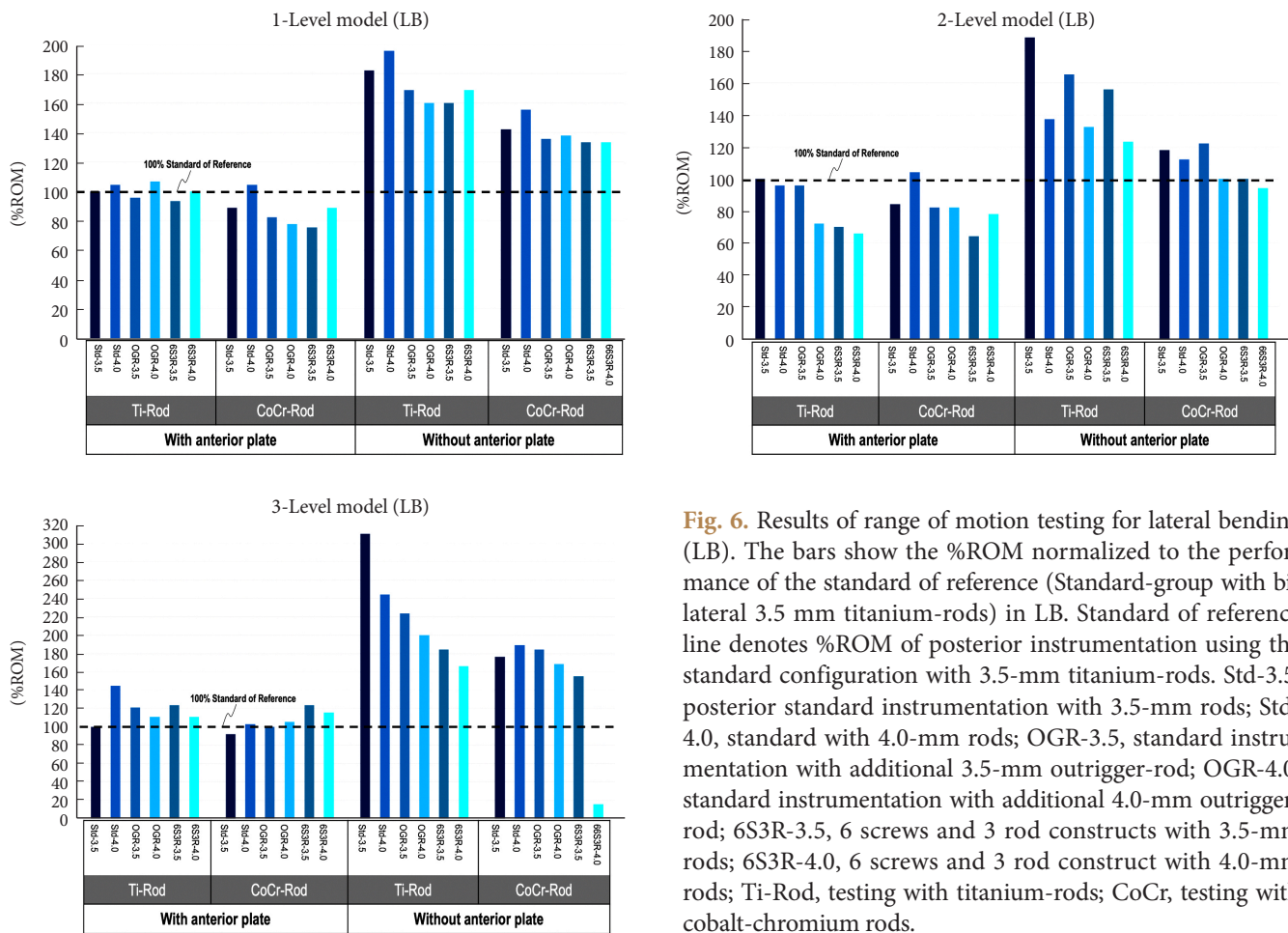


Fig. 6. Results of range of motion testing for lateral bending (LB). The bars show the %ROM normalized to the performance of the standard of reference (Standard-group with bilateral 3.5 mm titanium-rods) in LB. Standard of reference line denotes %ROM of posterior instrumentation using the standard configuration with 3.5-mm titanium-rods. Std-3.5, posterior standard instrumentation with 3.5-mm rods; Std-4.0, standard with 4.0-mm rods; OGR-3.5, standard instrumentation with additional 3.5-mm outrigger-rod; OGR-4.0, standard instrumentation with additional 4.0-mm outrigger-rod; 6S3R-3.5, 6 screws and 3 rod constructs with 3.5-mm rods; 6S3R-4.0, 6 screws and 3 rod construct with 4.0-mm rods; Ti-Rod, testing with titanium-rods; CoCr, testing with cobalt-chromium rods.

group showed no significant difference between the use of 3.5- or 4.0-mm CoCr-rods among 2- and 3-level models tested compared to the SOR (Table 1). The same was true for the 2-level model in LB. This emphasizes the stabilization potential of the triple rod construct using lamina screws (6S3R-construct).

5. Interpretation of ROM Data

An interpretation of the normalized ROM results reported as a percentage of the absolute ROM (%ROM) is given for the comparison of ROM under axial rotation in a 1-level model: With the SOR, AR-testing resulted in a ROM of 1.7°. The standard-group using a 3.5-mm CoCr-rod showed 1.4° ROM in AR (Table 1), resembling approximately 18% ROM reduction. Accordingly, in our test-setup, a change in ROM of 0.1° was related to a change of 5.9% in ROM. In other words, a change in 1° refers to a difference greater than 50% of ROM. In similar biomechanical studies using human specimens, a 30% ROM difference was usually the cutoff to signify a difference among different constructs tested.^{4,5,23,30,40-42}

DISCUSSION

The authors of the current study sought to clarify which instrumentation pattern was suitable to be studied by long-term cyclic loading and to provide basic biomechanical data for a novel technique, namely the triple rod construct using lamina screws. These data are a contribution to guide future biomechanical and clinical research.

Using a setup that allowed a uniform comparison of different instrumentation patterns, this study showed that the SOR outperformed all other constructs, followed by the triple rod construct using lamina screws concerning ROM reduction. In AR, the 6S3R-construct achieved even similar ROM reduction to the SOR. The triple rod construct using lamina screws (6S3R) is used as part of posterior-only screw-rod instrumentation. It provides the greatest stability among all other techniques tested in FE, AR, and LB in 1- to 3-level models. Recently, laminar screws were proofed to be a safe alternative to traditional fusion constructs, especially to gain additional stability in the subaxial

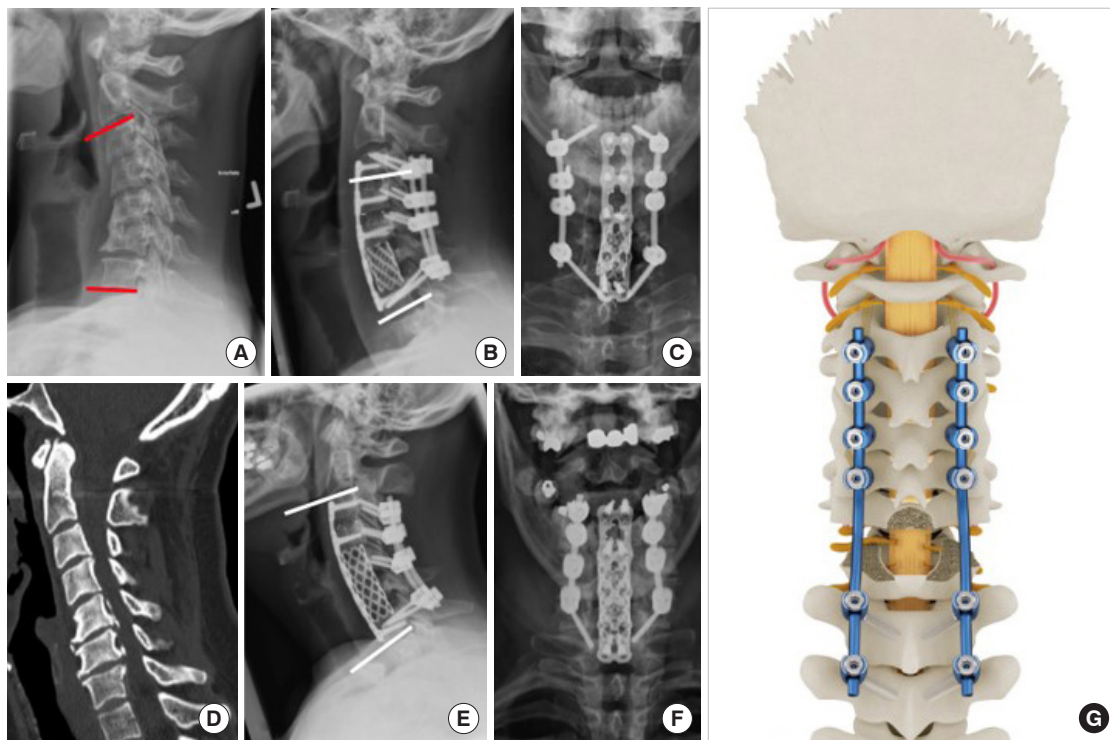


Fig. 7. Standard posterior instrumentation. Clinical example of a patient with moderate cervical kyphosis and residual stenosis following anterior cervical discectomy and fusion (A) receiving a 360° revision surgery (B, C). (D) Another patient with loss of cervical lordosis and severe stenosis due to ossification of the posterior longitudinal ligament receiving anterior multilevel corpectomies and plated reconstruction with posterior fusion (E, F). In both patients, there was no need for advanced posterior instrumentation, given the 360°-stabilization in both. (G) A standard posterior screw-rod construct was used (e.g., 3.5-mm titanium-rod).

spine applicable to a wide number of patients.⁴³ With a laminar screw in the upper and the lower end-vertebra of the subaxial spine, the additional rod bridges the end-levels effectively and, thus, further increases the ability to reduce ROM between levels instrumented. Clinical examples are shown in Figs. 7–9.

The use of multiple-rods has been shown to improve regional construct stiffness in thoracic and lumbar osteotomies. Therefore, at first glance, it seems counter-intuitive that the OGR-construct did not increase the reduction of ROM significantly in most testings compared to advanced posterior standard instrumentation with 4.0-mm Ti-rods or 3.5-mm/4.0-mm CoCr-rods. The authors used 3.5-mm and 4.0-mm rods for standard lateral cervical instrumentation. Due to the easy handling in case of rod bending for the 3rd rod within the triple rod construct using lamina screws, titanium 3.5-mm rods instead of CoCr were used without correction forces applied. As Figs. 2, 3 show, the additional outrigger-rod in an OGR-construct in the clinical setting (Figs. 10, 11) and the current biomechanical study are connected by lateral connectors positioned below the upper end-vertebra and above the lower end-vertebra. Accordingly, the ad-

ditional rod extends the cross-sectional area of fixation and, thus, moments of inertia of a given region of a screw-rod construct. However, end-level fixation strength is not changed. If the connectors of the OSR would be positioned proximal to the upper end-vertebra and distal to the lower end-vertebra, they might have the potential to improve stiffness of the whole construct from upper to lower level. This might result in the ability to reduce ROM closer to the 6S3R-construct. However, this kind of rod- and connector-alignment is not routinely done. It can be used if there is no space to place a connector between the heads of end-level pedicle screws to span an area of elevated instability, e.g., at the cervicothoracic junction, as shown in Fig. 12.

In published biomechanical and clinical studies which tested the benefits of adding multiple-rods, the biomechanical advantage was affected at the site of increased instability, which usually is a corpectomy or laminectomy defect or a 3-column osteotomy. That said, the multiple-rod constructs can further reduce ROM at the site of advanced instability, without improving overall stiffness of a construct that spans from end-level to end-level (Figs. 10, 11). With a triple rod construct using lami-

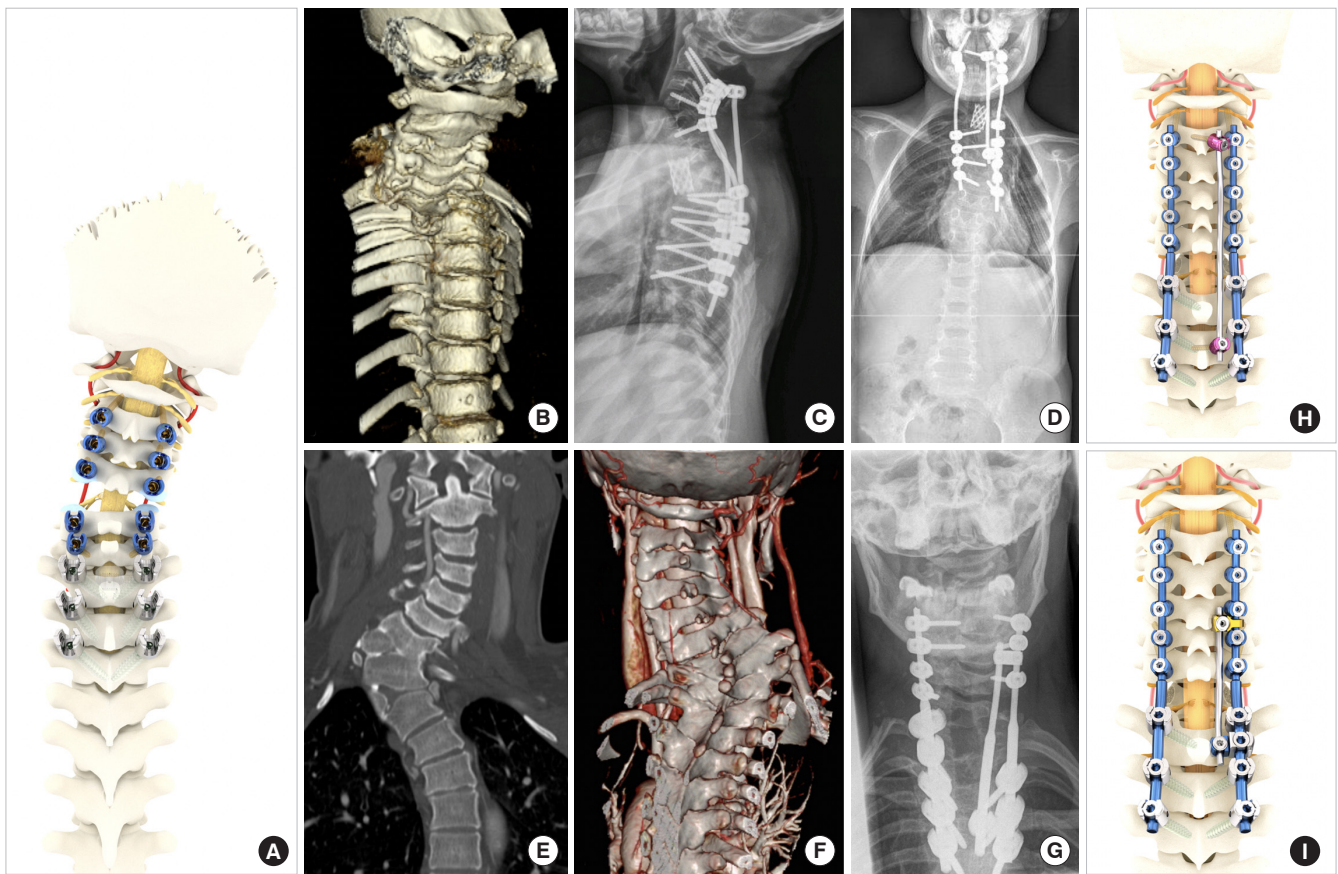


Fig. 8. Achieving the highest stability and improving fusion probability in a case of cervicothoracic vertebral column resection (VCR; A) with the use of either a 6S3R-construct (H) or a multiple-rod construct (I). (B–D) Correction of severe cervical deformity in a 5 years old patient with a history of multiple surgeries with a VCR of C7+T1 and application of 6S3R-technique. Notably, between the cervical screw heads, there was no space left to enable a multiple-rod construct. (E–G, I) A 27-year-old patient with congenital scoliosis due to dual-hemivertebrae of T1 and T3 (E, F). Posterior correction, stabilization, and fusion were achieved after VCR of T1 and T3 and instrumentation-correction of C4–T6 using a multiple-rod construct (G, I).

na screws, end-level anchorage characteristics are changed, and fixation strength is increased with 3 screws engaging into the upper and lower end-vertebra of the 3-rod construct. This was especially true for AR and FE effectively countering axial rotation as well as flexion and extension movements by an additional cranial and caudal bone contact area in the middle producing a “triangle-like” construct rather than a double rod laterally without a new bone contact area.^{44,45}

The main motion directions that challenge multilevel constructs are FE and AR. The current study could show that for a posterior-only construct, the selection of a 4.0-mm rod instead of a 3.5-mm Ti-rod causes an improvement in reduction of ROM in 2- and 3-level constructs in AR and LB, without any influence in FE. On the other hand, the use of CoCr-rods showed a significant influence among 2- and 3-level models in AR, among all models tested in LB, and a colinear trend was evident in FE,

too. If one considers improving construct stiffness by rod selection, the use of a 3.5-mm CoCr-rod might be the best choice from perspective of our study.

During surgery, the selection of a rod depends on the surgeon's objectives. The stiffness of a rod is an estimate for the magnitude of recoil forces that act upon the screw-bone interfaces after screw-rod reduction and locking is completed (force/deformation). The yield strength of a rod describes the transition zone from elastic to plastic rod deformation (ductility/fragility). The rigidity of a rod also gives information on the maintenance of a rod shape after implantation. A CoCr-rod with a similar diameter has higher stiffness, yield strength, and rigidity than a Ti-rod.^{46–49} With increasing diameter, these characteristics of all rods increase. The durability of the CoCr-rod compared to the Ti-rod is not different according to recent studies.^{50–52} In the clinical situation of a cervical deformity with need for reduc-



Fig. 9. Clinical example of a 6S3R-construct. (A–C) A 65-year-old patient presenting with a history of failed anterior cervical discectomy and fusion for degenerative instability, multilevel stenosis, and myelopathy. (D) Before presentation he had already received anterior and posterior revision and instrumentation, which had also failed. The patient had multilevel residual stenosis and showed a C5–7 palsy on the left side. (E, F) A revision was done with posterior instrumentation, decompression, and application of a 6S3R-construct, a large fusion mass was applied. An anterior revision was done with redo corpectomies C4, C5, C6 and C7, mesh cage insertion, and anterior screw-plate fixation using cement augmentation for the screws at T1. The patient achieved an excellent outcome (G–I) without need for painkillers and had regained full motor function. Mild distal junctional kyphosis could be seen at 1-year follow-up at T4–5.

tion and correction maneuvers, a well-balanced decision has to be made. A rod that is too stiff bears the risk for early screw-bone interface failure, pull-out, and bone fracture during the deformity correction procedure. A clinical case of deformity correction in osteoporotic bone highlights these concerns (Fig. 13). Accordingly, with the characteristics mentioned above of CoCr-rods, a 3.5-mm CoCr-rod might be preferred in perspective of the biomechanical evidence provided in the current study, whereas a 4.0-mm CoCr-rod might be too stiff, increasing stress at the end-levels, particularly in osteoporotic bone.

In 2 previous studies by Scheer et al.,^{53,54} the authors showed increased stiffness at the site of a 3-column osteotomy using 3.5-mm CoCr-rods compared to 3.5-mm Ti-rods and 4.5-mm Ti-rods compared to 3.5-mm Ti-rods. Higher stiffness was also shown in specimens that underwent a closing-wedge osteotomy compared to an open-wedge osteotomy.⁵⁴ While these results echo the current findings, most surgeons have standardized their techniques to the use of 3.5- or 4.0-mm rods of either material using multiple-rods to achieve improved construct stability at the site of an osteotomy.¹⁵ When choosing CoCr-rods

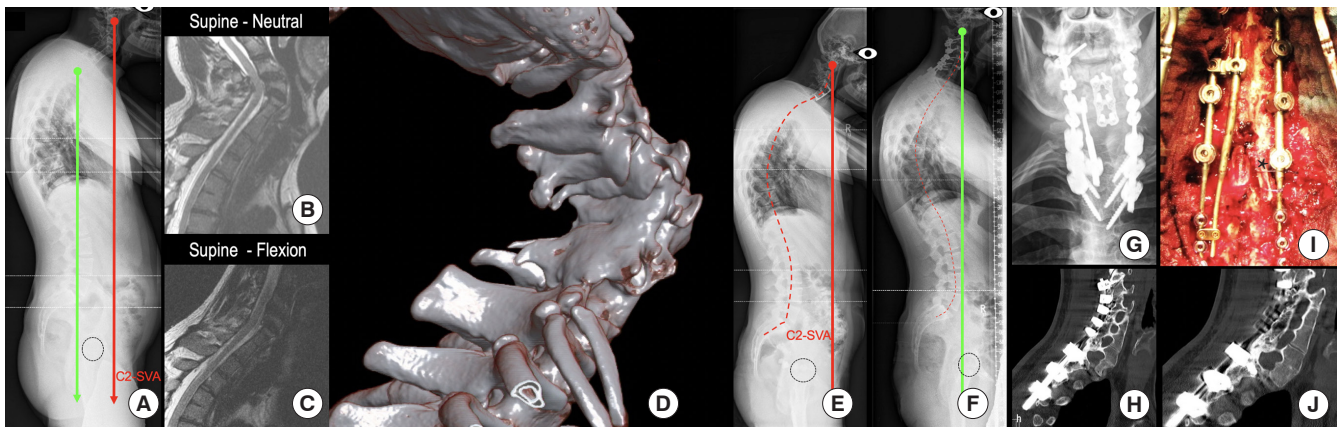


Fig. 10. Posterior screw-rod construct using multiple rods/outrigger rods. (A) A-18-year-old patient with a history of head-position dependent weakness (in extension), signs of cervical myelopathy, and painful fatigue with head dropping anteriorly over the course of day. The patient displayed Klippel-Feil syndrome with multiple block vertebrae in the upper thoracic spine fused in hyperkyphotic alignment with a compensatory regional hyperlordosis at C4–5 with instability (B, D). The angular stenosis, in extension, resolved in neutral slightly flexed head position, as shown on the dynamic magnetic resonance imaging (B, C). (E) The patient underwent planned staged surgery. First, an anterior cervical discectomy and fusion C3–5 with fusion in a neutral, slightly lordotic position was done using intraoperative neuromonitoring. (F) This worsened the global cervical balance as expected. Second, surgery, as planned, was with a reorientation of C2-sagittal vertical axis posteriorly and restoration of cervical balance by pedicle subtraction osteotomy of T1. A posterior fusion bridge was achieved using rib graft material. The clinical course was uneventful. Computed tomography-scan at 5 years (G–J) follow-up showed an asymptomatic fracture of the single right rod, no fracture on the left multiple-rods, and solid fusion of the rib graft bridging the facet gutter of C7–T1. The patient was asymptomatic and osseous fusion was achieved, no intervention was necessary.

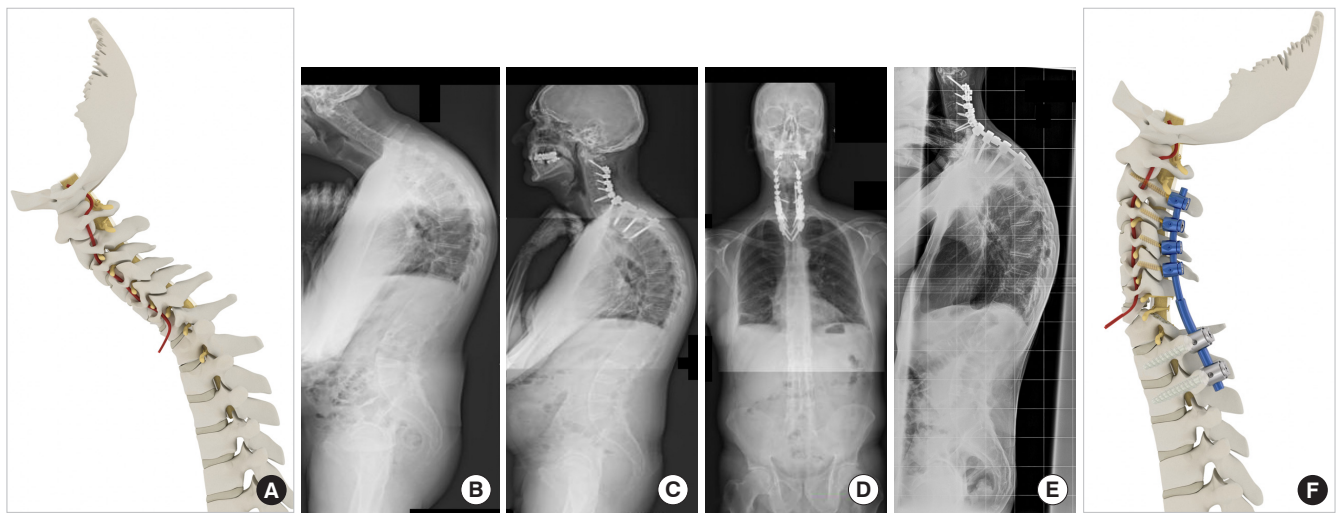


Fig. 11. Multiple-rods use in cervical deformity using closing-opening osteotomy. A 45-year-old patient with progressive and rigid cervical kyphosis due to ankylosing spondylitis (A, B). The patient underwent complication-free closing-opening-wedge osteotomy of C7–T1 (C, F) and stabilization with 3 rods (D, E). After recovery from severe pancreatitis, which occurred 2 weeks after surgery, he had excellent clinical results at 2-year follow-up.

in the cervical spine, one should be aware of increased stress that might be generated at the end-levels. In the thoracolumbar spine, a reduced rate of rod fractures with the use of CoCr-rods was shown in a series of adult spinal deformity patients of Han

et al.,⁵⁵ but the rate of proximal junctional kyphosis was significantly increased with the use of CoCr-rods compared to Ti-rods. Hence, particularly in the osteoporotic spine, selection of rod diameter and material should be made in awareness of the po-

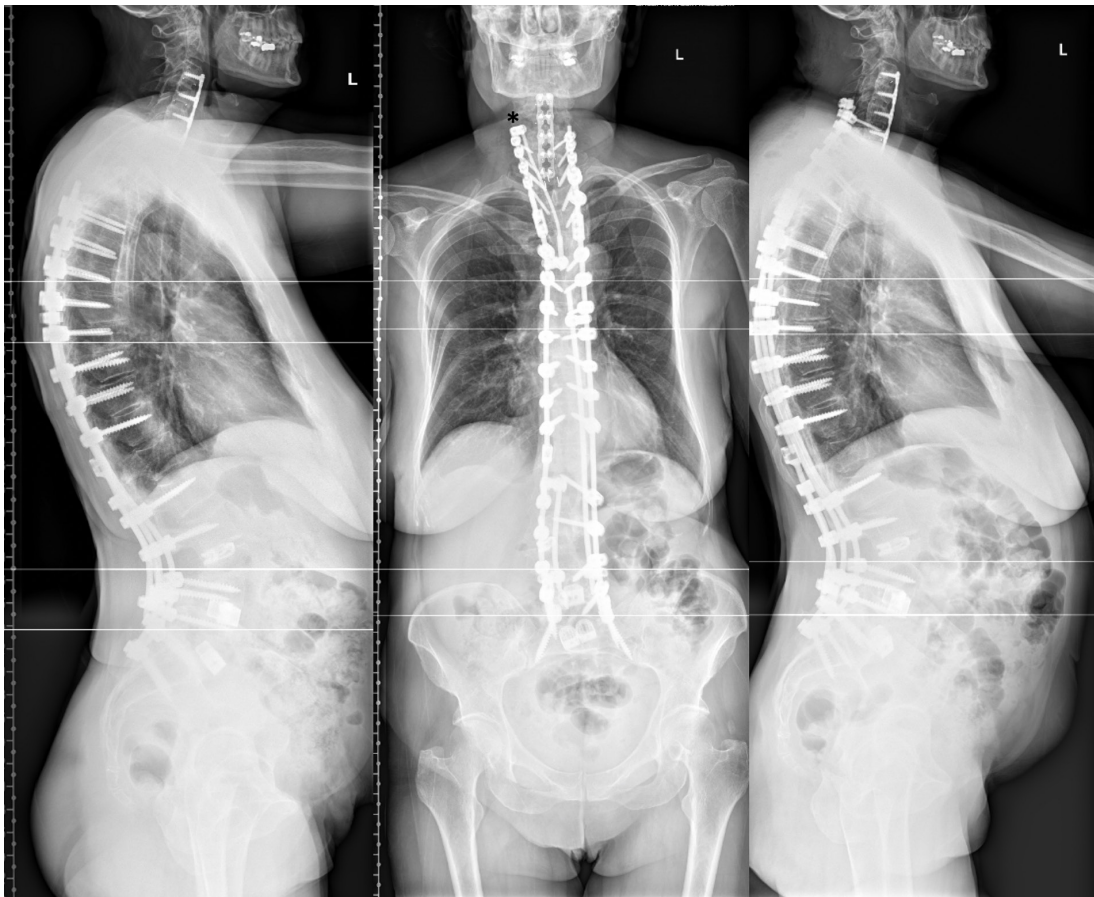


Fig. 12. On-top connection of outrigger/satellite rods. A 72-year-old patient with a history of thoracolumbar deformity surgery and anterior cervical discectomy and fusion C3–7 for cervical myelopathy. Patient presents with new-onset weakness of C8 and a herniated disc C7–T1 circumducting the dural sac at C7–T1. Treatment was anterior decompression, implantation of a hyperlordotic cage C7–T1 as well as posterior decompression and advanced instrumentation C6–T3 using 3 rods crossing the cervicothoracic junction. The third rod was connected on top of the instrumentation on the right side (*) because of limited space for a connector between the screw heads aligned in regional lordosis C6–T1.

tential implications this has on end-level stress and failure risk.^{56,57} Future studies will have to provide further information on the impact of rod characteristics on end-level stress also in the cervical spine.

Considering improvement of overall construct strength of a posterior-only construct, the triple rod construct using lamina screws resembles a promising technique because of its biomechanical superiority in the current study. The triple rod construct using lamina screws is of particular clinical value in cases that do not allow connection of lateral connectors to a bilateral standard rod construct, as shown in Fig. 8.

The use of multiple-rods can increase construct stiffness at the area they are bridging. They are suitable to reduce ROM at the zone of increased instability, e.g., at the site of a corpectomy or 3-column osteotomy to mitigate fusion. Multiple-rod con-

structs will not improve total construct stiffness from end-level to end-level compared to the triple rod construct using lamina screws and the SOR in the current study.

The superiority of the SOR with anterior plating and posterior standard instrumentation supports the clinical rationale of adding a plate whenever an anterior corpectomy is done as a simple measure to increase stability in all planes.^{2-4,6,19,25,26,58,59}

The use of 2 cross-links was shown to improve ROM reduction of 3-column injuries in AR in biomechanical studies. However, the use of a single cross-link for a 2-column injury did not improve stiffness in AR.⁶⁰ Majid et al.⁶¹ showed that the use of 2 cross-links in a postlaminectomy spine reduced ROM by approximately 10% in all directions. While the use of multiple cross-links provides increased resistance to AR in constructs fixating the subaxial and the cervicothoracic spine, the clinical

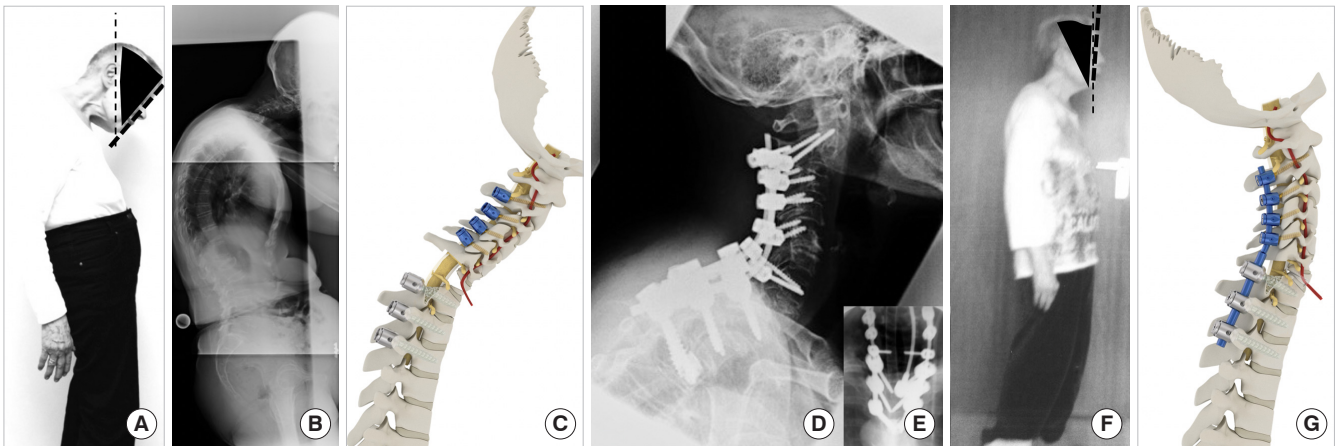


Fig. 13. Cervical spine deformity correction in a patient with osteoporosis. A 78-year-old patient with dropped head syndrome and high thoracic hyperkyphosis as well as osteoporosis. The patient suffered from severe pain and was bothered by loss of visual axis and compensatory posture (A, B). After initiation of teriparatide medication for 3 months, posterior surgery was done with a pedicle subtraction osteotomy of T1 (C, G) and instrumentation of C2–T4. During correction and rod-locking, loosening of the pedicle screws in the lowest instrumented vertebra was noted, and salvage fixation was achieved using cement augmentation in T4. At 1-year follow-up, the patient was very satisfied and sent follow-up images (D, E, F). Construct stability could be maintained.

drawbacks may include the potential for tenting of the posterior soft-tissues and increasing the risk for hematoma formation and deep fascial dehiscence.

In the current article, the use of a single cross-link was not addressed, because this study focused on different instrumentation patterns and rod characteristics. In cases with high demand for resistance to AR forces, the use of cross-link has a biomechanical rationale given the published literature.

Concerning advanced instrumentation techniques to reconstruct the destabilized cervical spine, one should not forget that the objective of increased stabilization is to mitigate fusion. Accordingly, Fig. 10 shows a patient that experienced rod fracture at the site of a cervicothoracic 3-column osteotomy. Adding a meticulous posterior fusion mass bridging the osteotomy sites and the, still mobile, discs adjacent to the pedicle subtraction osteotomy, the patient finally achieved a posterior fusion and, later, an anterior column fusion, too.

Therefore, Fig. 14 emphasizes how to achieve a stable fusion bridge in cervicothoracic deformity surgery either by using a posterior-only or a combined anteroposterior approach.

A specimen-based biomechanical study usually compares construct stiffness and differences after fatigue testing among multiple groups.^{4,5,23,30,42} As a result, statistical analysis usually provides significant results even though these are based on a small sample size of usually 6 to 12 specimens.^{4,5,23,30,42} To test small technical nuances and changes in construct patterns in the current study, a polyamide model provided the best method

to achieve homogenous comparisons.

In a cadaver-based test-setup, ligaments and joints usually are left intact.³⁹ In the current test-setup, we compared construct performance in a worst-case-scenario resembled by 3-column destabilization. Likewise, the differences found among groups are supposed to be smaller in specimen testing with ligaments and facet joint coupling left intact.

The different constructs were instrumented within the customized spine tester applying an axial preload of 2 kg. This ensured a stable preloaded cage fixation in the anterior part of the 3-column destabilized spine model, nevertheless minimal changes in construct alignment within the spine tester could explain small outliers observed among constructs tested. These do not change the main findings and conclusions of the study.

CONCLUSION

This is the first study comparing the mechanical characteristics of a 3-column deficient model reconstructed with an anterior mesh-cage and different posterior screw-rod instrumentation patterns with or without an anterior plate. The triple rod construct using lamina screws was shown to outperform all other constructs. However, posterior-only instrumentation with a triple rod construct using lamina screws and CoCr-rods was able to reduce ROM comparable to that of a 360°-construct in 2- and 3-level models for AR and LB.

Transferring the biomechanical data into the clinical setting,

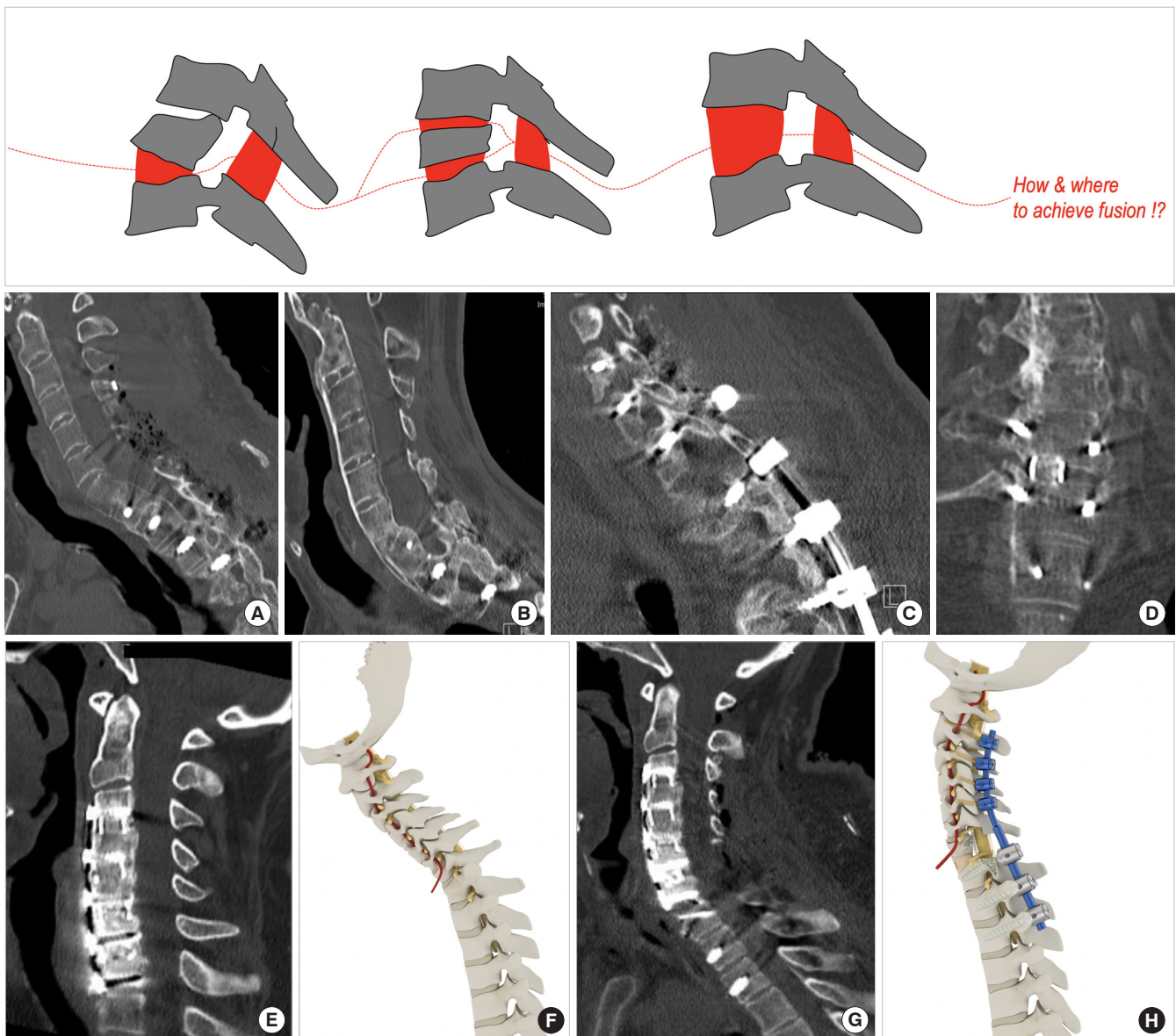


Fig. 14. Concepts for spinal fusion in cervicothoracic 3-column osteotomies. The illustration sketch stresses the challenges that patients with cervical deformity correction, osteotomy and large decompression defects pose. The destabilized spine must become fused. Thus, planning of deformity surgery must include a solution for fusion achievement. (A) In ankylosing spondylitis and with Smith-Petersen osteotomy, spontaneous fusion is likely (B). However, in patients with opening-wedge osteotomies, one shall consider a posterior fusion bridge (C) using rib graft, spinous process, split lamina, allograft fibula or even a transforaminal interbody fusion procedure (e.g., at C7–T1; D). (E–H) When segmental correction of cervical kyphosis can be done, a front-back strategy benefits from structural anterior column reconstruction and fusion using novel hyperlordotic cages.

the use of CoCr-rods can improve construct stiffness in patients with posterior-only screw-rod instrumentation without anterior plating. The use of outrigger-rods did not have a significant impact on overall construct stiffness, but can be a valuable technique to augment regional stiffness and bridging of a zone with increased instability (e.g., an osteotomy site).

The 6S3R-group was shown to outperform all other constructs

with posterior-only instrumentation and seems to resemble the new SOR for advanced posterior fixation of the 3-column destabilized cervical spine.

CONFLICT OF INTEREST

The authors have nothing to disclose.

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