



A biomechanical comparison of crossed and parallel rod configurations in atlantoaxial internal fixation

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Abstract

Background Posterior atlantoaxial fixation with screw rod forms an approximate “II” shape or “H” increasing transverse link for better stability. In order to improve stability and in consideration of difficult placement of transverse connecting rod, possibility of inadequate bone graft, some scholars have preliminarily researched biomechanics of a novel crossed rod as an approximate “X” configuration of screw rod.

Purpose The aim of this study was to evaluate and compare the biomechanics of the crossed and parallel rod configurations in the screw rod system for posterior atlantoaxial fixation on a cadaveric model.

Methods Six fresh cervical specimens were used to complete the range of motion (ROM) testing by applying pure moments of ± 2.0 nm. Following intact state and under destabilization testing, screws were implanted. The specimens were then tested in the following sequence: Group BLS + PR (C2 bilateral laminar screws + parallel rod), Group BLS + CR (C2 bilateral laminar screws + crossed rod), LPRLS + PR (C2 left pedicle screw and right laminar screw + parallel rod), LPRLS + CR (C2 left pedicle screw and right laminar screw + crossed rod), BPS + PR (C2 bilateral pedicle screws + parallel rod) and BPS + CR (C2 bilateral pedicle screws + crossed rod). The ROM of the C1–2 segments was measured in flexion–extension, lateral bending and axial rotation. Six surgical constructs were compared between the groups and with intact condition, respectively.

Results The six fixed modes significantly increased stability compared with both the intact and destabilization group in flexion–extension, lateral bending and axial rotation ($p < .05$). In extension, BPS + CR and BLS + CR showed greater stability than BLS + PR ($p < .05$). During flexion, the six fixation methods showed no statistical significance ($p > .05$). In left lateral bending, stability of the other five screw rod fixation techniques significantly increased when compared with BLS + PR ($p < .05$). In the right lateral bending direction, the stability of BLS + PR was worse than that of BPS + CR and BPS + PR ($p < .05$). In the left axial rotation, stability of BLS + CR, LPRLS + CR and BPS + CR was greater than that of BLS + PR, LPRLS + PR and BPS + PR ($p < .05$). In the right axial rotation, the stability of BPS + CR and BLS + CR was greater than that of BLS + PR ($p < .05$).

Conclusion The six investigated fixation methods provide sufficient biomechanical stability. The crossed rod configuration can further enhance the axial rotation stability of the screw rod system, which consists of C1 bilateral pedicle and C2 pedicle, or C2 lamina screws. The crossed rod can also improve the stability of the screw rod system made up of C1 bilateral pedicle and C2 lamina screws in lateral bending and extension. The crossed rod configuration is reliable and provides superior stability for clinical application.

Keywords Posterior atlantoaxial fixation · Biomechanics · Screw rod system crossed rod · Parallel rod

Introduction

At present, posterior atlantoaxial fixation most commonly uses a screw rod system [1]. Typically, the connecting rods sit on the left and right sides, forming an approximate “II” shape. Some biomechanical reports [2, 3] have indicated that the screw rod system consisting of C1 bilateral pedicle and C2 pedicle screws can provide firm biomechanical

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stability. Owing to the anatomic complexity, inter-patient variation and the danger of vertebral artery and nerve injury, C2 lamina screws have shown worse biomechanical stability [4]. Preliminary study [5] has shown that the transverse link can improve biomechanical stability, where the screw rod system forms an approximate “H” shape. However, because of difficult placement and potential decrease in bone graft formation from the transverse link, there has been increased interest in an alternate, simple means for enhancing the biomechanical stability of the screw rod system.

The crossed rod, made up by connecting rods to the contralateral screws, forms an approximate “X” shape, with multi-triangle construction. Preliminary research has shown, for occipito-cervical internal fixation, in flexion–extension and axial rotation, that the occipital plate connected to the C2 bilateral laminar screw by crossed rod was more stable than the parallel rod, and it has been proposed that the crossed rod could be applied in the clinic [6]. Kai Shen et al. has shown that the crossed rod configuration could provide a better stability than the traditional parallel rod configuration, which consists of unilateral C1 posterior arch screw and C2 laminar screw [7]. As the triangular structure is more stable than the quadrilateral structure, crossed rod configuration forms an approximate “X” shape that may further increase the stability of the posterior atlantoaxial screw rod system which forms an approximate “II” shape, in consideration of improving the stability of the screw rod without having an adverse effect on the bone graft.

In this study, we investigated the stability of posterior atlantoaxial fixation with the screw rod system, using crossed and parallel rods, including a neoteric assembly of screws composed of a C1 bilateral pedicle screw combined with a laminar screw on one side and a pedicle screw on the other, at C2.

Materials and methods

Specimen preparation and model manufacture

Six fresh frozen human cadaver occipito-cervical spines (occiput–C7), obtained from the Department of Anatomy at Southern Medical University, were used in this investigation, with the C1–C2 segment as the level of interest. There were two female and four male cadavers. The mean age of cadavers was 54 years (range 40–65 years), and the mean weight was 62.7 kg (range 52–72 kg). None were damaged and all were tested within a month of death. Dual-energy radiograph absorptiometry (DEXA, QDRA-010; Hologic Discovery, Waltham, MA, USA) was used to quantify the bone mineral density of the lumbosacral region (mean bone mineral density, 0.95 ± 0.26 g/cm²). The spines had no fractures, deformities or metastatic disease, as confirmed by X-ray and CT (Fig. 1). The spines were carefully denuded of adherent musculature while preserving the spinal ligaments, joints and disk spaces. An occiput with four fixed nails and C7 with two fixed nails were cast in polymethylmethacrylic (Isocryl; Lang Dental, Wheeling, IL). The specimens were covered in gauze soaked in saline and frozen at -20 °C. The day before testing, the specimens were thawed overnight at room temperature. The specimens were kept moist during testing.

Fixation and test sequence

Each cervical specimen was tested in the following sequence:

1. Intact.
2. Destabilization group: For each specimen, the center nodule anterior arch of atlas and both sides of the nodule, within 1 cm, were cut off by abrasive drilling. The odontoid was then severed from the pars basilaris. We then orderly



Fig. 1 All specimens were confirmed, by CT and X-ray, to be without fractures, deformities or any metastatic disease

broke the ligaments of the atlantoaxial and eliminated the latter half of the lateral joint capsule [8]. An experimental model of atlantoaxial instability was constructed.

3. After destabilization, each specimen was stabilized in the following sequence (Fig. 2). For each specimen, after the titanium polyaxial screws (3.5×28 mm; PROTEX CT; Globus Medical, Audubon, PA, USA) were implanted, the trajectories of the screws were estimated by CT (Fig. 3). Once achieved, the screws were not repeatedly placed in order to avoid bone-screw interference, and the architecture of the rods was implemented depending on the fixation means.

4. C2 bilateral laminar screws + parallel rod (BLS + PR).
5. C2 bilateral laminar screws + crossed rod (BLS + CR).
6. C2 left pedicle screw and right laminar screw + parallel rod (LPRLS + PR).
7. C2 left pedicle screw and right laminar screw + crossed rod (LPRLS + CR).
8. C2 bilateral pedicle screws + parallel rod (BPS + PR).
9. C2 bilateral pedicle screws + crossed rod (BPS + CR).

Biomechanical test

The specimens were thawed and tested at room temperature and kept moist during testing by sprinkling with 0.9% normal saline. The Kirschner wires with identification

points were implanted at the front, back, left and right of C1 and C2. To reduce error, touching between identification points was averted [9]. The testing of pure models was completed prior to testing the experimental groups. The occiput of each spine was fixed to the load frame of a custom-built six degree of freedom spine simulator, and a pure moment of 2.0 N·m was applied to the cervical spine specimen using a testing system of cables and pulleys [10] (Fig. 4). Each of the test constructs was subjected to three load–unload cycles in each of the physiological planes, generating flexion–extension, lateral bending and axial rotation motion, and the loading time was maintained at 2.0 N·m for 30 s to reduce the influence of viscoelasticity. The laser 3D scanning system (3D.digital corp.America) was used to process images for identifying, locating and calculating markers of C1 and C2 positions in the space and to reconstruct 3D motion of the spinal segments. Full coordinates were used to calculate the parameter of range of motion (ROM) across the C1–C2 level using reverse engineering software (Geomagic studio 11.0). The fixation of each specimen was evaluated by X-ray after testing each fixation mean (Fig. 5).

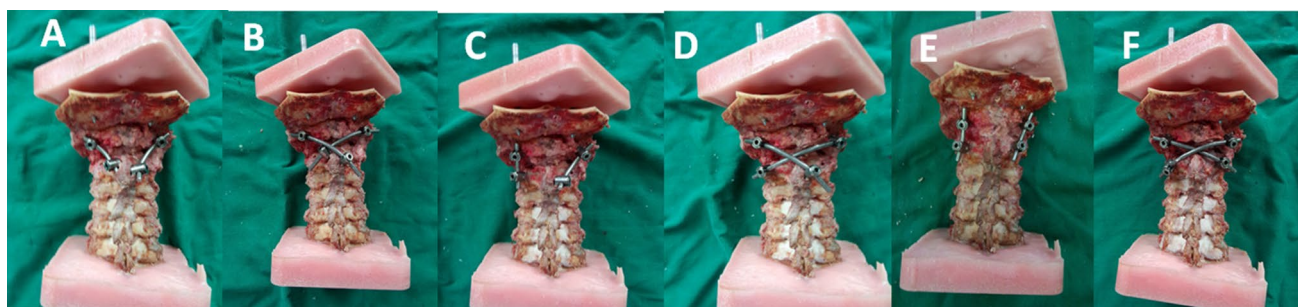


Fig. 2 Six different posterior atlantoaxial fixations **a** BLS+PR (C1 bilateral pedicle screws+C2 bilateral laminar screw+parallel rod); **b** BLS+CR (C1 bilateral pedicle screws+C2 bilateral laminar screw +crossed rod); **c** LPRLS+PR (C1 bilateral pedicle screw +C2 left pedicle screw right laminar screw +parallel rod); **d** LPRLS+CR

(C1 bilateral pedicle screw+C2 left pedicle screw right laminar screw+crossed rod); **e** BPS+PR (C1 bilateral pedicle screws+C2 bilateral pedicle screws+parallel rod); and **f** BPS+CR (C1 bilateral pedicle screws +C2 bilateral pedicle screws +crossed rod)

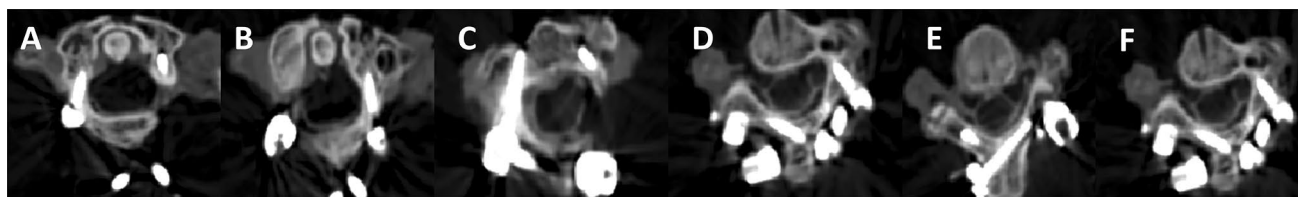


Fig. 3 All screws were positioned in accordance with the screw placement standard, ensuring that the path was satisfactory and did not penetrate the cortex. **a** The C1 left pedicle screw track was completed. **b** The C1 right pedicle screw track was completed. **c** The C2

left pedicle screw track was completed. **d** The C2 left pedicle screw track was completed. **e** The C2 right lamina screw track was completed. **f** The C2 left lamina screw track was completed



Fig. 4 Each specimen was fixed to the load frame of a custom-built six degree of freedom spine simulator, and a pure moment of 2.0 nm was applied to the cervical spine specimen using a testing system of cables and pulleys

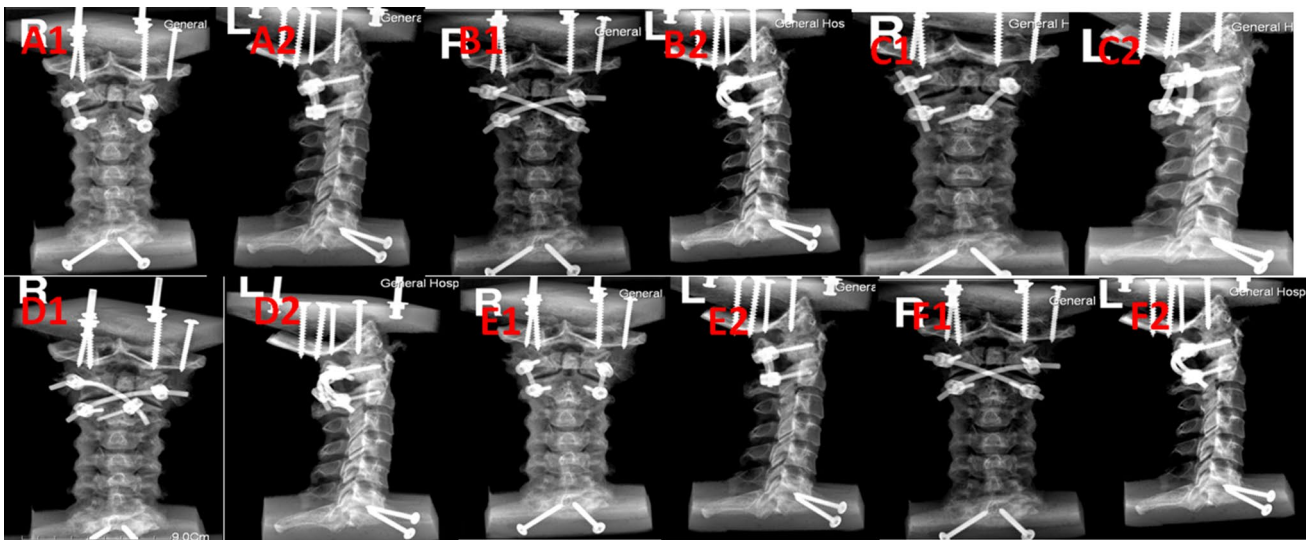


Fig. 5 The fixation of each specimen was evaluated by X-ray after testing each fixation mean. X-rays of **a** BLS+PR; **b** BLS+CR; **c** LPRLS+PR; **d** LPRLS+CR; **e** BPS+PR; and **f** BPS+CR

Statistical analysis

All data were subject to normal distribution based on K-S test, which were expressed as the mean and standard deviation. Statistical analyses were performed using SPSS 20.0 (SPSS Inc., Chicago, IL). Analysis of variance was applied for comparison of data, followed by Tukey's post hoc analysis for multiple comparison procedures. A Bonferroni test was used to compare groups with each other. Significance was accepted at $p < 0.05$.

Results

The means \pm standard deviations for range of motion in extension (EXT), flexion (FLEX), left lateral bending (LLB), right lateral bending (RLB), left axial rotation (LAR) and right axial rotation (RAR) are presented in Table 1 and Fig. 6. The biomechanical results showed that all fixation groups significantly reduced flexibility in all directions compared with both the intact and destabilization group ($p < 0.001$).

Table 1 Summary of ROM data after status

Group	C1-2 ROM (°)					
	Extension	Flexion	Left lateral bending	Right lateral bending	Left axial rotation	Right axial rotation
Intact	10.49 ± 0.74	9.61 ± 0.62	6.20 ± 0.66	6.75 ± 0.67	27.35 ± 0.93	26.66 ± 1.10
Destabilization	21.73 ± 1.07 ^a	18.45 ± 0.82 ^a	8.13 ± 0.40 ^a	8.23 ± 0.72 ^a	37.32 ± 1.39 ^a	38.41 ± 1.60 ^a
BLS + PR	3.58 ± 0.95 ^{ab}	3.31 ± 1.19 ^{ab}	3.07 ± 0.75 ^{ab}	3.10 ± 1.22 ^{ab}	2.07 ± 0.44 ^{ab}	2.10 ± 0.56 ^{ab}
BLS + CR	2.15 ± 0.87 ^{abc}	2.65 ± 1.28 ^{ab}	1.74 ± 0.27 ^{abc}	2.10 ± 0.65 ^{ab}	1.17 ± 0.29 ^{abc}	1.16 ± 0.70 ^{abc}
LPRLS + PR	3.24 ± 1.05 ^{ab}	3.11 ± 0.92 ^{ab}	1.78 ± 0.38 ^{abc}	2.46 ± 0.81 ^{ab}	1.95 ± 0.35 ^{ab}	1.68 ± 0.54 ^{ab}
LPRLS + CR	2.48 ± 0.58 ^{ab}	2.46 ± 1.47 ^{ab}	1.59 ± 0.28 ^{abc}	2.28 ± 0.84 ^{ab}	1.30 ± 0.30 ^{abc}	1.10 ± 0.45 ^{ab}
BPS + PR	2.75 ± 0.64 ^{ab}	2.79 ± 0.50 ^{ab}	1.61 ± 0.39 ^{abc}	1.30 ± 0.61 ^{abc}	1.81 ± 0.23 ^{ab}	1.66 ± 0.56 ^{ab}
BPS + CR	2.09 ± 0.75 ^{abc}	2.24 ± 1.07 ^{ab}	1.48 ± 0.51 ^{abc}	1.19 ± 0.62 ^{abc}	1.04 ± 0.33 ^{abc}	0.81 ± 0.53 ^{abc}

Values are given as mean ± SD

ROM indicates ranges of motion. The ROM is given in degrees

^aStatistical represents a significant difference from the intact specimen ($P < 0.05$)

^bStatistical represents a significant difference from destabilization ($P < 0.05$)

^cStatistical represents a significant difference from the BLS + PR construct ($P < 0.05$)

Flexion–extension

In extension, the average ROM of C1-2 in intact conditions was $10.49^\circ \pm 0.74^\circ$. The BLS + PR and BLS + CR construct was 34.1% and 20.5% of the intact (intact = 100%), respectively. The LPRLS + PR and LPRLS + CR construct was 30.8% and 23.6% of the intact, respectively. The BPS + PR and BPS + CR construct was 26.2% and 19.9% of the intact, respectively. The stability arrangement from large to small was Groups BPS + CR, BLS + CR, LPRLS + CR, BPS + PR, LPRLS + PR and BLS + PR. There was no statistical significance between Groups BLS + CR, LPRLS + CR, BPS + CR and BPS + PR ($p > 0.05$), and no significant differences were observed between Groups LPRLS + CR, LPRLS + PR, BPS + PR and BLS + PR ($p > 0.05$), but the stability of Groups BPS + CR and BLS + CR was greater than that of BLS + PR ($p < 0.05$). During the flexion direction, the average ROM in intact conditions was $9.61^\circ \pm 0.62^\circ$. The BLS + PR, BLS + CR, LPRLS + PR, LPRLS + CR, BPS + PR and BPS + CR construct was 34.4%, 27.6%, 32.4%, 25.6%, 29.0% and 23.3% of the intact, respectively. The six fixation methods showed no statistical significance ($p > 0.05$).

Lateral bending

In the left lateral bending, the average ROM of C1-2 in intact conditions was $6.20^\circ \pm 0.66^\circ$. The arrangement of stability from large to small was Groups BPS + CR, BLS + CR, LPRLS + CR, BPS + PR, LPRLS + PR and BLS + PR, which was 23.9%, 25.6%, 26.0%, 28.1%, 28.7% and 49.5% of the intact, respectively. No significant differences were observed between Groups BPS + CR, BLS + CR, LPRLS + CR, BPS + PR and LPRLS + PR

($p > 0.05$). Stability of the other five screw rod fixation techniques increased significantly when compared with Group BLR + PR ($p < 0.05$). In the right lateral bending direction, the average ROM in intact conditions was $6.75^\circ \pm 0.67^\circ$. The arrangement of stability from large to small was Groups BPS + CR, BPS + PR, BLS + CR, LPRLS + CR, LPRLS + PR and BLS + PR, which was 17.6%, 19.3%, 31.1%, 33.8%, 36.4% and 45.9% of the intact, respectively ($p < 0.001$). The stability of Group BLS + PR was least stable than that of BPS + CR and BPS + PR ($p < 0.05$).

Axial rotation

In the left axial rotation, the average ROM of C1-2 in intact conditions was $27.35^\circ \pm 0.93^\circ$. The arrangement of stability from large to small was BPS + CR, BLS + CR, LPRLS + CR, BPS + PR, LPRLS + PR and BLS + PR, which was 3.18%, 4.3%, 4.8%, 6.6%, 7.1% and 7.6% of the intact, respectively. No statistical significance was observed between Groups BPS + CR, BLS + CR and LPRLS + CR ($p > 0.05$), and no significant differences were observed between Groups BLS + PR, LPRLS + PR and BPS + PR ($p > 0.05$). BPS + CR, BLS + CR and LPRLS + CR proved superior to BLS + PR, LPRLS + PR and BPS + PR ($p < 0.05$). In the right axial rotation, the average ROM in intact conditions was $26.66^\circ \pm 1.10^\circ$. The motion of BPS + CR, BLS + CR, LPRLS + CR, BPS + PR, LPRLS + PR and BLS + PR in comparison with the intact condition was 3%, 4.1%, 4.4%, 6.2%, 6.3% and 7.9%, and 17%, respectively. The stability of Groups BPS + CR and BLS + CR was greater than that of BLS + PR ($p < 0.05$).

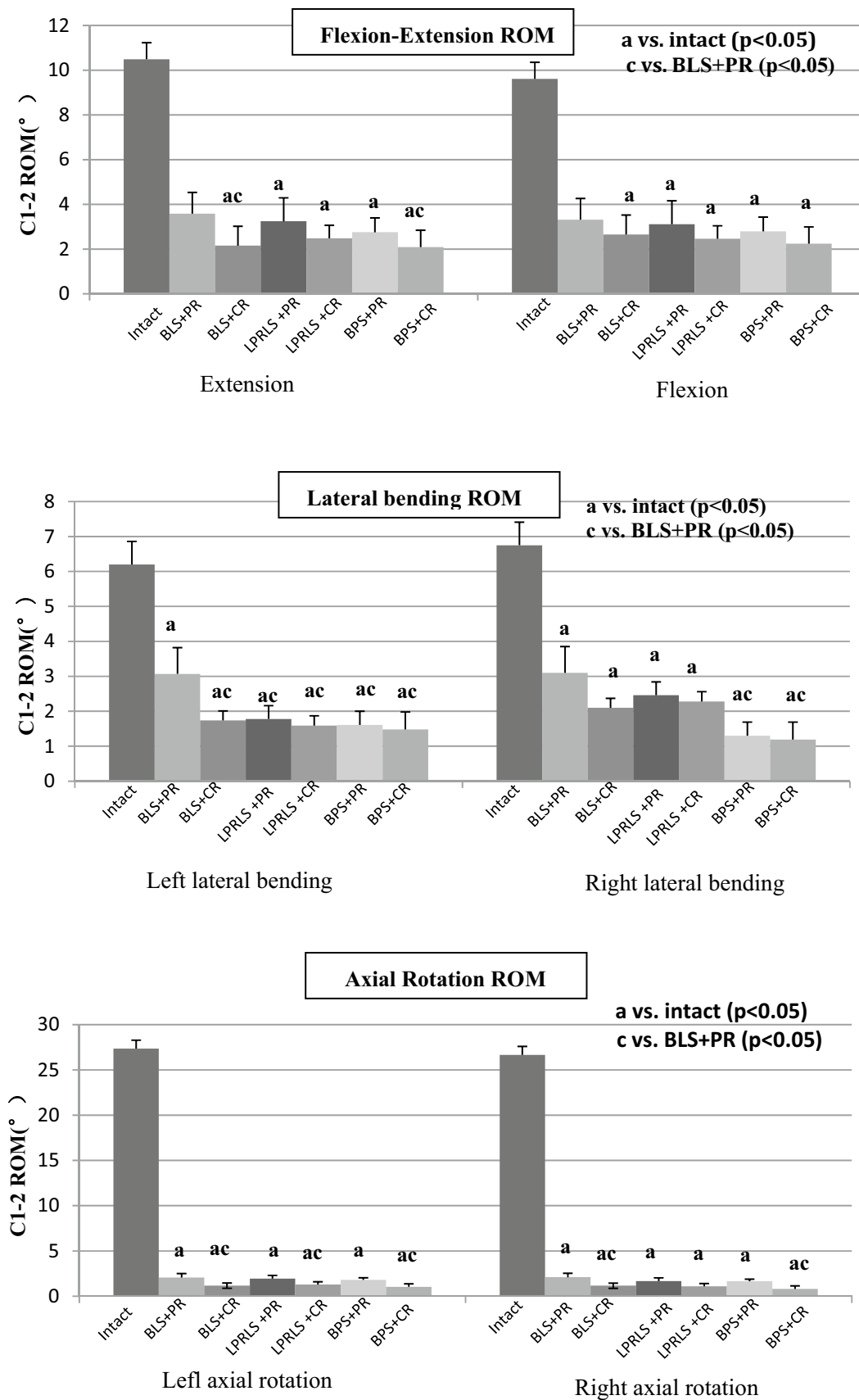


Fig. 6 Comparison of range of motion (ROM) in (top) flexion–extension, (middle) lateral bending and (bottom) axial rotation. ^aStatistical represents a significant difference from the intact specimen ($p < 0.05$). ^cStatistical represents a significant difference from the BLS + PR ($p < 0.05$)

Crossed rod and parallel rod comparisons

In BLS construct, the crossed and parallel rod configurations did not show significant differences in range of motion in extension ($p > 0.05$). However, in flexion, lateral bending and axial rotation, the crossed rod significantly increased stability compared to the parallel rod ($p < 0.05$). In LPRLS construct, the crossed rod provided better stiffness than the parallel rod in axial rotation, but no significant differences were observed between them in flexion–extension and lateral bending ($p > 0.05$). In BPS construct, the crossed rod provided better stiffness than the parallel rod in axial rotation, but no significant differences were observed between them in flexion–extension and lateral bending ($p > 0.05$).

Discussion

Trauma, infection, tumor, congenital and acquired malformations will lead to the atlantoaxial instability, resulting in severe pain, mobility impairment, neurologic damage and even death. It is well known that solid internal fixation is required for atlantoaxial instability. Posterior internal fixation using a screw rod system has been widely used due to its superior stability, as evidenced in several biomechanical [11, 12] and clinical studies [13, 14]. The screws of the upper cervical spine, including C1 lateral mass, C1 pedicle, C2 pars, C2 pedicle and C2 laminar form different fixed combinations with rods. C1 pedicle screws are widely applied due to characteristics that are preferable to those of C1 lateral mass screws [15]. C2 pedicle and laminar screws perform better than C2 pars screws, and C2 pedicle screws function better than C2 laminar screws [16, 17]. To date, C2 pedicle screws have been the first choice for treatment in the clinic. The configuration of C1 and C2 pedicle screws provides optimal biomechanical stability in the screw rod system [2, 3]. However, some studies [18, 19] have indicated difficult implantation of C2 pedicle screws due to the size of the pedicle, variations in foramen transversarium and variations in the vertebral artery. In these instances, C2 laminar screws have been used as the alternative [20]. Dimitriev et al. [17] compared the stability of C1 pedicle screws combined with C2 laminar screws, with C1 pedicle screws combined with C2 pedicle screws, and found that the first combination encountered shortcomings in flexion–extension and axial rotation for atlantoaxial instability due to odontoid fractures. Lehman et al. [4] proposed that the transverse link could

remedy the defective construction of C1 pedicle and C2 laminar screws. However, difficult placement and potential reduction of bone graft have prevented the transverse link from being adopted in the clinic. We were, therefore, interested in finding a simple and practicable process to improve the stability of the screw rod system. In an in vitro biomechanical study by Gabriel et al. [5], the crossed rod was used in occipito-cervical fixation with a C2 laminar screw. The crossed rod provided sufficient biomechanical stability, and improved stiffness, compared to the parallel rod configuration. Preliminary research has demonstrated that the crossed rod configuration could provide a better stability than the traditional parallel rod configuration, which consists of unilateral C1 posterior arch screw and C2 laminar screw [6]. Therefore, crossed rod configuration may further increase the stability of the posterior atlantoaxial screw rod system, in consideration of improving the stability of the screw rod without having an adverse effect on the bone graft.

The atlas has a special anatomical structure. It connects the occipital bone and C2 through the bilateral lateral mass joints and has no vertebral structure or spinous process structure. Because of the lack of spinous process structure, the posterior part of occipito-cervical connection is different from lower cervical, thoracic and lumbar spines, thus the absence of obstructions of bony structures, making cross rod fixation possible. In the present study, we compared the stabilizing capabilities of the posterior atlantoaxial screw rod techniques using a cadaveric spine. The experiment simulated the surgical procedures. The successful placement of the crossed rod indicated that the crossed rod fixation technology was feasible, and it should be directly transferred to clinical application after the biomechanical test verification.

The aim of this study was to evaluate and compare the biomechanics of crossed and parallel rod configurations in the screw rod system for posterior atlantoaxial internal fixation. Among all surgical constructs, the stability of BLS + PR construct is the least stable of the tested surgical procedures. Whether the crossed or parallel rod configuration, the screw rod system consisting of C1 bilateral pedicle and C2 pedicle screws was more stable than the screw rod system consisting of C1 bilateral pedicle and C2 lamina screws. As expected, crossed rod could provide instant stability in all directions for C1–C2 segment after destabilization. The results demonstrate that the crossed rod configuration significantly enhanced the stability of the screw rod system, which consisted of C1 bilateral pedicle and C2 pedicle screws, or C2 lamina screws in axial rotation and C1 bilateral pedicle and C2 lamina screws in the lateral bending and extension direction.

In this study, we used human cadaveric occipito-cervical spines. Although this study has shown positive biomechanical results, several limitations must be considered. In vitro surgical reconstruction and biomechanical testing were

carried out under ideal conditions. The effect of muscles and complex movements occurring in vivo was neglected, as were complications which could be encountered in the clinic due to illness. The DEXA method is that the devices are actually designed for scans on patients. It is not a routine evaluation tool in the cervical spine. Its results may be affected by soft tissue surrounding the bone, bone size, BMI, vascular calcification, degenerative changes and previous spinal surgery [21]. Since this is no longer present in the specimen, the values of the measurements can be erroneous. The crossed rod configuration may not be achieved if there is anatomical obstruction. Besides, the number of specimens enrolled in the study was small and the clinical evidence of crossed rod fixation was also lacking. Although this study has confirmed the dependable stability of the crossed rod, further clinical research is required to verify the performance further.

This study evaluated the biomechanical stability of the crossed rod in posterior atlantoaxial internal fixation. Under appropriate circumstances, the crossed rod configuration may be a simple and efficient process to improve the rigidity of the screw rod system in clinical practice.

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Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

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