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Surgical nuances and construct patterns influence construct stiffness in C1-2 stabilizations: a biomechanical study of C1-2 gapping and advanced C1-2 fixation

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Abstract

Purpose Stabilization of C1-2 using a Harms–Goel construct with 3.5 mm titanium (Ti) rods has been established as a standard of reference (SOR). A reduction in craniocervical deformities can indicate increased construct stiffness at C1-2. A reduction in C1-2 can result in C1-2 joint gapping. Therefore, the authors sought to study the biomechanical consequences of C1-2 gapping on construct stiffness using different instrumentations, including a novel 6-screw/3-rod (6S3R) construct, to compare the results to the SOR. We hypothesized that different instrument pattern will reveal significant differences in reduction in ROM among constructs tested.

Methods The range of motion (ROM) of instrumented C1-2 polyamide models was analyzed in a six-degree-of-freedom spine tester. The models were loaded with pure moments (2.0 Nm) in axial rotation (AR), flexion extension (FE), and lateral bending (LB). Comparisons of C1-2 construct stiffness among the constructs included variations in rod diameter (3.5 mm vs. 4.0 mm), rod material (Ti. vs. CoCr) and a cross-link (CLX). Construct stiffness was tested with C1-2 facets in contact (Contact Group) and in a 2 mm distracted position (Gapping Group). The ROM (°) was recorded and reported as a percentage of ROM (%ROM) normalized to the SOR. A difference > 30% between the SOR and the %ROM among the constructs was defined as significant.

Results Among all constructs, an increase in construct stiffness up to 50% was achieved with the addition of CLX, particularly with a 6S3R construct. These differences showed the greatest effect for the CLX in AR testing and for the 6S3R construct in FE and AR testing. Among all constructs, C1-2 gapping resulted in a significant loss of construct stiffness. A protective effect was shown for the CLX, particularly using a 6S3R construct in AR and FE testing. The selection of rod diameter (3.5 mm vs. 4.0 mm) and rod material (Ti vs. CoCr) did show a constant trend but did not yield significance.

Conclusion This study is the first to show the loss of construct stiffness at C1-2 with gapping and increased restoration of stability using CLX and 6S3R constructs. In the correction of a craniocervical deformity, nuances in the surgical technique and advanced instrumentation may positively impact construct stability.

Keywords Biomechanical study · C1-2 · Instrumentation · Mechanical testing · Gapping · Construct stability · Implant pattern · ROM

Heiko Koller and Sebastian Hartmann have contributed equally and also shared first authorship.

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Introduction

The stabilization and fusion of C1 and C2 using the Harms–Goel technique has been established as the standard of reference (SOR) for surgical treatment of atlantoaxial instabilities [1–8]. It has also been shown that different degrees of osseous destruction and ligamentous injury result in varying states of increased motion and thus the need for the advanced fixation of C1-2 [9, 10]. Recently, Lu and Koller [11] described a technique of C1-2 fixation using a so-called 6-screw–3-rod (6S3R) construct. This included the addition of C1- and C2-laminar screws connected by a 3.5 mm rod to a C1-2 Harms–Goel construct. The authors reported an optimized resistance to reset forces with reduction in a rigid atlantoaxial dislocation, obeying the need for inclusion of the occiput [12].

Biomechanical and clinical studies have analyzed variations in construct patterns, including C1 arch and C1 hemi-arch screws, C1 hooks, C2 laminar screws and uni- and bicortical screw fixation or extension into the subaxial spine [9, 10, 13–15]. Most biomechanical studies have tested primary construct stability to compare the construct stiffness and the reduction in the range of motion (ROM) at C1-2 [15]. In most of these studies, the mechanical differences among the tested techniques were small [10], while clinical studies have shown significant differences regarding the long-term performance of each technique. Likewise, Du et al. [16] and Savage et al. [17] have shown that a bilateral construct consisting of C1-lateral mass screws and C2-laminar screws provides similar construct stiffness, while Parker et al. [18] and Chang et al. [19], in clinical case series, have shown higher failure rates using C2-laminar screws compared to C2-pedicle screws.

Biomechanical studies that apply cyclic loading to assess C1-2 construct stability and offer insight into the potential long-term performance of each construct are scant [10, 17, 20]. These studies usually allow the comparison of only two or three techniques because this setup requires vast laboratory resources and increased costs.

The deformity inherent to atlantoaxial dislocations is a combination of translation and kyphosis with a loss of height between the occiput, atlas and axis [11, 21, 22]. Surgical correction is achieved with applying extension moments and posterior translation forces, and these correction manoeuvers frequently result in atlantoaxial distraction. This gain in height at C1-2 has been noticed as C1-2 gapping on postoperative imaging (Fig. 1a, b). C1-2 gapping may also be a result of C1-2 fixation in a distracted position, which in return can cause a mechanical overload of instrumentation and failure postoperatively (Fig. 2) [23]. In the clinical situation, a strong posterior occiput to cervical instrumentation might ameliorate the mechanical stress-shielding consequences of stress-shielding the C1-2 joints with loads shared by the posterior screw–rod construct only and a lack of lateral column buttress, but this approach requires a longer fusion [12, 15]. Another alternative is to buttress the lateral C1-2 columns by grafts or cages, but this technique is more technically demanding (Fig. 1e). The biomechanical consequences of C1-2 gapping have not yet been studied.

Accordingly, using a standard C1-2 Harms–Goel construct, the objectives of this biomechanical study were trifold. The first objective was to study the biomechanical consequences of C1-2 gapping on construct stiffness using varying instrumentation patterns to build the basis for future research on this issue. The second objective was to study the biomechanical performance of a 6S3R construct affecting the immobilization of C1-2 in comparison with a SOR. Third, we sought to compare different C1-2 construct patterns that differ by rod diameter, rod material and the number of screws and rods. The results of this study should offer best-fit estimates to plan cyclic loading studies, including only those techniques that show a difference in primary construct testing.
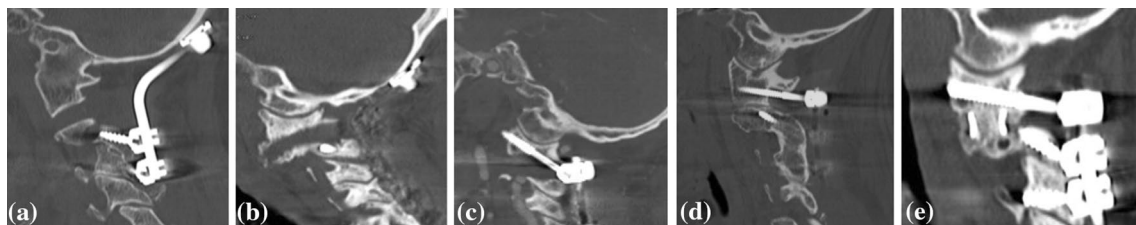
Fig. 1 **a**–**e** C1-2 reduction and gapping. Clinical case examples stress the clinical phenomenon of C1-2 gapping. In cases with craniocervical kyphosis and loss of C0-C2 height, e.g., in basilar invagination (**a**) or basilar impression from rheumatoid arthritis (**b**), C1-2 facet distraction resembles one of the treatment targets and is the result of reduction maneuvers. However, unintended distraction of the C1-2 facet, as shown in a trauma patient (**c**), can cause overloading of instrumentation and promote loosening or failure. **d** Bone on bone contact of C1-2 facets or the lateral column buttress between C1-2 using structural bone grafts or cages can secure maintenance of the reduction and fusion process
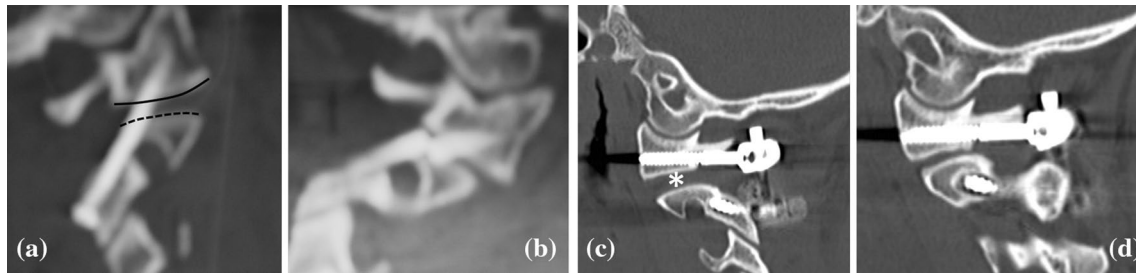
Fig. 2 Mechanism of biomechanical overloading of implants with C1-2 fixated in distraction position. **a** Clinical case example of a patient with three-part Jefferson Burst fracture reduced and instrumented with 3.5-mm-diameter screws using the Magerl technique. **b** One year after instrumented symptomatic implant failure occurred. **b** Clinical case example of a patient with atlantoaxial dislocation due to os odontoideum reduced and instrumented with 3.5-mm-diameter screws according to the Harms–Goel technique. Postoperative CT-scan shows C1-2 facets in a gapping position (asterisks). At 4 years postoperative, loss of height C1-2 with collaps of the gapping position occurred with mild screw loosening of C2 and evidence of non-union C1-2

Materials and methods

Mechanical laboratory study

Using polyamide models, this study compared the construct stiffness of different C1-2 instrumented constructs, including variations in rod diameters, rod materials, screw–rod patterns and the application of cross-links (CLX). Construct stiffness was tested with C1-2 facets contacting each other, thus allowing load sharing (Contact Group, Fig. 3a), and with C1-2 facets fixated in a distracted gapping position without any facet contact, thus causing stress shielding (Gapping Group, Fig. 3b).

3D models and implant configuration

First, 3D plastic models of C0-2 were created from DICOM data of a reconstructed CT scan of a healthy 43-year-old patient who showed a normal cervical spine during a fine-cut CT trauma scan. Using CAD software (NX/Unigraphics, Siemens/Erlangen, Germany), the C0 and C1 lateral masses were immobilized, and the C0 condyles were linked to a socket, which could be affixed to the testing apparatus to

Fig. 3 Mechanical testing assembly. **a** Testing with C1-2 contact maintained by approximation of C1-2 facets (blue). **b** Testing with distraction position of C1-2 facets. The distance d2 (**b**) mirrors the distance reduction according to d1 on the C1-2 rod (**a**)
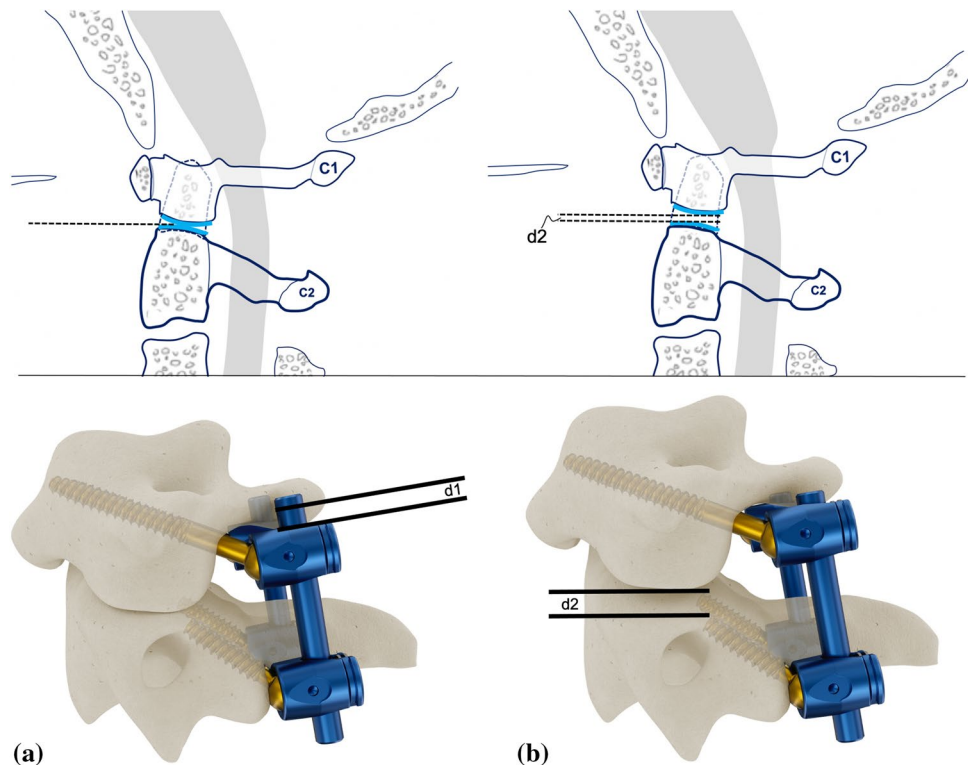
ensure stability without additional motions between C1 and C0. For C2, the lower part of the axis vertebra was also extended with a socket for connection purposes. The models were printed on a Formiga P110 using selective laser sintering (SLS) technology. The material was PA 2200 (tensile modulus 1650 Mpa, density 930 kg/m^3; EOS, Pflugerville/USA).

Then, the models were instrumented with a modern constrained screw–rod system (Symphony, Depuy Synthes, Raynham/USA) that includes different screw diameters (3.5 mm vs. 4.0 mm) and rod materials (titanium/Ti vs. cobalt chromium/CoCr), solid and cannulated self-tapping screws, and full-threaded screws for C2 and shank-shaft screws for C1. For this study, the screw diameter was 3.5 mm, and the screw tract was prepared using a 2.4-mm-diameter drill. The screw length in C1 and C2 was 30 mm. All screws were locked with a 3.0 Nm torque meter with an antitorque limiting handle. Care was given to align the heads of the screws perpendicular to the posterior C2 pars surface during screw–rod locking to establish a comparable screw–rod pattern among all tests.

Finally, in sequential order, C1-2 was instrumented with a different rod assembly. This included bilateral same diameter rods (3.5 mm vs. 4.0 mm) and rod materials (Ti vs. CoCr). Each instrumented C1-2 model was tested with CLX (+CLX-Group) and without (-CLX-Group). The different rod materials, rod diameters and the construct pattern were instrumented using a customized spine tester with an applied axial preload of 2 kg. This ensured a stable contact of C1-2 articular surfaces. In addition, each instrumented C1-2 model was advanced by applying a 3.5 mm laminar screw in C1 according the technique described by Lu and Koller [11] and in C2 according to Wright [24]. The length of the laminar screws was 24 mm. The C1 and C2 laminar screws were connected by a 3.5 mm Ti rod. A schematic illustration of the tested constructs is provided (Fig. 4).

Analysis of ROM and construct stiffness

The ROM was evaluated in a customized six-degree-of-freedom spine tester. The spine tester used is explained and visualized in detail elsewhere [25–27]. In several studies, a full-range physiologic flexion–extension range of C0-2 could be reproduced under bending moments of 1.5 Nm applied through C0 [15, 28–30]. Accordingly, in this study, the C1-2 models were loaded with pure moments of 2.0 Nm in axial rotation (AR), flexion extension (FE), and lateral bending (LB). The moments were applied by a stepper motor, and a six-component load cell attached to the cranial end of the spine was used for feedback control of the applied bending moments.

Three load cycles for each instrumentation and motion direction were carried out, and only the third cycle was used for data evaluation. The ROM for the instrumented cervical spines was determined. All flexibility tests were performed with the same hard plastic models to assume comparability. The biomechanical testing of the models was carried out in accordance with the recommendations for testing spinal implants by Wilke et al. [31].

Intersegmental motion was measured using an ultrasound-based motion analysis system (CMS70P6-V5 with Winbiomechanics software, Zebris, Isny, Germany, Fig. 5). The flanges for the fixation of the C1-2 model
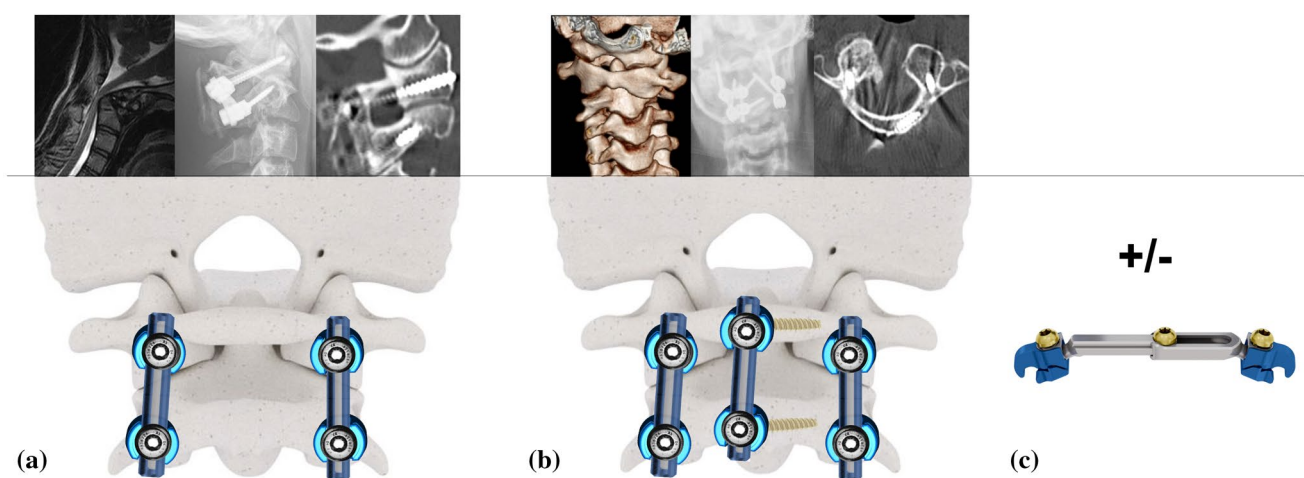

Fig. 4 Schematic illustration of construct pattern tested **a** Instrumentation according to Harms–Goel technique of C1-2 stabilization. **b** So-called 6-screw–3-rod (6S3R) construct with the Harms–Goel instrumentation being added by a lamina screw in C1 and in C2 linked with a titanium 3.5 mm rod. **c** All constructs where tested with and without the use of a cross-link. The cross-links connected the left and the right C1 and C2 screws of the Harms–Goel construct

Fig. 5 Mechanical testing assembly. **a**, **b** Anteroposterior view of the C1-2 model of the Contact Group mounted in the testing apparatus. **c** Polyamide models of C1 and C2 fused to the polyamide sockets before fixation in the spine tester
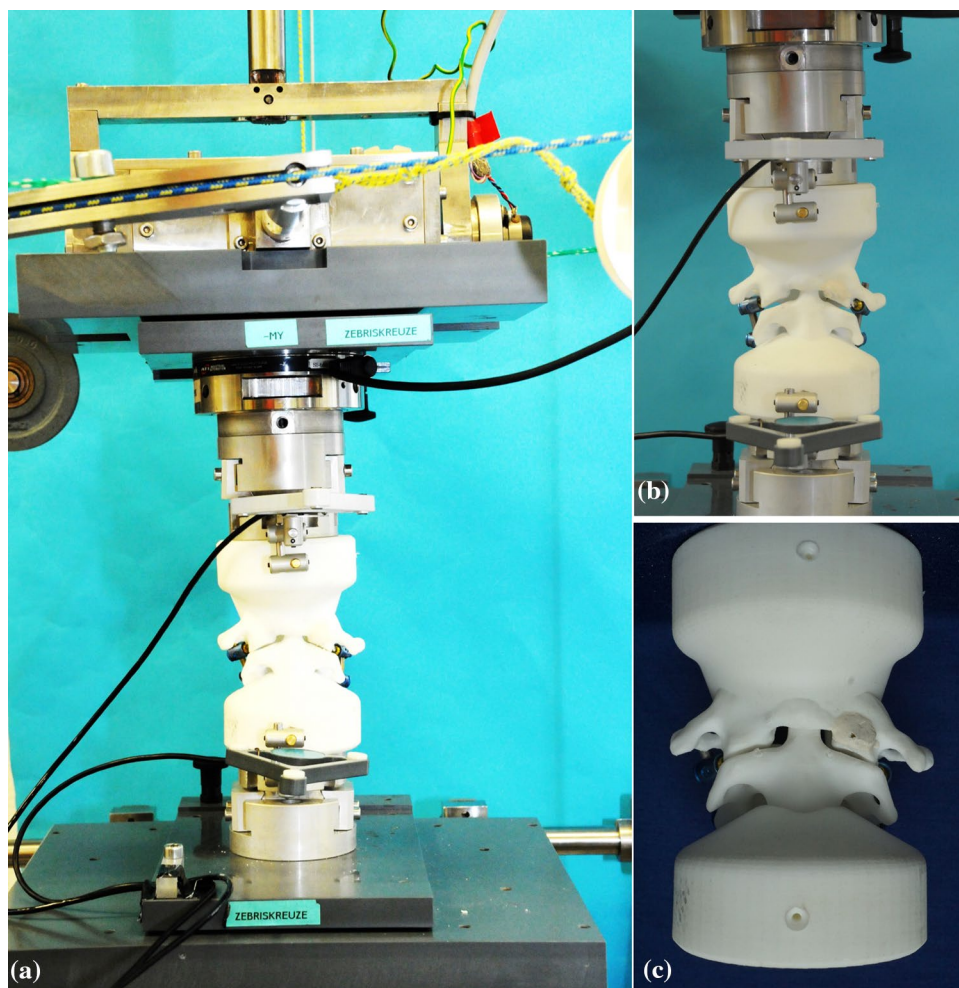
in the spine tester were affixed at the sockets of the hard plastic model, which transitioned from the C1 and C2 vertebra (Fig. 5).

Installing C1-2 instability

To simulate the clinical phenomenon of C1-2 gapping, all tests were repeated using the same models, rod diameter, rod material, and construct pattern with C1-2 joints in contact and in distracted positions. To prepare the Gapping Group, one side received a distraction of 2 mm using the distraction plier of the system, while the contralateral side maintained its position. After locking the initially distracted side, the same distraction was repeated on the other side to create 2 mm of C1-2 gapping before testing. In the clinical scenario, C1-2 gapping means that there is contact neither by cartilage nor by bony surfaces between the C1-2 vertebrae. This scenario was simulated in our biomechanical study.

Analysis of data

All data were stored digitally and analyzed using Microsoft Excel (Version 15.36, Microsoft Corporation 2017, Redmond, USA).

The ROM results for each construct were recorded, and the percentage of ROM (%ROM) was calculated and normalized to the performance of the SOR in the Contact Group. The SOR according to the Harms–Goel technique is represented by a posterior C1-2 construct using 3.5 mm Ti rods, which is the construct studied and applied most often in both clinical practice and scientific literature [7, 10].

For C1-2 fixation, the clinically most relevant forces are generated in AR and FE. The ROM of intact LB is small, and stabilization reduces LB slightly [10, 20, 29, 32]. A difference > 30% between the ROM of the SOR and the %ROM of any of the other constructs was defined as a significant difference in our model. This definition was abstracted from a systematic review of the literature [10] on biomechanical testing of different C1-2 constructs using

cadaveric specimens. A difference in the change of ROM by 1° repeatedly resulted in statistically significant differences in those studies [10] analyzed. In our study, differences in ROM among different C1-2 instrumentation pattern tested exceeding 30% were thought to exceed this 1° threshold.

Results

The study design resulted in a total of 96 test configurations. Descriptive analysis of the models did not show gross loss of screw-model fixation given the nondestructive loading conditions, nor did any screw–rod loosening occur. The results of ROM testing for AR, FE and LB are summarized (Table 1). The results for %ROM are visualized in figures (Fig. 6a (AR), Fig. 6b (FE), and Fig. 6c (LB)).

To clarify the interpretation of normalized ROM results reported as a percentage of the absolute ROM (%ROM), an example is given for the comparison of ROM under FE testing: With the SOR, FE testing resulted in a ROM of 4.35°. The standard 4.0 mm construct with CoCr as the rod material showed a 3.8° ROM in FE testing (Table 1), representing an 87.2% ROM compared with the SOR ROM. Accordingly, in this test, a change in ROM of 0.1° was related to a change of 3.4% ROM. In other words, a change in 1° refers to a change of approximately one-third %ROM. According to the systematic review of the literature by Du et al. [10], this

mean difference in the change of ROM by 1° repeatedly resulted in statistically significant differences in biomechanical testing of C1-2 constructs using cadaveric specimens.

Among all constructs tested, the results in the graphs indicate the largest change with the addition of a CLX, with an increase in construct stiffness up to 50%, and particularly with the addition of a C1/C2 laminar screw–rod connection, resulting in a 6S3R construct. These differences varied between the different planes of motion tested.

Among all states of instrumentation, C1-2 gapping resulted in a significant increase in C1-2 mobility. A protective effect was shown when using a CLX, particularly when using a 6S3R construct. This was particularly true in FE testing (Fig. 6b).

The selection of rod diameter (3.5 mm vs. 4.0 mm) and rod material (Ti vs. CoCr) did not show a significant effect in the short constructs tested from C1 to C2.

Axial rotation (Fig. 6a)

In the Contact Group, the use of a CLX significantly reduced the %ROM. An improvement in construct stiffness was noted when using a CoCr rod, particularly in the 6S3R group. The 6S3R construct outperformed all other constructs, particularly if no CLX was applied.

In the Gapping Group, the SOR failed to restore stability to the level present in the Contact Group. Use of a CLX

Table 1 Results of mechanical testing of construct stiffness

	C1-2 Contact				C1-2 Gapping			
	− Cross-link		+ Cross-link		− Cross-link		+ Cross-link	
	CoCr	Ti	CoCr	Ti	CoCr	Ti	CoCr	Ti
Axial rotation (°)								
Standard-3.5	1.33	1.23	1.03	0.85	1.39	1.34	1.07	1.19
Standard-4.0	1.13	1.26	0.58	0.70	1.42	1.36	0.96	1.03
6S3R-3.5	0.82	0.73	0.52	0.42	0.94	1.00	0.73	0.80
6S3R-4.0	0.84	0.79	0.42	0.52	0.90	0.96	0.51	0.72
Flexion–extension (°)								
Standard-3.5	4.35	4.31	4.40	3.20	9.87	11.41	9.48	10.33
Standard-4.0	3.76	4.04	3.78	3.24	8.88	10.09	8.96	9.53
6S3R-3.5	1.83	1.52	1.65	1.27	2.20	2.87	2.20	2.76
6S3R-4.0	1.50	1.60	1.36	1.42	2.15	2.44	1.84	2.21
Lateral bending (°)								
Standard-3.5	0.62	0.59	0.62	0.36	0.85	0.87	0.69	0.87
Standard-4.0	0.59	0.63	0.54	0.56	0.54	0.83	0.51	0.79
6S3R-3.5	0.49	0.51	0.53	0.35	0.7	0.87	0.64	0.8
6S3R-4.0	0.59	0.55	0.42	0.49	0.41	0.71	0.44	0.67

Presented data resembles raw data (°) of range of motion analysis in axial rotation, flexion–extension and lateral bending testing

Legend Ti-Rod testing with titanium rods, *CoCr* testing with cobalt chromium rods ± cross-link = testing with/without cross-links. *C1-2 Contact* atlantoaxial facet contact with load-sharing, *C1-2 gapping* atlantoaxial facets unloaded

Fig. 6 Results of mechanical testing of construct stiffness for axial rotation (**a**), flexion–extension (**b**), and lateral bending (**c**); results presented as percentage ROM (%ROM) normalized to standard of reference (SOR). Legend: SOR line denotes the percentage range of motion (%ROM) of posterior C1-2 instrumentation using the standard configuration with 3.5 mm titanium rod (S-3.5). S-3.5 = standard, 3.5 mm rod, S-4.0 = standard, 4.0 mm rod, 6S3R-3.5 = 6-screw and 3-rod construct with 3.5 mm rods, 6S3R-4.0 = 6-screw and 3-rod construct with 4.0 mm rods, Ti-Rod = testing with titanium rods, CoCr = testing with cobalt chromium rods. ± cross-link = testing with/without cross-links. C1-2 contact = atlantoaxial facet contact with weightbearing, C1-2 gapping = atlantoaxial facets unloaded
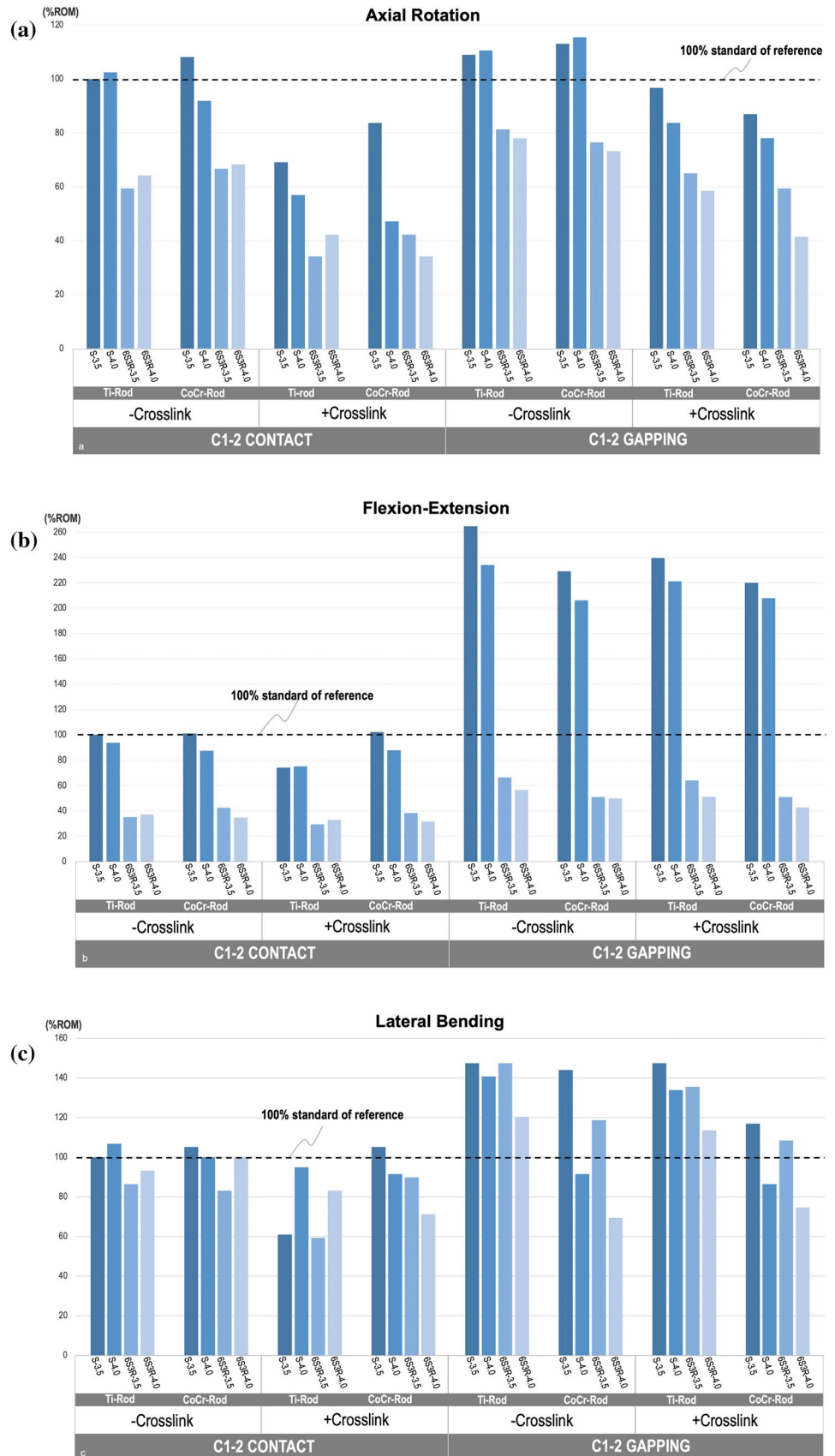
restored construct stiffness to a better degree than the SOR in the Contact Group.

While rod material and diameter did not show a significant effect on the %ROM, the use of a 6S3R construct again outperformed all other constructs tested.

Flexion extension (Fig. 6b)

In the Contact Group, the use of a CLX did not significantly reduce the %ROM. An improvement in construct stiffness was noted only when using a 6S3R construct. The 6S3R construct outperformed all other constructs with or without CLX.

In the Gapping Group, the same differences were noted. Except for the 6S3R construct, all other constructs failed to restore stability to the level provided by the SOR in the Contact Group.

In favor of CoCr and 4.0 mm rods, the rod material and diameter did show a trend for improved construct stiffness among all tests, but this difference did not achieve significance according to the definition we used.

Lateral bending (Fig. 6c)

The characteristic differences among the groups and constructs tested were also revealed in LB testing, with the + CLX group and the 6S3R construct showing better %ROM reduction compared to the SOR group. However, the differences were smaller than in AR and FE testing and heterogeneous.

Discussion

The current mechanical study is the first to test and reveal differences in construct stiffness among different construct patterns from the perspective of C1-2 gapping. We addressed the clinical question: what is the influence of a gap in the C1-2 facet joints on construct stiffness? Among all testing modes, C1-2 gapping caused a significant loss of construct stiffness compared to the contact group. Stability could be restored to the SOR values by using a CLX in AR testing, particularly by using a 6S3R construct.

In the treatment for atlantoaxial deformities that imply translation, axial rotation, kyphosis and vertical settling, triplanar correction to decompress and realign the craniocervical junction may result in C1-2 gapping [8, 11, 21, 22, 33] (Fig. 1e). This gapping has not been addressed well in clinical and biomechanical studies. In addition, a loss of correction and a gradual loss of height can occur as a result of C1-2 gapping [22, 34] (Fig. 2 c + d), particularly if the lateral column is not buttressed by a graft or cage or if the posterior construct is not advanced by length and fixation points to the occiput and the subaxial spine [9, 12, 23, 34].

In the situation of C1-2 gapping, our data indicate that the use of a CLX can restore construct stiffness within the range of the SOR or even improve it when a 6S3R construct is used. This was shown to be true in AR and particularly FE testing. Resistance to FE forces is highest in patients who undergo C1-2 reduction with correction of either translational deformity, kyphosis or both [11, 22]. The current study indicated that for resisting FE, the use of a 6S3R construct might be clinically warranted. The use of CoCr and 4.0 mm rods instead of 3.5 mm and Ti rods could also improve construct stiffness in FE and represent another surgical nuance to improve construct stiffness. A CLX did not significantly improve the reduction in %ROM in the sagittal plane testing.

Ligamentous injury to C0-2 results in instability in both the transverse and vertical planes [20, 29, 35]. The quality of a construct to resist AR forces is of paramount interest in the stabilization of ligamentous injuries of C0-2. The rod material and diameter did not show a fundamental impact on the resistance to AR forces. However, the use of a CLX showed a significant impact in both the C1-2 Contact and Gapping Groups. The same was true for the 6S3R group.

The characteristic differences among groups and constructs tested were small in LB testing. This was expected given the major planes of C1-2 ROM that a C1-2 construct is challenged with, which are FE and AR [10, 32, 36].

The current data add credence to the decision-making process in reconstruction of a highly destabilized atlantoaxial construct. A 6S3R construct not only improves the resistance, particularly against FE forces, but also provides additional stability in AR bending. When large reduction forces are anticipated in a clinical case, a standard C1-2 Harms–Goel construct might benefit from the selection of a CoCr rod material and a 4.0 mm rod diameter, particularly from the instrumentation and connection of additional C1 laminar and C2 screws.

In clinical situations with a high requirement to resist AR forces, an easy way to improve axial torque resistance is by the addition of a CLX. A study by Mizutani et al. [37] has shown an increased fusion rate with the addition of a CLX to a C1-2 posterior construct.

The current study design allowed us to analyze major differences in C1-2 construct stiffness among a high number of different construct patterns. Different from testing with human cadaveric bone, the graduation of screw–bone interfaces during the sequential analysis of a multitude of tests does not impact ROM data in our design. This allows a comparable testing scenario for all constructs studied. In the current study, only the primary construct stability of C1-2 was tested. Major characteristic differences seen among the constructs may now be used to tailor biomechanical studies

that use cyclic loading in order to evaluate the long-term benefit of using, e.g., 3.5 mm diameter and Ti rod constructs compared to 4.0 mm diameter and CoCor rod constructs. Additionally, comparing the C1-2 Contact and Gapping Groups under cyclic conditions can reveal whether the addition of a CLX suffices to improve long-term stability in comparison with the more technically demanding 6S3R construct. Time to failure, loosening or fracture under cyclic loading can provide a deeper understanding of each construct characteristic discussed.

The novel 6S3R construct provides stiffness by a third longitudinal screw–rod connection in the midsagittal line. This increases the square diameter of longitudinal rod fixation stress-shielding in C1-2. It might be scrutinized whether the use of a C1 hook to C1 hook construct or the use of a C1 hook to C2 laminar screw construct might provide the same stability [14, 38]. This issue warrants further research.

Our biomechanical study showed the potentially detrimental effect of C1-2 gapping on construct stability. In the clinical setting, C1-2 gapping can be addressed by a C1-2 lateral buttress technique using structural grafts or a cage (Fig. 1e). Most cases of C1-2 fixation are performed for the treatment for traumatic and neoplastic disease, rheumatoid arthritis, or degeneration and do not display large deformities. The prevention of C1-2 gapping in these cases is the best way to avoid unnecessary loss of construct stiffness when using the SOR. Our biomechanical data indicate that particularly in trauma cases involving ligamentous injury and damage to the C1-2 capsules, every attempt to get the

C1-2 facet joints to touch each other shall be made in order to avoid C1-2 gapping.

It is of note that C1-2 gapping can easily occur when the patient is fixed in a Mayfield head holder, Crutchfield tong or any other constraining device that positions the head with the operation table in a concord position (anti-Trendelenburg), where the patient's head is elevated, and the feet are lowered to reduce venous congestion, which is desirable during the dissection and instrumentation of C1-2. Likewise, aggressive taping of the shoulders can also result in an undesirable distraction of the C1-2 facet joints and care must be taken not to fuse the patient with an unnecessary gapping. However, if a concord position is desired, one should take care to apply a buttress at the feet to prevent advanced slippage of the patient downward along the gravity line during surgery. As shown in our study, even though C1-2 gapping can be mild, it can be biomechanically effective, with a 2 mm joint distance only without surface contacts, and might mitigate clinical failure (Fig. 2).

Thus, at the end of surgery and during C1-2 screw–rod locking, it can be helpful to change patient position in a slight head-down Trendelenburg position, which facilitates approximation of the C1-2 joints. Atlantoaxial joint contact can be controlled using a dissector that stops in the C1-2 joint at the peak facet joint contact (Fig. 7b, c).

C1-2 gapping can be controlled by radiographs and from the perspective of C1-2 cartilage anatomy (Fig. 7a). A study by Koller et al. [39] on 100 normal cervical spine radiographs measured a radiographic atlantoaxial joint height

Fig. 7 Atlantoaxial joint anatomy and controlling C1-2 joint contact. **a** Convex approximating articular surfaces formed by hyaline cartilage. Note the concave osseous shape of the C1 inferior lateral mass and the rather flat configuration of the osseous superior surface of C2. Legend: C1 = atlas, C2 = axis, C2N = cross-transection of C2 nerve root, * = venous plexus C1-2, VA = vertebral artery, segment. **b** Clinical case example of C1-2 dislocation in a pediatric patient. **c** Intraoperative x-rays show instrumentation of C1-2 and anatomical reduction with the C1-2 joint contact controlled using a dissector
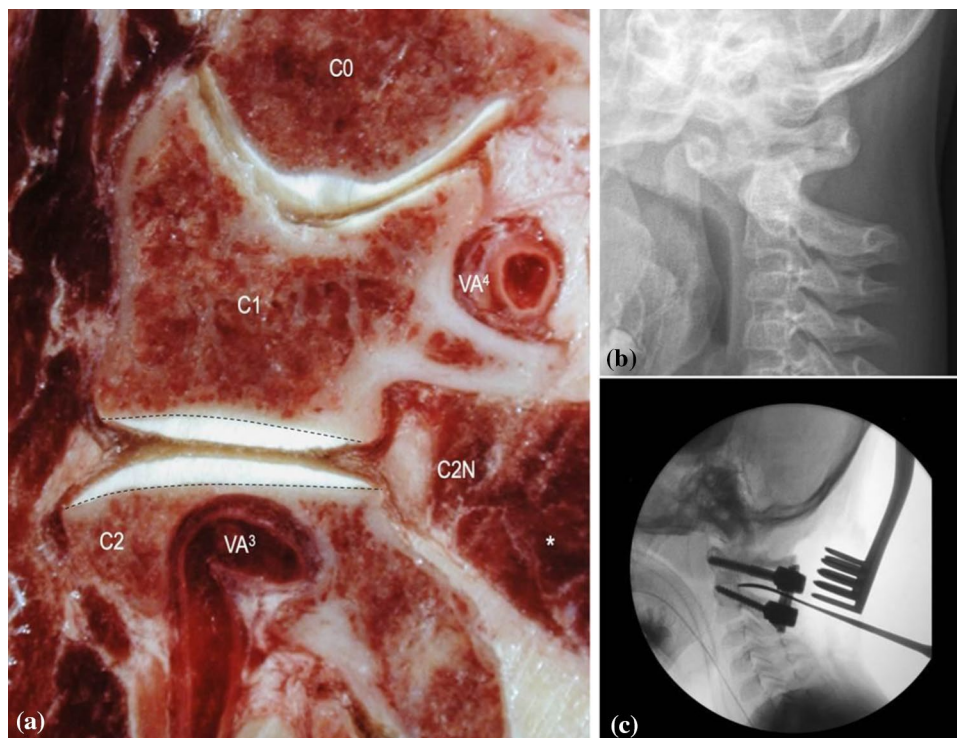
of 3.4 ± 0.9 mm. Anatomical studies by Koebke et al. [40] showed that the maximum height of the inferior convex-shaped cartilage of C1 is 1.7–2.0 mm, while the superior articular cartilage of C2 is dome-formed when cut sagittally, with the middle part being 1.5–1.9 mm. Accordingly, in addition to intraoperative testing, a radiographic C1-2 joint height < 4 mm and similar to the preoperative joint height in the weight-bearing position can be a valuable orientation for the surgeon during intraoperative assessment using radiographs or CT scans.

Limitations

The authors acknowledge that our selected study design has limitations. A classic biomechanical study using human cadaveric specimens usually compares construct stiffness among groups of six to 12 specimens [22]. This setup results in data sets that can be used for statistical analysis and, even though they are based on small sample sizes, frequently results in statistically significant findings. Nevertheless, to test small technical nuances and changes in construct patterns in a short segment construct, that is, a construct with short lever-arms between C1-2, the use of hard plastic models provided us the best method for homogenous comparisons. The elasticity, the contact surface and the surface geometry of the polyamide models did not change over time because we used hard plastic polyamide material and we did not apply cyclic loading testing or destructive testing.

While ligaments and joint capsules add to C1-2 stability in the clinical setting and in cadaveric testing [20, 29, 32, 35], these restraints were removed in the current model to compare construct performance in a worst-case instability model. One can speculate that a comparison of results using human specimens and testing with residual ligamentous restraints would have abolished the small differences shown between rod diameter and rod material. However, most biomechanical studies using human specimens have created instability models including various degrees of ligament transection or odontoidectomy [10, 20] to have comparable destabilized conditions among the constructs tested, similar to the objectives in our study.

Conclusions

Using an idealized mechanical model, this study is the first to show the loss of construct stiffness in C1-2 gapping among all common construct patterns used to stabilize the atlantoaxial complex.

The restoration of construct stiffness to the conditions of the SOR is possible using a CLX, particularly with a 6S3R construct. Clinical cases and the current biomechanical data

provide evidence that patients with intended C1-2 gapping after a reduction in atlantoaxial deformity and fixation of C1-2 only might benefit from advanced instrumentation techniques.

Declaration

References

1. Hauck S, Beisse R, Gonschorek O (2008) Stabilization of unstable fracture of the atlas and dens with the Harms-construct—clinical outcomes. Eur Spine J 17:1540
2. Tan J, Ni CH, li LJ, Zhou W, Qian L (2006) C1 lateral mass—C2 pedicle screws and crosslink compression for instable atlas fracture. Zhonghua Yi Xue Za Zhi 86:1743–1747
3. Harms J, Melcher RP (2001) Posterior C1–C2 fusion with polyaxial screw and rod fixation. Spine 26:2467–2471
4. Tessitore E, Momjian A, Payer M (2008) Posterior reduction and fixation of an unstable Jefferson Fracture with C1 lateral mass screws, C2 isthmus screws, and crosslink fixation: technical case report. Neurosurg (ONS Suppl 1) 63: 100–103.
5. Ames CP, Acosta F, Nottmeier E (2005) Novel treatment of basilar invagination resulting from an untreated C-1 fracture associated with transverse ligament avulsion. J Neurosurg Spine 2:83–87
6. Aryan HE, Newman CB, Nottmeier EW, Acosta FL Jr, Wang VY, Ames CP (2008) Stabilization of the atlantoaxial complex via C-1 lateral mass and C-2 pedicle screw fixation in a multicenter clinical experience in 102 patients: modification of the Harms and Goel techniques. J Neurosurg Spine 8:222–229
7. Heyde C, Robinson Y (2019) C1 lateral mass screw fixation. Springer, Heidelberg
8. Laheri V, Goel A (1994) Plate and screw fixation for atlanto-axial subluxation. Acta Neurochir 129:47–53
9. Lu Y, Lee YP, Bhatia NN, Lee TQ (2019) Biomechanical comparison of C1 lateral mass-C2 short pedicle screw-C3 lateral mass screw-rod construct versus goel-harms fixation for atlantoaxial instability. Spine 44:E393-399
10. Du JY, Aichmair A, Kueper J, Wright T, Lebl DR (2015) Biomechanical analysis of screw constructs for atlantoaxial fixation

in cadavers: a systematic review and meta-analysis. J Neurosurg Spine 22:151–161

11. Haydn H, Koller H, Lu DC (2019) C1 translaminar screw fixation. Springer, Heidelberg

12. Bhatia R, Desouza RM, Bull J, Casey AT (2013) Rigid occipitocervical fixation: indications, outcomes, and complications in the modern era. J Neurosurg Spine 18:333–339

13. Cadena G, Duong HT, Liu JJ, Kim KD (2018) Atlantoaxial fixation using C1 posterior arch screws: feasibility study, morphometric data, and biomechanical analysis. J Neurosurg Spine 30:314–322

14. Reis MT, Nottmeier EW, Reyes PM, Baek S, Crawford NR (2012) Biomechanical analysis of a novel hook-screw technique for C1–2 stabilization. J Neurosurg Spine 17:220–226

15. Puttlitz CM, Melcher R, Kleinstueck FS, Harms J, Bradford DS, Lotz JC (2004) Stability analysis of the craniovertebral junction fixation techniques. J Bone Joint Surg 86-A:561–568

16. Du YQ, Li T, Ma C, Qiao GY, Yin YH, Yu XG (2020) Biomechanical evaluation of two alternative techniques to the Goel-Harms technique for atlantoaxial fixation: C1 lateral mass-C2 bicortical translaminar screw fixation and C1 lateral mass-C2/3 transarticular screw fixation. J Neurosurg Spine 17:1–7

17. Savage JW, Limthongkul W, Park HS, Zhang LQ, Karaikovic EE (2011) A comparison of biomechanical stability and pullout strength of two C1–C2 fixation constructs. Spine J 11:654–658

18. McGirt MJ, Parker SL, Garcés-Ambrossi GL, Mehta VA, Sciubba DM, Witham TF, Gokaslan ZL, Wolinksy JP (2009) Translaminar versus pedicle screw fixation of C2: comparison of surgical morbidity and accuracy of 313 consecutive screws. Neurosurg 64:343–348

19. Chang CC, Huang WC, Tu TH, Chang PY, Fay LY, Wu JC, Cheng H (2018) Differences in fixation strength among constructs of atlantoaxial fixation. J Neurosurg Spine 30:52–59

20. Koller H, Resch H, Tauber M, Zenner J, Augat P, Penzkofer R, Acosta F, Kolb K, Kathrein A, Hitzl W (2010) A biomechanical rationale for C1-ring osteosynthesis as treatment for displaced Jefferson burst fractures with incompetency of the transverse atlantal ligament. Eur Spine J 19:1288–1298

21. Jian FZ, Chen Z, Wrede KH, Samii M, Ling F (2010) Direct posterior reduction and fixation for the treatment of basilar invagination with atlantoaxial dislocation. Neurosurg 66:678–687

22. Ding X, Abumi K, Ito M, Sudo H, Takahata M, Nagahama K, Iwata A (2012) A retrospective study of congenital osseous anomalies at the craniocervical junction treated by occipitocervical plate-rod systems. Eur Spine J 21:1580–1589

23. Duan W, Chou D, Jiang B, Liu Z, Zhao X, Xia Z, Jian F, Chen Z (2019) Posterior revision surgery using an intraarticular distraction technique with cage grafting to treat atlantoaxial dislocation associated with basilar invagination. J Neurosurg Spine 5:1–9

24. Wright NM (2004) Posterior C2 fixation using bilateral, crossing C2 laminar screws: case series and technical note. J Spinal Disord 17:158–162

25. Disch AC, Schaser KD, Melcher I, Luzzati A, Feraboli F, Schmoelz W (2008) En bloc spondylectomy reconstructions in a biomechanical in-vitro study. Eur Spine J 17:715–725

26. Schmoelz W, Erhart S, Unger S, Disch AC (2012) Biomechanical evaluation of a posterior non-fusion instrumentation of the lumbar spine. Eur Spine J 21:939–945

27. Hartmann S, Thomé C, Tschugg A, Paesold J, Kavakebi P, Schmölz W (2017) Cement-augmented screws in a cervical two-level corpectomy with anterior titanium mesh cage reconstruction: a biomechanical study. Eur Spine J 26:1047–1057

28. Melcher RP, Puttlitz CM, Kleinstueck FS, Lotz JC, Harms J, Ds B (2002) Biomechanical testing of posterior atlantoaxial fixation techniques. Spine 27:2435–2440

29. Puttlitz CM, Goel VK, Clark CR, Traynelis VC, Scifert JL, Grosland NM (2000) Biomechanical rationale for the pathology of rheumatoid arthritis in the craniocevertebral junction. Spine 25:1607–1616

30. Panjabi M, Dvorak J, Duranceau J, Yamamoto I, Gerber M, Rauschning W, Bueff HU (1988) Three-dimensional movements of the upper cervical spine. Spine 13:726–730

31. Wilke HJ, Wenger K, Claes L (1998) Testing criteria for spinal implants: recommendations for the standardization of in vitro stability testing of spinal implants. Eur Spine J 7:148–154

32. Bogduk N, Mercer S (2000) Biomechanics of the cervical spine. I: Normal kinematics. Clin Biomech 15:633–648

33. Goel A (2007) Atlantoaxial joint jamming as a treatment for atlantoaxial dislocation: a preliminary report. Technical note. J Neursurg Spine 7:90–94

34. Lall R, Patel NJ, Resnick DK (2010) A review of complications associated with craniocervical fusion surgery. Neurosurg 67:1396–1402

35. Radcliff KE, Hussain MM, Moldavsky M, Klocke N, Vaccaro AR, Albert TJ, Khalil S, Bucklen B (2015) In vitro biomechanics of the craniocervical junction-a sequential sectioning of its stabilizing structures. Spine J 15:1618–1628

36. Zhang H, Bai J (2007) Development and validation of a finite element model of the occipito-atlantoaxial complex under physiologic loads. Spine 2007:968–974

37. Drazin D, Mussain M, Harris J, Hao J (2016) The role of sacral slope in lumbosacral fusion: a biomechanical study. J Neurosurg Spine 23:754–762

38. Guo X, Wang M, Wang J, Li S, Zhou F (2008) Bilateral atlas laminar hook combined with transarticular screw fixation for an unstable bursting atlantal fracture. Arch Orthop Trauma Surg 129:1203–1209

39. Koller H, Acosta F, Tauber M, Komarek E, Fox M, Moursy M, Hitzl W, Resch H (2009) C2-fractures: part I. Quantitative morphology of the C2 vertebra is a prerequisite for the radiographic assessment of posttraumatic C2-alignment and the investigation of clinical outcomes. Eur Spine J 18:978–991

40. Koebke J, Brade H (1982) Morphological and fucntional studies on the lateral joints of he first and second cervical vertebrae in man. Anat Embryol 164:265–275