CLINICAL ARTICLE

Biomechanical Effects of Lateral Inclination C_1 and C_2 Pedicle Screws on Atlantoaxial Fixation

Lei Zhang, MD, Huan Wang, MD

Department of Spine Surgery, Shengjing Hospital of China Medical University, Shenyang, China

Objective: To assess the biomechanical effect of lateral inclination C_1 and C_2 pedicle screws on the atlantoaxial fixation through vitro human cadaveric study.

Methods: From January 2016 to December 2017, fresh-frozen cadaveric cervical spines with intact ligaments from eight donated cadavers at an average age of 71.5 ± 10.6 years, comprising of six males and two females, were collected. There were no fracture and congenital malformation in all specimens according to the imaging examination. The range of motion (ROM) of the specimens were tested in their intact condition and destabilized condition. Next, the specimens were randomly divided into two groups to ensure no differences in sex and age: Group 1 was medial inclination C_1 pedicle screw and C_2 pedicle screws (C_1MPS-C_2PS) and Group 2 was lateral inclination C_1 pedicle screw and C_2 pedicle screws (C_1LPS-C_2PS). The ROM of the fixation scenarios were recorded. Thereafter, all the specimens with fixation constructs were tested for 1,000 cycles of axial rotation and tensile loading to failure was carried out collinearly to the longitudinal axis of all the screws, the data were documented as screw pullout strength (SPS) in newtons. All the recorded data subjected to quantitative analysis.

Results: The ROM of specimens was increased significantly in destabilized condition and significantly reduced in fixation condition compared with intact condition. In C_1LPS-C_2PS groups, the C_1-C_2 cervical segment showed 3.96° ±1.21° and 3.75° ± 1.33° in flexion and extension direction, 2.85° ± 0.91° and 2.96° ± 0.71° in right and left lateral bending, 2.20° ± 0.43° and 2.15° ± 0.40° in right and left axial rotation. In C_1MPS-C_2PS groups, it showed 4.24° ±1.31° and 3.98° ± 1.21° in flexion and extension direction, 2.76° ± 1.10° and 3.23° ± 0.62° in right and left lateral bending, 2.20° ± 0.46° and 2.21° ± 0.42° in right and left axial rotation. There was no statistically significant difference on ROM and screw pullout strengths (764.29 ± 129.00 N *vs* 714.55 ± 164.63 N) between the two groups. However, there was one specimen in the C_1MPS-C_2PS group showing rupture the inferior wall of the left screw trajectory owing to the relatively thin posterior arch of the atlas, the screw pullout strength was significantly reduced (left pullout strength value: 430.5 N, right pullout strength value: 748.4 N). Therefore, in the case of the thin posterior arch of the atlas, the C_1LPS-C_2PS group had strong long-term biomechanics.

Conclusion: The lateral inclination C_1 pedicle screw can achieve the same biomechanical strength as the traditional atlas pedicle screw. However, for the case where the posterior arch of the atlas is relatively thin, a lateral inclination C_1 pedicle screw is more suitable.

Key words: Atlantoaxial fixation; Cadaveric study; Lateral inclination C_1 pedicle screw; Lateral inclination C_2 pedicle screw; Narrow C_1 posterior arch

Introduction

Cervical spine injury, especially the atlantoaxial joint, has been frequently associated with the spinal canal or the large blood vessels supplying blood to the brain[1]. The atlantoaxial joint is known as the most unique part of the spine and is also the most mobile segment of the spine,

Address for correspondence Huan Wang, MD, Department of Spine Surgery, Shengjing Hospital of China Medical University, No. 36, Sanhao Street, Heping District, Shenyang, China 110004 Tel: +86-18904008058; Fax: +86-24-96615; Email: spinewh@163.com
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largely depending on the ligamentous supports and the integrity of the odontoid for its stability[2]. In turn, the atlantoaxial unstableness is considered to be a congenital neurologic event that mainly brings about influence in toy breed dogs but also occurs in adults, which may be a consequence of an acute traumatic event, degenerative diseases, tumor, arthritis and infection[3–5].

Available approaches used to treat the atlantoaxial unstableness include posterior atlantoaxial fixation, which has been deemed to be an effective method to treat atlantoaxial unstableness and is comprised of wiring techniques, interlaminar clamp fixation, transarticular fixation, screw-plate systems, screw-rod systems, and hook-screw systems[6]. The fusion of the complex involving the C_1 and C_2 vertebrae may be a prerequisite in the context of atlantoaxial unstableness, which shows an extremely mobile property, placing great demand on the atlantoaxial fixation construct for adequate rigidity required for its fusion. The causes that lead to the unstableness of C_1-C_2 have been confirmed to be numerous, including trauma, inflammatory arthritis, congenital malformations, malignancies, rotatory subluxations, skeletal dysplasias, and pharyngeal infections. Additionally, the clinical symptoms of the unstableness of the atlantoaxial complex are identified to be various, such as neck pain, headaches, ataxia, transient paresis and intermittent loss of consciousness[7, 8]. Evolved from wiring techniques, immobilization modalities for the treatment of C_1-C_2 unstableness have developed into various kinds of screw-rod constructs, such as positioning of sidelong big screws, transarticular screws, intralaminar screws, as well as pedicle screws[9–12].

A large number of studies have highlighted that the screw fixation of the atlantoaxial complex can provide immediate stability and excellent fusion success for patients who suffer from atlantoaxial instability[7, 13, 14]. In specific terms, C_1-C_2 transarticular screw fixation for atlantoaxial unstableness has been reported to be safely placed with good accuracy, with the calculated deviation of the planned position and actual position being 0.8798 mm [15]. In addition, C_1-C_2 intralaminar screw fixation indeed shows improved biomechanical properties as it is capable of decreasing the flexion/extension range of motion (ROM) and improving stiffness[16]. In the C_1 lateral mass-C_2 pedicle screw fixation, the use of a short pedicle screw has the potential to serve as an alternative in the event of other screw fixation methods are found to be not feasible[17]. What is more, the C_1-C_2 pedicle screw fixation has been extensively reported to be safe and effective for the treatment of atlantoaxial dislocation as it can provide excellent bony purchase and avoid neurovascular complications, even in pediatric patients younger than 5 years where all patients were found to present with radiographic stability and symptom resolution[18, 19]. The C_2 pedicle screw fixation has been detected to be more biomechanically stable whereby it provides patients with increased postoperative ROM in comparison to the other techniques of the C_2 fixation[20]. Specifically, the C_2 pedicle screw fixation has been shown to provide an enhancement in the biomechanical stability and increase the cervical construct in relation to the pars screw fixation owing to the elevation of the length and bony purchase of pedicle screws within the pedicle and vertebral body[21].

Meanwhile, a lateral inclination approach has been signified to improve the safety of the surgery and minimize the screw perforation, and provide more pullout strength and better biomechanical stability; for instance, published data have established that when compared to a medial inclination screw trajectory, C_1 pedicle screw trajectory with lateral inclination can bring about a good outcome in the treatment of atlantoaxial unstableness since it induces a wider medullary cavity width, a higher posterior arch height and lateral mass height, as well as a longer pedicle length[22]. The C_1 posterior arch screw method has been applied in C_1 rigid balanced immobilization[23–25] owing to the numerous advantages which include: (i) high fusion percentage and lower complication ratio; and (ii) less bleeding at venous plexus and soreness of the C_2 roots of the nerve[26, 27]. However, of the C_1 pedicle screw method also faces some shortcomings, including the filmy external bone of the C_1 posterior arches in a manner that the screw or drill would sideslip when operating, causing damage to the vertebral artery. Hence, under such circumstances, surgeons can choose alternative techniques for patients who experience a C_1 posterior arch less than 4 mm to prevent injury of the vertebral artery[28]. However, the aforementioned method may fail to reach a dependable biomechanical immobilization. Therefore, we set lateral inclination of a C_1 pedicle screw (C_1LPS), with an entry point near the posterior tubercle and trajectory angle with transverse leaning. This study was designed: (i) to verify whether the two screw techniques can provide good short-term and long-term biomechanical stability; (ii) to compare stability and reliability of C_1LPS-C_2PS and medial inclination C_1 pedicle screw and C_2 pedicle screws (C_1MPS-C_2PS); and (iii) based on the results, to recommend the appropriate fixation technique for atlantoaxial instability, especially for patients with narrow C_1 posterior arch.

Materials and Methods

Inclusion and Exclusion Criteria

The inclusion criteria of this study were as follows: (i) eight top cervical spines (occiput-C_4) were collected from donated cadavers (six males and two females, with a mean age of 71.5 $\pm$ 10.6 years) between January 2016 and December 2017; (ii) C_1LPS-C_2PS and C_1MPS-C_2PS were placed; (iii) the stability and reliability of C_1LPS-C_2PS and C_1MPS-C_2PS; (iv) ROM test and pullout strength test; and (v) an *in vitro* human cadaveric study.

The human cadaveric cervical spines samples were excluded: (i) anterior cervical surgery history; (ii) incomplete cervical spine tissues or ligaments between C_1 and C_2; (iii) age < 18 years; (iv) width of C_1 pedicle and C_2 pedicle <4.5 mm; and (v) with fracture and congenital malformation in tissues through radiography examination.

All of the specimens were stored at −20°C and randomly allocated without differences in sex and age into such two groups as C_1LPS and C_1MPS for further studies.

Instability Model

The instability model was conducted as follows: each specimen was thawed in a 30°C normal saline bath, and its posterior soft tissues were stripped of, which included the supraspinous and interspinous ligaments. Thereafter, the facet joints of the C_1-C_2 articulation were subjected to destabilization. A quarter-inch straight osteotome was used to create an odontoidotomy at the base of the odontoid process.

Surgical Technique

The instability model was randomly divided into two groups. Group 1 was medial inclination C_1 pedicle screw and C_2 pedicle screws (C_1MPS-C_2PS) and Group 2 was lateral inclination C_1 pedicle screw and C_2 pedicle screws (C_1LPS-C_2PS).

Group 1 received medial inclination C_1 pedicle screw and C_2 pedicle screws. The insertion of the screw trajectory for the C_1 medial pedicle screw fixation was carried out using the method described in a previous study by Resnick,[29] the C_1 screws (3.5 mm in diameter, 26–30 mm in length, Vertex System, Atlas Cables, Medtronic, Sofamor Danek, Memphis, TN, USA) were inserted through the posterior arch of C_1 into the lateral mass. During the process, the entry point of the C_1 screw should be at least 2 mm below the superior rim of the C_1 posterior arch and aligned with the central part of C_1 lateral mass. Then the trajectory was approximately 10° in the medial direction and 5° in the cephalad direction.

Group 2 received lateral inclination C_1 pedicle screw and C_2 pedicle screws (C_1LPS-C_2PS). The insertion of the screw trajectory for the C_1 medial pedicle screw fixation was carried out using preoperative plan on imaging results. The C_1 posterior tubercle was regarded as the anatomical milestone on samples to measure the distance. The entry point for C_1LPS was defined using calipers in accordance to the distance measured prior to the operation from the backside tubercle of C_1 to the best screw entry point. The pedicle angle of C_1LPS was equal to the middle boundary tangent of the lateral well and the transverse boundary tangent to the spinal canal. The difference between C_1MPS and C_1LPS is shown in Fig. 1. Subsequently, an opening was created using a drill with high speed. The pedicle screws were fixed freehand, followed by drilling the predetermined trajectory, and subsequently, the screws (diameter 3.5 mm, longing 22 mm) were set in both groups (Fig. 2).

In addition, the method described by Harms and Melcher was used for the screw trajectory for the C_2 pedicle screw placement.[30] The entry point for the C_2 screw (3.5 mm in diameter, 26–30 mm in length, Vertex System, Atlas Cables, Medtronic, Sofamor Danek, Memphis, TN, USA) was the cranial and medial quadrant of the isthmic surface of C_2 in line with the trajectory of the pedicle. Next, the screw trajectory was put approximately 20° to 30° medially and in the cephalad direction along the C_2 pedicle[31].

Outcome Evaluation

ROM

ROM was assessed to show the flexibility of cervical spines. ROM tests included six parameters, such as flexion (FLEX), extension (EXT), right lateral bending (RLB), left lateral bending (LLB), right axial rotation (RAR), and left axial rotation (LAR). The overall motion of cervical spines in the context of cervical collar application was assessed by measuring the changes of the head relative to the trunk by wireless human motion tracker system (Xsens Technologies, Enschede, Netherlands). The 3-dimension measurement included extension/flexion and rotation and lateral bending (Fig. 3). Two inertial measurement units (IMUs) were put on the forehead and sternum of each cadaver, respectively. The neutral state of each cadaver was placed in a supine position on a table before maneuvers was marked as baseline. Flexion was defined as positive values. The rotation and lateral bending were assessed using absolute values, regardless of the right or the left rotation and the right or the left lateral bending[32].

Screw Pullout Strength (SPS)

Cyclical fatiguing and pullout tests are important methods to investigate if the pullout strengths after cyclic uniplanar loading of cervical pedicle screws are superior to lateral mass screws. A total of 1,000 cycles of axial loads (± 50 N) were employed at the head of screws with the applied force at 90° to the screw macroaxis. Cephalocaudad toggling was carried out at a frequency of loading at 1 Hz. The employed options followed the fatigue testing method applied in the subaxial cervical spine[33]. The normal saline was spread on the specimens to keep them moist during the process of testing to optimally preserve their native properties.

At the end of periodic loads, pullout strength was examined for the C_1LPS and C_1MPS. Subsequently, a steel cable was secured to the head of all screws. A strength was then used along with the screw axis using a Servomotor at 0.25 mm/s[34]. A force sensor was employed in order to calculate the cable tension, which was then employed to measure the strength in Newtons (Fig. 4).

Statistical Analysis

All statistical analyses were conducted using SPSS 21.0 software (IBM, Armonk, NY, USA), with two-tailed $P < 0.05$ as a level of statistical significance. Comparison of mean stability (ROM) among multiple groups was performed by one-way analysis of variance, followed by Tukey's post-hoc test. The mean pullout strength between the two groups was analyzed by a two-tailed Student t test. Data were expressed as the mean ± standard deviation and as minimum and maximum values. With a power analysis at an α (P value) = 0.05 and β (power) = 0.08.

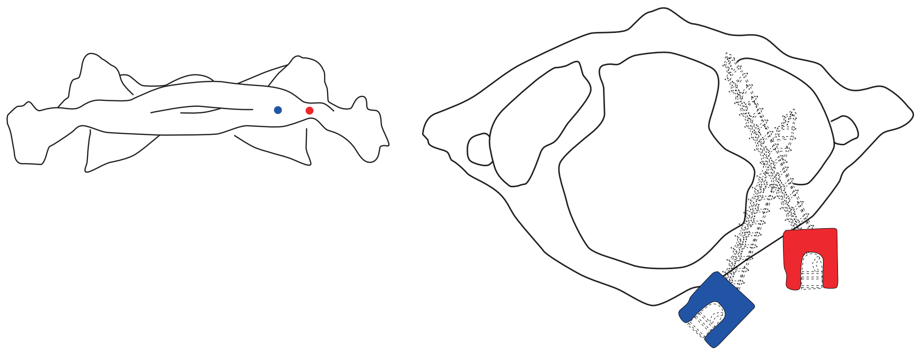

Fig. 1 Pedicle screw placement diagrams. Medial inclination C_1 pedicle screw (red): the entry point of the C_1 screw should be at least 2 mm below the superior rim of the C_1 posterior arch and was aligned with the central part of C_1 lateral mass. Then the trajectory was approximately 10° in the medial direction. Lateral inclination C_1 pedicle screw (blue): the entry point for C_1LPS was defined using calipers in accordance to the distance measured prior to the operation from the backside tubercle of C_1 to the best screw entry point. The pedicle angle of C_1LPS was equal to the middle boundary tangent of the lateral well and the transverse boundary tangent to the spinal canal.

Fig. 2 The optimal screw entry point of medial inclination C_1 pedicle screw (C_1MPS) and lateral inclination C_1 pedicle screw (C_1LPS).

Fig. 3 ROM test. The prepared specimens were attached to the rigid base in a testing frame. Using a system of loading arms, pulleys, and weights, quasi-static loads were applied to the skull, leading to sequential pure moments of 0, 0.5, 1.0, 1.5, 1.0, 0.5, and 0 Nm. Moments were applied to generate the following 6 loading modes: extension; flexion; left and right lateral bending; and left and right axial rotation.

Results

ROM Test

To compare the stability and extension of C_1LPS and C_2PS, we performed ROM assay for six motion directions in two groups using wireless human motion tracker system. The cervical spines were first detected in intact condition, the C_1-C_2 cervical segment showed 17.02° ± 2.24° and 7.95° ± 1.05° in flexion and extension direction, 6.24° ± 1.26° and 6.03° ± 1.74° in left and right lateral bending, 28.24° ± 2.75° and 26.93° ± 3.04° in left and right axial rotation. After C_1-C_2 destabilization *via* odontoidectomy, six motion directions exhibited significantly larger ranges than intact specimens. The flexion/extension ROM increased by 60.59% and 67.92% ($F = 144.1$, $P < 0.001$ and $F = 71.90$, $P < 0.001$), left and right lateral bending ROM increased by 91.71% and 74.84% ($F = 68.20$, $P < 0.001$ and $F = 42.47$, $P < 0.001$), left and right axial rotation ROM increased by 71.55% and 61.58% ($F = 503.7$, $P < 0.001$ and $F = 300.1$, $P < 0.001$), as compared with intact cases, respectively.

Both C_1LPS-C_2PS and C_1MPS-C_2PS fixation methods could stabilize C_1-C_2 segment and significantly decrease ROM in all six directions, when compared with intact ($P < 0.0001$, $P < 0.001$, $P < 0.05$, $P < 0.01$, $P < 0.0001$, $P < 0.0001$) and with destabilized conditions ($P < 0.001$, $P < 0.001$, $P < 0.05$, $P < 0.01$, $P < 0.0001$, $P < 0.0001$). In the flexion/extension direction, C_1LPS-C_2PS showed ROM of (3.96° ± 1.21° and 3.75° ± 1.33°) and C_1MPS-C_2PS showed ROM of (4.24° ± 1.31° and 3.98° ± 1.21°), though C_1LPS-C_2PS group exhibited no significant difference in ROM data with C_1MPS-C_2PS group ($P > 0.05$). Negligible difference

Fig. 4 Apparatus for testing pullout strength. A force was applied in line with the screw axis using a Servomotor at a rate of 0.25 mm/s. A force sensor was used to measure the tension at the cable.

($P > 0.05$) was observed in right and left lateral bending ROM data (2.85° ± 0.91° and 2.96° ± 0.71°) for C_1LPS-C_2PS and (2.76° ± 1.10° and 3.23° ± 0.62°) for C_1MPS-C_2PS. The right and left axial rotation ROM for C_1LPS-C_2PS group was (2.20° ± 0.43° and 2.15° ± 0.40°), and that for C_1MPS-C_2PS group was (2.20° ± 0.46° and 2.21° ± 0.42°), the difference of which was not statistically significant between the two groups ($P > 0.05$) (Table 1).

Screw Pullout Strength

After performing 1,000 cycles of axial motion, we measured SPS of the C_1LPS-C_2PS and C_1MPS-C_2PS groups respectively. The C_1LPS-C_2PS group showed an SPS of 764.29 ± 129.00 (N), and the C_1MPS-C_2PS group showed an SPS of 714.55 ± 164.63 (N) for cervical spines. Although C_1LPS displayed a higher SPS than C_1MPS, higher standard deviations contributed to a high P value ($t = 0.7191$, $P = 0.4839$) and resulted in no significant difference. However, one specimen in the C_1MPS-C_2PS group had a rupture to the inferior wall of the screw trajectory due to the relatively thin posterior arch of the atlas. The SPS of the left and right sides were 430.5 N and 748.4 N, respectively, and the SPS of the left side was significantly reduced. Although only one abnormal sample value was found, we speculated, based on this finding, that the stability of C_1LPS may be higher than that of C_1MPS when the posterior arch of the atlas was relatively thin.

Discussion

Investigation Background

The atlantoaxial joint represents the most flexible section of the cervical spine, and strong intervertebral fusion is generally believed to be optimally achieved when the motion is minimized by fixation[35]. Diverse fixation methods are various for C_1, such as wiring fixation, interlaminar clamps, transverse big screws, transarticular screws, intralaminar screws, as well as pedicle screws. Specifically, the C_1 back wise arch screw option has become more popular in recent years. It was widely reported that it had more pullout strength, less soreness of the C_2 root of the nerve and venous plexus, and a more visible entry point[26, 27, 36]. Therefore, the C_1 posterior arch screw technique has become a more common option for C_1 inflexible strong fixation, especially for short-fragment cervical fixation[25, 37, 38].

Disadvantages of the C_1 Pedicle Screw Method and the Focus of the Current Study

However, the C_1 pedicle screw method still faces some disadvantages, including the filmy external bone of the C_1, back wise arches in a manner that the screw or drill could sideslip when operating, resulting in injury to the vertebral artery. Gergely *et al.* [39] proved that height of penetration point of the pedicle screw was 4.70 mm in males, and 3.91 in females, respectively. Height of penetration point under 4 mm was 19.2% in males and 65% in females. Our previous study also found similar results. The same problem was also mentioned in the study conducted by Tan *et al.* [28], exposing the C_1 "pedicle" with the removal of the external portion that has about 4 mm of the

TABLE 1 Range of motion at 1.5 Nm for each of the six motion directions in both groups (°)

Motion Direction	FLEX	EXT	RLB	LLB	RAR	LAR
Intact	17.02 ± 2.24	7.95 ± 1.05	6.03 ± 1.74	6.24 ± 1.26	26.93 ± 3.04	28.24 ± 2.75
Destabilized	27.53 ± 2.86*	13.35 ± 1.52*	11.56 ± 1.77*	10.91 ± 1.22*	46.20 ± 3.91*	45.63 ± 2.60*
C_1LPS-C_2PS	3.96 ± 1.21*	3.75 ± 1.33*	2.85 ± 0.91*	2.96 ± 0.71*	2.20 ± 0.43*	2.15 ± 0.40*
C_1MPS-C_2PS	4.24 ± 1.31*	3.98 ± 1.21*	2.76 ± 1.10*	3.23 ± 0.62*	2.20 ± 0.46*	2.21 ± 0.42*

The values given are mean ± standard deviation. Data comparison among multiple groups was performed by one-way analysis of variance, followed by Tukey's post-hoc test; *Significantly different from Intact; EXT, extension; FLEX, flexion; LAR, left axial rotation; LLB, left lateral bending; LPS, lateral inclination pedicle screw; MPS, medial inclination pedicle screw; PS, pedicle screw; RAR, right axial rotation; RLB, right lateral bending.

long bone of the back wise arch. The back wise arch along the trajectory of the C_1 back arch screw succeeded in enlarging the screw penetration point height. Whereas, removing a part of cortex of the C_1 posterior arch would affect the SPS. Zhang *et al.*[40] mentioned the notching method by embedding the screw into the narrow back wise arch by notching the substandard arch and placing the screw outside the inferior wall and partially outside the back wise arch. Theoretically speaking, like the transverse big screw modality, this notching may confer an injury risk to the C_2 root of the nerve and venous plexus, similar to, when the substandard boundary of the C_1 posterior arch was dissected. Additionally, notching enters the substandard cortex of the back wise arch, resulting in disordered SPS. Hence, we designed a lateral inclination C_1 pedicle screw (C_1LPS), which has a point of penetration near the posterior tubercle and trajectory angle accompanied by transverse inclining. The current study aimed to assess the acute fragmental immobilization and long-range screw stability given by lateral inclination C_1 pedicle screw.

ROM Test

The ROM represents the immediate biomechanical strength of the fixed system. The larger ROM reflects the worse stability. The significance of fixation is to improve stability. The ROM is small, the fixation is reliable, and the immediate biomechanical strength of the fixed system is high.

Both C_1LPS-C_2PS and C_1MPS-C_2PS verified essential and nearly equal advances in wide stability in flexion, extension, lateral bending and axial motion. The C_1LPS-C_2PS and C_1MPS-C_2PS implants greatly attenuated C_1-C_2 movement in intact conditions by 70.1% and 69.6% in flexion, independently ($P < 0.01$), and by 50.2% and 50.4% in extension, independently ($P < 0.01$). In transverse flexion, C_1LPS-C_2PS decreased C_1-C_2 movement in intact conditions by 53.2% in left bending and 53.8% in right bending ($P < 0.01$). C1MPS-C_2PS decreased C_1-C_2 movement in the complete state by 52.3% in left flexion and 54.8% in right flexion ($P < 0.01$). In axial rotation, the C_1LPS-C_2PS and C_1MPS-C_2PS systems dramatically decreased flexibility by 86.7% and 87.8% in right axial motion, and by 88.3% and 91.7% in left axial motion, respectively. ROM data indicated both C_1LPS-C_2PS and C_2MPS-C_2PS methods could markedly decrease atlantoaxial motion range and stabilize cervical spines compared to intact and destabilized conditions and no marked difference between the C_1LPS-C_2PS and C_1MPS-C_2PS conditions for flexion-extension, rotation, or lateral bending, suggesting that the C_1LPS-C_2PS has the same stability as C_1MPS-C_2PS, and that C_1LPS-C_2PS as well as C_1MPS-C_2PS contributes to remarkably decreased flexibility more than destabilizing it.

Screw Pullout Strength Test

The pullout strength after the fatigue test represents the long-term stability of the fixed system. The larger pullout strength indicates the higher long-term biomechanical strength of the fixed system.

In our study, we found C_1LPS displayed a higher SPS than C_1MPS (764.29 $\pm$ 129.00 N *vs* 714.55 $\pm$ 164.63 N). This result was in good agreement with Zhang *et al.* [40]. However, high standard deviation precluded statistical significance. Although, one screw in the C_1MPS-C_2PS group ruptured the inferior wall of the screw trajectory due to the relatively thin posterior arch of the atlas, its SPS (430.5 N) was obviously less than the other screw (760.01 $\pm$ 138.45 N). But even if excluding this abnormal value, we still found that C_1LPS showed a little higher SPS than C1MPS (764.29 $\pm$ 129.00 N *vs.* 755.13 $\pm$ 118.78 N). Final statistical results indicated that C_1LPS presented with no significant difference in pullout strength when compared with C1MPS.

Limitations

The current study has certain limitations, however. Similar to numerous *in vitro* biomechanical studies, muscle strength achievements to fragmental stability not routinely result in a cadaveric setting since it is quite hard to replicate them in a consecutive and dependable way during experimentation[41]. Still, further studies with larger sample sizes are needed, especially samples where pedicle screws notch the inferior arch. More tests with larger sample sizes are warranted in the future for confirming the current results. *In vitro* biomechanical studies serve as a base for clinical decision-making, and cannot be directly employed in clinical field currently. Theoretically, C_1LPS could increase the risk for running counter to the lateral wells and injuring the vertebral artery during pedicle screw insertion, and requires further research. Additionally, iatrogenic vertebral artery injury has led to the development in some patients suffering from brainstem ischemia or unilateral cerebellar strokes, which is fatal as reported by various studies[42–47]. Therefore, the C_1LPS-C_2PS system needs continuous improvement before being applied to clinical practice.

Conclusion

Overall, the findings from the present study suggest that lateral inclination C_1 pedicle screw functions in an equivalent manner to the medial inclination C_1 pedicle screw, both in acute and long-term. Furthermore, lateral inclination C_1 pedicle screw proved to be more suitable for narrow C_1 posterior arch. This is expected to relieve the neck pain and avoid the risk of further neurological deficit.

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