北京航空航天大学四年级博士生和五年级直博生

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Spine

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Biomechanical Role of the C1 Lateral Mass Screws in Occipitoatlantoaxial Fixation

A Finite Element Analysis

Haibo Liu, MS,[*,†] Baocheng Zhang, MD,[‡] Jianyin Lei, MS,[*] Xianhua Cai, MD,[‡] Zhiqiang Li, PhD,[*] and Zhihua Wang, PhD[*]

Study Design. Finite element analysis.
Objective. To determine and compare the construct stability of occipitoatlantoaxial (C0–C1–C2) fixation provided by occipital plate, rod, and screw fixation with or without C1 lateral mass screw (C1LMS).
Summary of Background Data. Occipitoatlantoaxial fixation techniques use C2 pedicle screw (C2PS) with and without C1LMS that are then incorporated into occipital plate fixation points using occipital screw. There has, however, been no consensus about the standard occiput to C2 fixation in literature and few reports exist about the effects of additional intervening rigid C1LMS on the biomechanics. The role of biomechanics of the addition of C1LMS in occipitoatlantoaxial fixation for fusion is not known.
Methods. A nonlinear finite element model (FEM) of the intact upper cervical spine had been developed and validated. Then an FEM of an unstable model treated with occipital plate combined with C2PS and C1LMS fixation (C1LMS + C2PS + plate), was compared to that with C2PS fixation (C2PS + plate). Vertical load of 50 N was applied on the C0, to simulate head weight and 1.5 Nm torque was applied to the C0 to simulate flexion, extension, lateral bending, and axial rotation.
Results. Compared with C2PS + plate, the C1LMS + C2PS + plate reduced the range of motion of C0–C2 segment by 3.0%, 35.4%, 29.2%, and 56.9% in flexion, extension, lateral bending, and axial rotation, respectively, and it also led to lower occipital screw and superior rod stresses in all loading conditions.
Conclusion. The addition of supplemental C1LMS to occiput-C2 fixation not only enhances greater stability, especially during axial rotation, but also has the capability of distributing the stress evenly and reduces the risk of construct failure because of occipital screw pullout and rod fracture. Therefore, this method may be important to elderly patients with osteopenia or osteoporosis and it may promote a high occipitoatlantoaxial fusion rate.
Key words: C1 lateral mass screw, C2 pedicle screw, finite element analysis, occipital screw, occipitoatlantoaxial fixation.
Level of Evidence: N/A
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The occipitocervical junction (OCJ) at the atlanto-occipital and atlantoaxial joints is the most mobile segment of the cervical spine, involving 50% of flexion, extension, and axial rotation.[1] OCJ stability only depends on complex capsuloligamentous structures, making it susceptible to cause a variety of unstable conditions, such as trauma, infection, rheumatoid arthritis, tumors, congenital deformity, and degeneration.[2,3] OCJ instability may manifest as disabling pain, cranial nerve dysfunction, paresis, and even sudden death.[4] Surgical fixation of OCJ instability is further complicated because of the unique neurologic, musculoskeletal, and vascular anatomy of the spine, and the need to restrict all planes of motion.[1]

Currently, occipital plate, rod, and screw fixation have been used widely in upper cervical spine fusions.[5–8] These techniques use C2 pedicle screws (C2PS) with and without C1 lateral mass screws (C1LMS) that are then incorporated into occipital plate fixation points using occipital screw. Several biomechanical and finite element studies have compared the stability of various occipitoatlantoaxial stabilization techniques[1,9–12]; however, to date there are no

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Drs Liu and Zhang have contributed equally to the study as the first authors.

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consensus about the standard occiput to C2 fixation in the literature[1,9] and only one article exists about the effects of additional intervening rigid C1LMS on the biomechanics.[13] Takigawa *et al*[9] recommended occipital plate connected to C2PS (C2PS + plate) as the standard occiput to C2 fixation; however, Helgeson *et al*[1] added C1LMS into the OC fixation and treated C1LMS + C2PS + plate as standard construct. Two constructs may be suitable for patients with various conditions of OCJ instability. The role of biomechanics of the addition of C1LMS in OC fixation with fusion is not known.

The finite element analysis is suited to parameter studies and determines more values than cadaveric studies in predicting the stress distribution and displacement of degenerated and instrumented spine in spinal biomechanical studies.[14,15] Therefore, we built a finite element model (FEM) of the intact upper cervical spine to reproduce physiologic conditions. Then an FEM of the instability OCJ, treated with C1LMS + C2PS + plate fixation, was compared with the C2PS + plate fixation. The present study aims to evaluate the two constructs in biomechanics, particularly the supplemental effects of C1LMS. The biomechanics of two constructs were assessed using the range of motion (ROM) of C0–C2 level and stress distributions of the occipital screw, rod, and C1LMS.

MATERIALS AND METHODS

Finite Element Model of the Intact and Unstable Upper Cervical Spine

The present study was approved by the Hospital Ethics Committee (Wuhan General Hospital of Guangzhou Command). A three-dimensional (3D) model of a cervical spine supplied by a 35-year-old healthy male volunteer was reconstructed using computed tomography (CT) images. Continuous CT scanning from occipital to C2 using 16-slice spiral CT at 0.5 mm accuracy was performed. The images were postprocessed for boundary detection using a commercially available segmentation package (Mimics 10.01, Materialise NV, Belgium). An accurate geometric model of the upper cervical spine was established on the basis of the different gray-scale values of the cervical tissues.

A commercially available segmentation package (Hypermesh 12.0, Altair Engineering, Inc. Troy) was applied to divide and optimize grids on each part of the bony model based on the data of geometric model. The cortical bone was 1.5 mm thick.[16–18] The cancellous bone core was modeled separately to assign different material properties to each component. Moreover, the joint cartilage is 1.5 to 2 mm thick.[16–18] The transverse ligament is quite a tough tissue with low elasticity and thus was simulated using solid elements. The start and end points and the geometric characteristics of the other ligaments on the present FEM were obtained from relevant literature.[19] Nonlinear connector elements used force-displacement curves as material property input for ligaments.[20,21] After preparing a mesh in Hypermesh, the FEM was actually run on Abaqus, which was used to analyze the von Mises stress distribution on constructs in the cervical spine. The strain and deformation of all constructs and cervical spine were also obtained using ABAQUS software. Furthermore, ROM was obtained from calculating the FEM deformation.

In summary, a complete FEM of the intact upper cervical spine were implemented, including vertebral body, posterior elements, and a number of ligaments: anterior atlanto-occipital membrane, anterior longitudinal ligament, ligamentum flavum, posterior atlanto-occipital membrane, joint capsule, transverse ligament of the atlas, alar ligament, vertical cruciate, and apical ligament. The entire FEM consists of 32,405 elements and 26,295 nodes. Moreover, the material properties of the model were homogeneous and isotropic according to literature (Table 1). All joint surfaces were subjected under a face-to-face contact at a frictional coefficient of 0.1 to simulate the sliding between joint surfaces.[20,22]

OCJ instability can be attributed to ligaments adjacent to the odontoid process losing elasticity. Based on intact model, the unstable upper cervical spine model was established, wherein several ligaments structures, including anterior C0–C1 joint capsule, anterior atlanto-occipital membrane, apical ligament, alar ligament, vertical cruciate, and transverse ligament were removed.[9]

Finite Element Model of Occipitoatlantoaxial Fixation

The posterior construct was primarily comprised occipital plate, three occipital screws ($D = 4.5$ mm), C1LMS ($D = 3.5$ mm), C2PS ($D = 3.5$ mm), rods ($D = 3.5$ mm), and other surgical instruments. The entry point, the orientation of drill holes, and the insertion technique of the C1LMS and C2PS were based on the technique described by Harms and Melcher.[23] The entry points of the occipital screws were placed below the external occipital protuberance and medial of occipital.[10] All screws, except the occipital ones, were polyaxial and were placed to achieve bicortical purchase. The 2-mm-thick occipital plate, which was manufactured according to the morphology of the occipital, contained three rigidly locked holes for midline occipital screw placement. The extended arms bear the integrated polyaxial connectors on both sides of rod attachments. The rods were bent to approximate the occipitocervical curvature and were fastened with integrated polyaxial screws. After placing the screws and rods, all connections were completely tightened (Figure 1A, B). The EMBEDDED constraint command from ABAQUS was used to achieve the connections between screws and bone in FEM.

Medical titanium alloy was used for all construct components, including the screws, rods, and plate. The elastic modulus was 1.13 GPa and the Poisson's ratio was 0.25.

Boundary and Loading Conditions

The inferior surface of the C2 vertebra was constrained completely. A vertical load of 50 N and a torque of 1.5 Nm were applied to the C0 to simulate the weight of the head and various loading conditions of the cervical spine under

TABLE 1. Material Properties Used for Various Components of the Current Model

Material Properties	Young's Modulus (E: MPa)	Poisson Ratio (μ)
Cortical bone	12,000	0.3
Cancellous bone	500	0.3
Posterior bone	3500	0.3
Cartilage articularis	10	0.3

different body configurations. The torque along the axis generates flexion/extension (x-axis, ±1.5 Nm), lateral bending (y-axis, ±1.5 Nm), and axial rotation (z-axis, ±1.5 Nm) in the cervical spine. Moreover, the loading and boundary conditions were fixed for each FEM.[1,11] ROM of C0–C2 segment and peak von Mises Stress of constructs were quantified. Figure 2 shows the schematic of loading condition.

RESULTS

Validation of the Finite Element Model

To validate our model, we compared the neutral zone (NZ) and ROM of the C0–C1 and C1–C2 segments of the intact FEMs with the results of the *in vitro* test performed by Panjabi *et al*,[24–27] because the boundary and loading conditions in these studies were comparable. The NZ and ROM of the intact FEM were within reported data (Tables 2 and 3). Moreover, the NZ and ROM of the unstable model were larger than that of the intact model in extension, lateral bending, and axial rotation (Tables 2 and 3). Especially in extension, due to the absence of the C0–C1 anterior joint capsule and anterior atlanto-occipital membrane, atlanto-occipital dislocation took place in the neutral zone. Furthermore, there was no lifting force on the anterior arch of atlas. Thus the NZ and ROM of C1–C2 in the unstable model were small. There were no significant differences in flexion ROM between the intact model and unstable model, whereas the occipital and atlas had significant anterior displacement of 2.8 mm due to lack of transverse ligament. It has been known that the NZ was a more sensitive parameter of spinal instability.[27]

Range of Motion Data

Both constructs significantly reduced ROM compared with the unstable state. Compared with C2PS + plate, the C1LMS + C2PS + plate reduced the ROM by 3.0%, 35.4%, 29.2%, and 56.9% in flexion, extension, lateral bending, and axial rotation, respectively (Figure 3). This indicates that the C1LMS + C2PS + plate construct may offer similar stability to C2PS + plate construct in flexion but higher stability in extension, lateral bending, and axial rotation.

Implants Stress

Considering instrumentation failure most commonly occurs at the occipital screw and superior part of the rod (or rod curvature) after surgery,[5,28] only the von Mises Stress on the occipital screw and superior rod was calculated. The von Mises stress contour plot (Figure 4) showed the different stress distributions of two constructs in the state of equilibrium under the different loading conditions. The von Mises stress concentrations in the C2PS + plate mainly occurred at occipital screw, occipital plate, and superior portions of the rod, whereas the von Mises stress concentrations in the C1LMS + C2PS + plate construct were mainly found at inferior rod, caudal C1LMS, and caudal C2PS sites under different loading conditions. Peak stress, however, did not necessarily appear in the state of equilibrium. Figure 5 shows that both of occipital screw and superior portion of the rod of the C1LMS + C2PS + plate model had lower peak stress than that of C2PS + plate model in the process of initial loading to equilibrium state. Compared with C2PS + plate, the peak stress of occipital

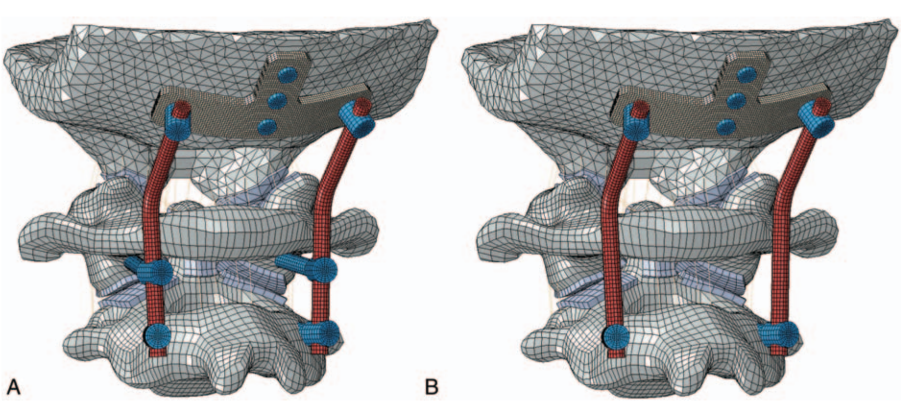

Figure 1. Cross-sectional view of C1LMS + C2PS + plate and C2PS + plate: (**A**) occipital plate, C1 lateral mass screw, C2 pedicle screw, and rod fixation (C1LMS + C2PS + plate); (**B**) occipital plate, C2 pedicle screw, and rod fixation (C2PS + plate).

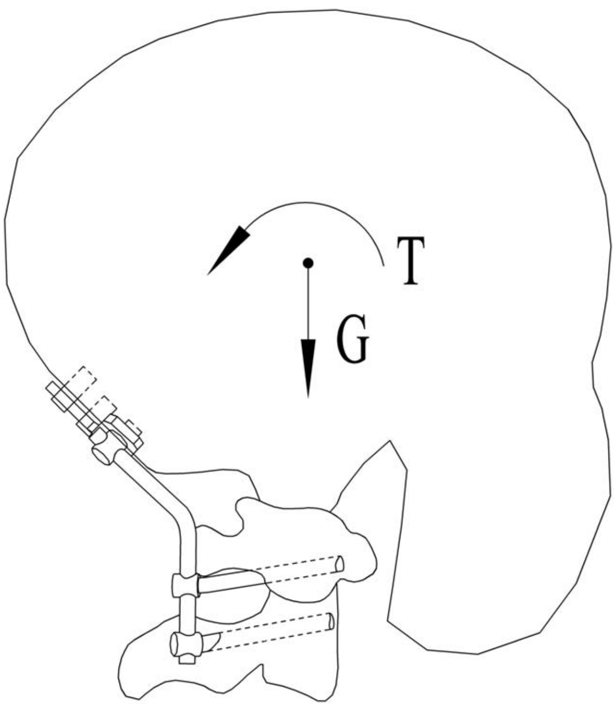

Figure 2. Schematic of loading condition.

screw in the C1LMS + C2PS + plate decreased by 40.6%, 29.0%, 38.0%, and 71.1% in flexion, extension, lateral bending, and axial rotation, respectively, and the peak stress of superior rod also decreased by 20.1%, 39.9%, 42.9%, and 43.9% in flexion, extension, lateral bending, and axial rotation, respectively (Figure 5A–D).

DISCUSSION

In recent years, occipital fixation using occipital plate, which allows placement of bicortical occipital screws in the thickest and strongest bone along the occipital midline, offers biomechanical stability and promotes fusion. This design not only can provide efficient fixation, but also can compress or distract the rods to achieve reduction. Clinical studies have demonstrated that the occipital plate combined with pedicle screws provided a high fusion rate and maintained alignment in the OCJ region, even in elderly patients with poor preoperative function[6] and in pediatric patients.[8] Hankinson *et al*[8] have reported a 100% occipitoatlantoaxial fusion rate using an occipital plate combined with pedicle screws in the pediatric population (range 1.3–18.8 years), and they also found that pediatric patients with occiput-C2 constructs including C1LMS (C1LMS + C2PS + plate fixation) had a 100% fusion rate when compared to those only undergoing C2PS + plate fixation. Thus, C1LMS may not be required to achieve occiput to C2 fusion in pediatric patients. There are no clinical studies referring to the role of C1LMS in occipitoatlantoaxial fusion in adult patients or in elderly patients. A biomechanical study performed by Wolfla *et al*[13] showed that the placement of C1LMS did not increase occipitocervical construct stability when compared with construct that did not use C1LMS. The authors, however, reported they used C2 pars screws but not C2PS, which is considered the ''criterion standard'' for C2 fixation.

According to data of intact and unstable FEM in NZ and ROM, we confirmed the validity of our intact model and the unstable model, and we have used the FEM to analyze a novel device for stabilization of the C1-C2 segment in our previous study.[15] In our finite element study, we built two OCJ fixation constructs using C2PS technique to investigate the role of biomechanics of the addition of C1LMS in occiput-C2 fixation. The results indicated that compared with C2PS + plate fixation, the C1LMS + C2PS + plate reduced the ROM by 3.0%, 35.4%, 29.2%, and 56.9% in flexion, extension, lateral bending, and axial rotation, respectively. This indicated that C1LMS + C2PS + plate fixation may offer similar stability in flexion but greater stability in extension, lateral bending, and axial rotation in comparison to the C2PS + plate fixation. These different ROM between the two constructs may be due to the different length in moment arms in each construct. Placement of the C1LMS moved the center of the axial rotation from the region of C2PS to C1LMS, and then provided a shorter moment arm, resulting in less occiput displacement. Especially in axial rotation, the addition of C1LMS reduced the ROM by 56.9% because the remarkable rotation of C1–C2 joint was restricted.

The literature has shown that instrumentation failure most commonly occurs at the occipital screw and superior part of the rod after operation.[5,28] Bhatia *et al*[5] reported 4%

TABLE 2. Validation of the Finite Element Model by NZ (°)

Motion	Panjabi *et al*[24]		Intact Model		Unstable Model	
	C0–C1	C1–C2	C0–C1	C1–C2	C0–C1	C1–C2
Flexion	3.3 ± 1.8	4.6 ± 2.4	2.2	3.6	2.2	3.6
Extension	13.9 ± 4.1	8.7 ± 6.7	6.3	3.6	19.1	4.0
Lateral bending	2.5 ± 1.6	2.4 ± 1.2	3.6	6.8	4.8	4.2
Axial rotation	3.6 ± 1.5	39.6 ± 7.5	5.4	35.6	9.2	22.4

Values for lateral bending and axial rotation summated both left and right sides.
NS indicates neutral zone.

TABLE 3. Validation of the Finite Element Model by Range of Motion (°)

Motion	Panjabi *et al*[24–27]		Intact Model		Unstable Model	
	C0–C1	C1–C2	C0–C1	C1–C2	C0–C1	C1–C2
Flexion	10.8–17.2	9.8–16.2	8.7	11.8	8.8	11.6
Extension	10.8–17.2	6.0–16.0	8.4	11.8	19.1	4.0
Lateral bending	2.6–8.6	3.8–19.6	7.8	9.4	13.8	10.2
Axial rotation	1.0–10.5	24.2–46.4	2.8	49.2	9.2	44.4

Values for lateral bending and axial rotation summated both left and right sides.

patients undergoing occipitoatlantoaxial fixation had rod fracture in the stress region of rod curvature or occipital screw pullout. Guppy *et al*[7] also reported that the reoperations rate of occipitoatlantoaxial fusions in elderly patients was 14.9%, and some of reoperation cases were due to construct failure. We could explain this observation based on anatomical and contact characteristics. First, the occipital protuberance was thin and the purchase length of the occipital screw was short, leading to low holding capacity,[5] by contrast, the C1LMS and C2PS fixation techniques were stiffer due to the screw lengths and the length of screw purchase were longer, leading to effective holding capacity.[23] Second, the displacement of occipital screw and superior portion of the rod was greater compared with C1LMS and C2PS.

Lastly, the occipital screw and superior part of the rod bear main part of stress. The Figure 4A–D shows the von Mises stress concentrations in the C2PS + plate mainly occurred at the occipital screw, occipital plate, and superior portion of the rod. After placement of C1LMS, the von Mises stress concentrations in the C1LMS + C2PS + plate were mainly found at inferior portion of the rod, between the screws, caudal C1LMS, and caudal C2PS under varying loading conditions. The finding suggests that the addition of supplemental C1LMS in occiput-C2 fixation has the advantage of transferring the load and distributing the stress evenly (Figure 5A–D).

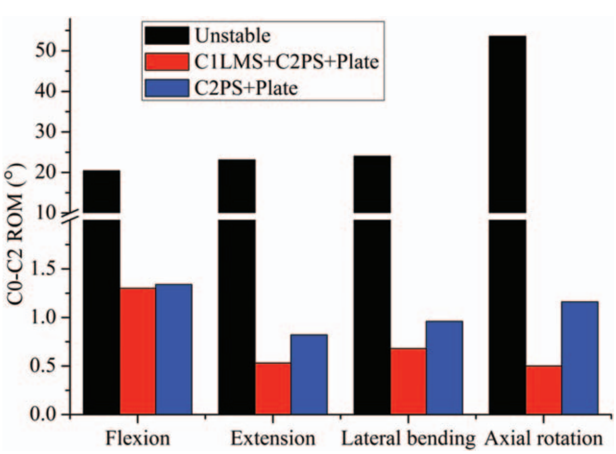

Figure 3. Comparison of C0–C2 ROM in the C1LMS + C2PS + plate and C2PS + plate under compressive load of 50 N and torque of 1.5 Nm. C1LMS indicates C1 lateral mass screw; C2PS, C2 pedicle screw; ROM, range of motion.

Our data also suggest that the von Mises stress of occipital screw and superior of rod in C2PS + plate was larger than that in the C1LMS + C2PS + plate during the process of initial loading to equilibrium state. Compared with C2PS + plate, the peak stress of occipital screw in the C1LMS + C2PS + plate decreased by 40.6%, 29.0%, 38.0%, and 71.1% in flexion, extension, lateral bending, and axial rotation, respectively, and the peak stress of superior rod also decreased by 20.1%, 39.9%, 42.9%, and 43.9% in flexion, extension, lateral bending, and axial rotation, respectively (Figure 5A–D). Because the addition of C1LMS provides another torque sharing element, it may decrease the stress of occipital screw as well as in the rod, and therefore reducing the risk of construct failure. The placement of C1LMS is, however, technically challenging and always susceptible to possible complications such as vertebral artery injury, blood loss, and longer overall operative time.[8] The addition of C1LMS to occiput-C2 fixation may not be necessary in pediatric patients[8] or adult patients, for whom bone mineral density often makes screw purchase stiffness to allow for a stronger fusion. For elderly patients with severe rheumatoid arthritis, the chronic smoker, tuberculosis, osteopenia, or osteoporosis, for whom bone mineral density is of inferior quality and screw purchase is weaker, the use of C1LMS should be considered in the surgeons' decision-making process.

The present study has demonstrated that although adding C1LMS provide a reinforcement effect to occiput-C2 fixation, it also has some limitations: the material properties for biological tissues used in the present FEM were linear, elastic, and homogeneous, which may affect the precision and reliability of the results. This limits the ability of the FEM to accurately simulate the physiological tissues and structures such as muscles, fat, skin, and tendons, which exhibit nonlinear, nonhomogeneous, and anisotropic characteristics.

In conclusion, the addition of supplemental C1LMS to occiput-C2 fixation not only enhances greater stability, especially during axial rotation, but also has the advantage of distributing the stress evenly and reduces the risk of construct failure due to occipital screw pullout and rod fracture. Therefore, this method may be a reasonable option in selected cases in severe rheumatoid arthritis, the chronic

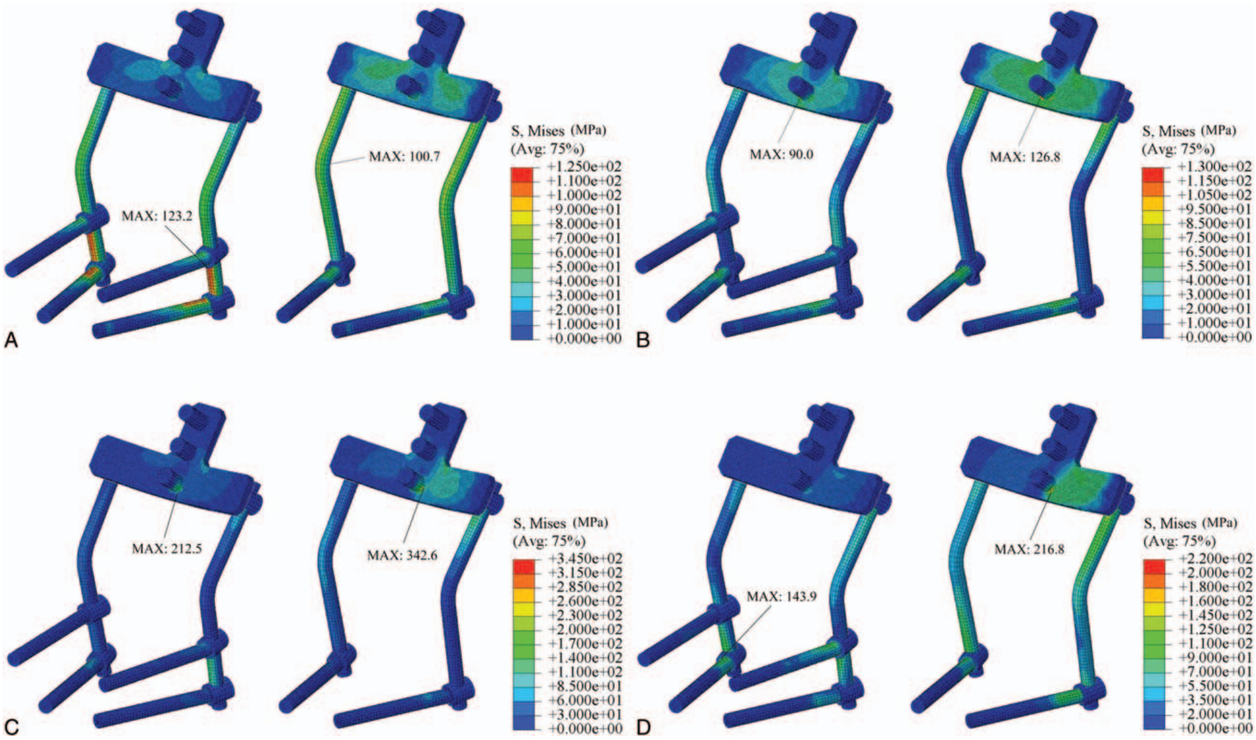

Figure 4. The von Mises stress contour plot of C1 lateral mass screw (C1LMS) + C2 pedicle screw (C2PS) + plate (left) and C2PS + plate (right) in the state of equilibrium under different loading conditions: (**A**) flexion, (**B**) extension, (**C**) lateral bending, (**D**) axial rotation.

smoker, tuberculosis, osteopenia, or osteoporosis elderly patients, where the bone mineral density is of inferior quality and screw purchase is weaker, and it may promote a high OCJ fusion rate. The study design was, however, only a computational simulation (with all its limitations), and the decision of which construct to use should be determined based more on clinical rather than solely on biomechanical concerns.[13] Further clinical trials are now required to validate the current findings, especially in the elderly population.

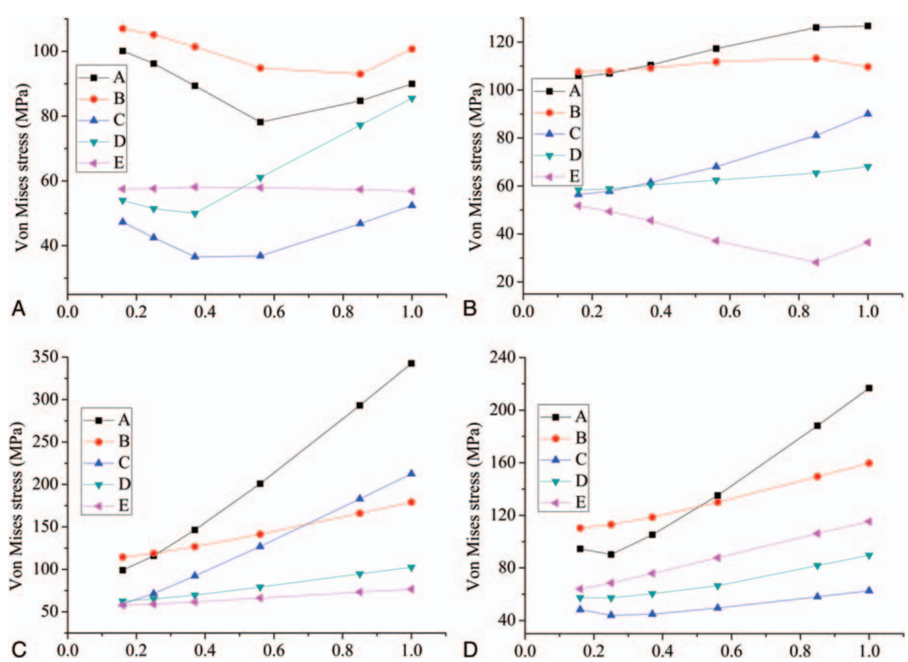

Figure 5. Peak von Mises stress of occipital screw, superior portion of rod and C1LMS in the C1 lateral mass screw (C1LMS) + C2 pedicle screw (C2PS) + plate and C2PS + Plate during the process of initial loading to equilibrium state under different loading conditions: (**A**) flexion, (**B**) extension, (**C**) lateral bending, (**D**) axial rotation (A: occipital screw of C2PS + plate; B: superior portion of the rod of C2PS + plate; C: occipital screw of C1LMS + C2PS + plate; D: superior portion of the rod of C1LMS + C2PS + plate; E: C1LMS of C1LMS + C2PS + plate).

➢ Key Points

- An FEM was used to investigate and compare the construct stability provided by two occipitoatlantoaxial (C0–C1–C2) fixation constructs: occipital plate combined with C1LMS, C2PS, and rods fixation (C1LMS + C2PS + plate) and that combined with C2PS and rods fixation (C2PS + plate).
- The finite element study showed that the C1LMS + C2PS + plate fixation may offer similar stability to C2PS + plate fixation in flexion but higher stability in extension, lateral bending, and axial rotation and it also led to lower occipital screw and superior rod stresses in all loading conditions.
- The addition of supplemental C1LMS to occiput-C2 fixation not only enhances greater stability, especially during axial rotation, but also has the advantage of distributing the stress evenly and reduces the risk of construct failure, and this method may be a reasonable option in the elderly population.

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