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ORIGINAL ARTICLE

Biomechanical analysis of the longitudinal ligament of upper cervical spine in maintaining atlantoaxial stability

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Study design: *In vitro* human cadaveric biomechanical study.
Objectives: To investigate the roles of transverse atlantal ligament (TAL) and longitudinal ligament (LL) of the upper cervical spine (UCS) in maintaining atlantoaxial stability.
Setting: China.
Methods: Six intact UCS specimens were harvested and embedded in polymethylmethacrylate. Three-dimensional movements including flexion, extension, right and left lateral bending, and axial rotation, as well as the C1–C2 displacement in flexion (atlantodental interval, ADI), were tested on specimens with the following state sequentially: (1) intact (intact group), (2) TAL transected (TAL group) and (3) TAL and LL disrupted (TAL + LL group) using an electromechanical testing machine.
Results: Compared with intact group, the flexion/extension motion range and ADI were significantly higher in TAL group when the loading was 10 N or >100 N. However, no significant differences were detected between the two groups within a range of physiological loading (10–100 N). Similarly, significant differences in right–left lateral bending and axial rotation between TAL and intact groups occurred only when the loading was 150 N. However, when both of the TAL and LL were resected, the atlantoaxial joint showed obvious instability compared with TAL or intact group, which were further demonstrated in the analyses of the three-dimensional movements (significant differences at any loading).
Conclusion: Within physiological loading range, the LLs have sufficient capacities to maintain the stability of atlantoaxial joint even if there are TAL injuries in atlas fractures.
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Keywords: atlas fractures; C1 lateral mass reduction; biomechanics; transverse atlantal ligament; longitudinal ligament

INTRODUCTION

Atlas fractures (also known as Jefferson fractures) are very common in cervical spine trauma accounting for about 25% of craniocervical injuries, 3–13% of cervical spine injuries and 1.3–2% of all spinal injuries.[1] Historically, atlas fractures have been categorized as stable or unstable injuries based on the structural integrity of the transverse atlantal ligament (TAL).[2] Stable atlas fractures (intact TAL) can be treated conservatively, but the optimal management of unstable atlas fractures (disrupted TAL) remains controversial. Nonsurgical treatments including continuous skull traction, cephalo–cervico–thoracic plaster or Halo vest immobilization,[3,4] frequently result in nonunion or malunion of C1–C2 and residual neck pain.[5–7] Subsequently, several researchers advocate atlantoaxial (C1–C2) or occipitocervical (C0–C2) fusion, however, these approaches sacrifice physiological motion functions of upper cervical spine (UCS), especially rotation.[8–10]

In recent years, clinicians have reported the successful application of direct C1 reduction and osteosynthesis for treating atlas fractures, which brings in good postoperative cervical functions, avoids the worrying instability in C1–C2 sagittal plane and preserves motion functions of the UCS.[2,11–13] However, the theoretical basis of this technique is unclear. In 2011, we also applied direct posterior C1 lateral mass screws compression reduction and osteosynthesis to successfully treat unstable atlas fractures and proposed the ‘buoy hypothesis’:[14] C0–C2 ligament system (Figure 1) comprises TAL (transverse bundles of crucial ligament) and longitudinal ligament (LL, containing longitudinal bundles of crucial ligament, alar ligament, apical ligament, tectorial membrane and accessory atlantoaxial ligament[15–18]). Although atlas undergoes axial loading and fractures, lateral mass has a propensity to displace laterally and the increased transverse tension may cause TAL rupture, but reserve the integrity of LL because of loss of C0–C2 height, which still has capacities to provide a second line of the defense in preventing anterior displacement of the atlas. However, TAL rupture results in concomitant failure of the vertical ligamentous tension and a laxity of the ligamentous complex at C0–C2, weakening the function of the ligaments. Therefore, reduction of the displaced C1 lateral mass by screws may restore the C0–C2 height and recreate the LL tension to maintain C1–C2 stability in the long term. Such process may be similar with a ‘buoy phenomenon’ that the rope connecting the buoy to the water bottom will get lax with the drop of water level, making the buoy unstable (Figure 2), whereas it gets stable with the rise of

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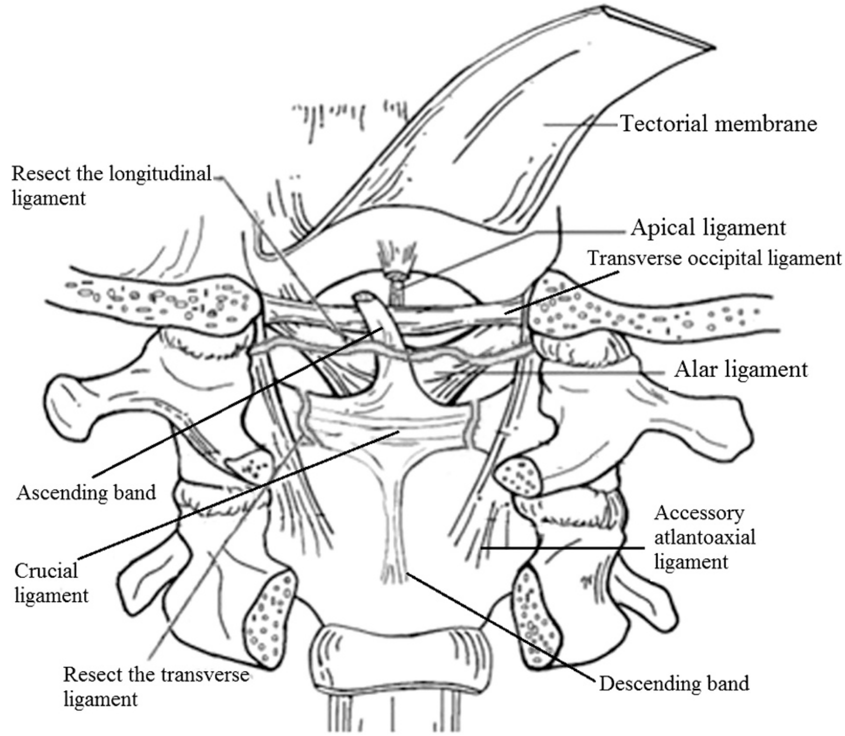

Figure 1 Resection position of transverse and LLs. The TAL was disrupted at bilateral tubercles of transverse ligaments through the foramen magnum (red mark). The LL was cut above the TAL (red mark). A full color version of this figure is available at the *Spinal Cord* journal online.

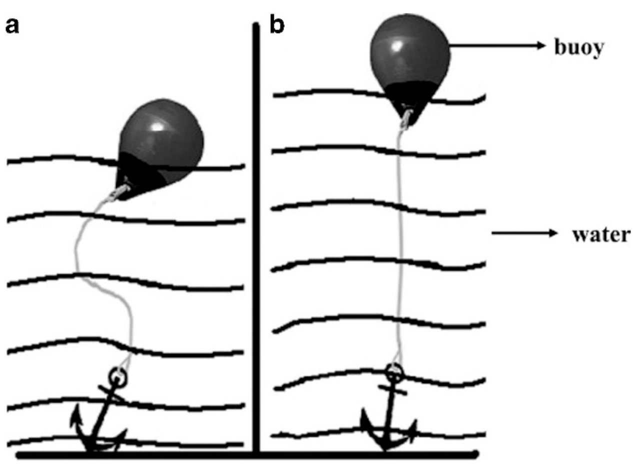

Figure 2 Buoy hypothesis that (**a**) the rope connecting the buoy to the water bottom gets lax with the drop of water level, making the buoy unstable; (**b**) the buoy gets stable with the rise of water level for the rope under tension.

water level for the rope under tension (Figure 2). This hypothesis emphasizes the capacities of LLs in maintaining UCS stability when the transverse ligament is ruptured.

The aim of C1 reduction and fixation is to reconstruct the annular structure of atlas and restore the tension of LLs.[14] In order to simplify the study, atlas fracture model was not constructed in our study, but intact UCS specimen was used to simulate the fixed and repaired atlas fractures model and then the TAL and LL were sequentially disrupted to further verify the effects of LLs. Three-dimensional movements were measured under different loading conditions. We hypothesize that the three-dimensional movements would not be significantly changed after only the TAL was disrupted because the C0–C2 height and tension of LL were still intact. But, they were significantly changed when both the TAL and LL were resected.

MATERIALS AND METHODS

Preparation of specimens

Six intact UCS specimens (C0–C3) were harvested from male patients (aged 37–67 years, average 52.3 years) who died of acute cardiac-cerebral vascular disorders or acute trauma (provided by Department of Anatomy, Tongji University School of Medicine, Shanghai, China). Each specimen underwent anteroposterior and lateral X-ray and computerized tomography scan to confirm that the bones were complete without any abnormalities (such as severe osteoporosis, cervical vertebrae injury, tumor or ossification of ligament). The specimens were numbered I–VI and stored at $-20\,^{\circ}C$ freezer. Specimens were thawed at room temperature for 8 h before experiment and then skin, paraspinal muscles, fat and other soft tissues were carefully removed leaving ligaments, joint capsules, intervertebral disc and bone structure intact. Part of occipital bone was retained. Thus, a complete UCS specimen was prepared. The occipital bone and C2–C3 vertebrae were embedded in a cube plexiglas cast with polymethylmethacrylate (self-solidifying type, Dental Materials Manufacturing Co., Shanghai, China). The specimens were kept moist by spraying the specimens with 0.9% physiological saline solution during sample preparation and testing.

Biomechanical testing

Three-dimensional movements including flexion, extension, right and left lateral bending and axial rotation, as well as the C1–C2 displacement in flexion (atlantodental interval, ADI) were measured on specimens in three different states sequentially: (1) intact specimens (intact group); (2) specimens with TAL transected (TAL group). The TAL was disrupted at bilateral tubercles of transverse ligaments through the foramen magnum (red mark, Figure 1); (3) specimens with both TAL and LL resected (TAL + LL group). The LL was cut above the TAL (red mark, Figure 1).

The embedding box of the C2 vertebra was fixed to the moving plate of the Zwick BZ2.5/TS1S universal testing machine (Zwick Roell, Ulm, Germany), leaving the spherical indenter 2-cm deviation from the center of occipital embedding box. Simulation of physiological movements (containing flexion, extension, left and right lateral bending) was achieved through loading the pressure at the top of the embedding box (Figure 3). Nails (diameter, 1 mm) were inserted into the anterior wall or accessory bone of C1 and C2 with tails marked black, which facilitated recognition by the computer image recognition system. More attention was paid to ensure the marked nails that did not contact each other during movement conditions. The contact load was applied using a Zwick BZ2.5/TS1S universal test machine with a loading rate of 5 mm min^{-1} (displacement control mode) and moment of 1.53 N m. Three charged-coupled device cameras (JAI Inc., Copenhagen, Denmark; CV-A1 Type, 1392 × 1040 pixels and 4.65 μm pixel resolution) were used to acquire sequential speckle images from the sagittal and coronal planes of the cervical vertebra with a recording frequency of 20 Hz during loading force, while 1 Hz for image acquisition. The sequential speckle images acquired during loading were analyzed with a commercial digital image correlation software (Matfolt Co., Ltd., Shanghai, China)[19] in which three-dimensional movement changes (angle and displacement) as well as ADI in C1–C2 flexion were calculated. As the C2 was fixed, ADI value could be determined through subtracting the thickness of anterior arch from the vertical distance between the marked point of C1 and the tangent of the anterior border of C2 (Figure 4). Axial rotation movement was examined on a biomechanical torsion testing machine (Changchun Research Institute for Testing Machines, Jilin, China) at a 5° min^{-1} torsional speed. Three repeats of maximum torque—zero-cycle loading were applied to the specimens to eliminate the influence of viscoelasticity from soft tissues and cervical creep and thus improve the accuracy of the results.

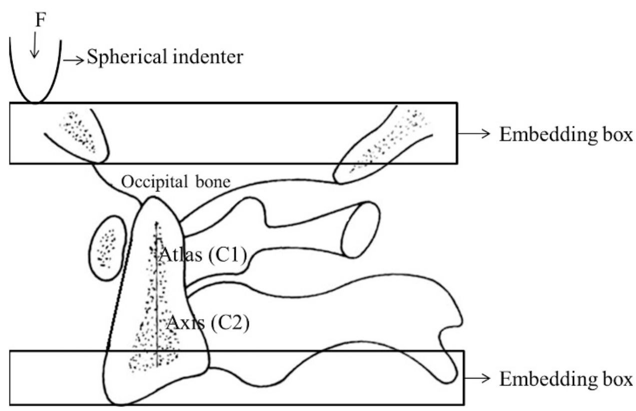

Figure 3 Schematic diagram of force loading.

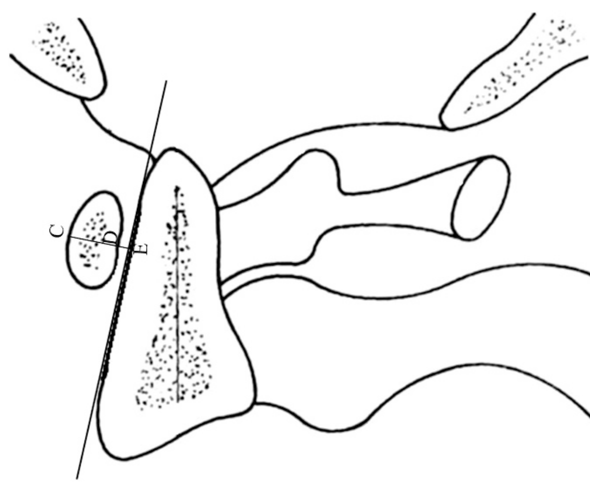

Figure 4 The measurement of ADI. ADI = CE–CD; CD is the thickness of anterior arch. CE is the vertical distance between the marked point of C1 and the tangent of the anterior border of C2.

Statistical analysis

All data were expressed as the mean ± s.d. (normally distributed data) of three duplicates and SPSS14.0 statistical software (SPSS Inc., Chicago, IL, USA) was used for data analysis. Comparisons among three groups were performed with one-way analysis of variance with *post hoc* least significant difference *t*-test. A *P*-value <0.05 was considered statistically significant.

RESULTS

Gross observation

When the TAL was transected, tension between C0 and C2 still remained and the specimen showed a stable structure. However, the atlantoaxial instability occurred and the range of motion of C1–C2 increased when the LL was further resected.

Changes in ADI in flexion

The ADI of C1–C2 increased with an increase in the loading. The displacement for TAL group was larger than that of intact group while the TAL + LL group showed the largest displacement (Table 1). There were significant differences in ADI between TAL and intact groups when the loadings were 10 N or ⩾100 N ($P = 0.026$, $P = 0.002$), but not in the range of 10–100 N (physiological load). TAL + LL group presented apparent instability compared with TAL or intact group, showing a significantly increased C1–C2 ADI in flexion with *P*-values in all loadings <0.01 (Table 1).

Table 1 ADI (mm) under incremental loading (10–150 N, $n = 6$)

Loading	*10 N*	*30 N*	*50 N*	*70 N*	*90 N*	*100 N*	*150 N*
Intact	0.79 ± 0.26	1.46 ± 0.29	1.67 ± 0.24	1.59 ± 0.30	1.67 ± 0.24	1.95 ± 0.18	2.23 ± 0.13
TAL disrupted	1.34 ± 0.36	2.08 ± 0.45	2.36 ± 0.47	2.19 ± 0.49	2.36 ± 0.47	2.90 ± 0.39	3.37 ± 0.59
TAL + LL disrupted	2.43 ± 0.51	3.28 ± 0.76	3.62 ± 0.79	3.44 ± 0.84	3.62 ± 0.79	4.32 ± 0.62	4.83 ± 0.72
P^a	0.026	0.063	0.086	0.053	0.053	0.002	0.002
P^b	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
P^c	<0.001	0.001	0.003	0.001	<0.001	<0.001	<0.001

Abbreviations: ADI, atlantodental interval; LL, longitudinal ligament; TAL, transverse atlantal ligament.
[a]TAL disrupted group vs intact group.
[b]TAL + LL disrupted group vs Intact group.
[c]TAL disrupted group vs TAL + LL disrupted group.

Table 2 Motion of C1–C2 segment under 0–150 N loading (°, $n=6$)

Loading	*10 N*	*30 N*	*50 N*	*70 N*	*90 N*	*100 N*	*150 N*
Flexion							
Intact	3.65±0.66	5.52±0.72	6.47±0.76	7.32±0.76	8.73±0.85	9.68±0.92	12.55±0.81
TAL	5.65±0.68	6.28±0.69	6.87±0.68	8.00±0.70	9.78±0.75	12.53±0.98	16.07±0.91
TAL+LL	9.98±1.03	12.37±1.00	14.20±1.34	16.37±1.15	17.60±1.20	18.55±1.18	22.13±1.00
P^a	0.001	0.124	0.486	0.204	0.076	<0.001	<0.001
P^b	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
P^c	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Extension							
Intact	5.58±1.00	7.23±1.08	8.27±1.02	9.45±1.06	11.03± 1.11	12.07±1.29	13.95±1.24
TAL	6.97±1.16	7.83±0.98	9.03±1.00	10.50±1.01	12.22±0.95	13.89 ±1.28	16.39±1.38
TAL+LL	12.0 0± 1.10	14.20±1.10	16.15±1.09	17.72±1.21	18.95±1.34	19.83±1.28	23.00±1.32
P^a	0.044	0.344	0.220	0.119	0.093	0.027	0.006
P^b	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
P^c	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Left bending							
Intact	2.85±0.53	3.75±0.54	4.62±0.62	5.42±0.79	6.00±0.74	6.40±0.71	7.37±0.69
TAL	2.97±0.58	3.88±0.53	4.91±0.62	5.75±0.66	6.64±0.65	7.28±0.68	8.40±0.61
TAL+LL	5.15±0.74	6.07±0.68	6.97±0.74	7.90±0.75	9.08±0.82	10.0±0.89	11.45±0.73
P^a	0.734	0.708	0.458	0.446	0.154	0.064	0.018
P^b	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
P^c	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Right bending							
Intact	3.25±0.53	4.15±0.51	5.05±0.62	5.82±0.71	6.48±0.75	6.88±0.69	8.63±0.56
TAL	3.28±0.53	4.17±0.54	5.07±0.52	5.92±0.62	6.79±0.66	7.82±0.75	9.67±0.65
TAL+LL	565±0.90	6.55±0.88	7.48±0.82	8.18±0.99	9.38±0.74	10.47±0.99	12.08±0.92
P^a	0.944	0.963	0.953	0.826	0.466	0.067	0.026
P^b	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
P^c	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Rotation							
Intact	28.93±2.51	34.25±2.66	39.30±2.65	43.38±2.70	46.98±2.50	49.83±2.99	56.35±2.79
TAL	31.52±2.78	36.97±2.40	40.23±2.60	45.07±2.84	50.15±2.51	52.47±2.38	61.53±2.85
TAL+LL	40.82±2.66	46.95±2.97	53.62±2.60	58.25±2.47	63.33±2.97	68.87±3.13	77.38±3.17
P^a	0.112	0.101	0.546	0.293	0.058	0.131	0.008
P^b	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
P^c	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Abbreviations: LL, longitudinal ligament; TAL, transverse atlantal ligament.
[a]TAL disrupted group vs intact group.
[b]TAL+LL disrupted group vs intact group.
[c]TAL disrupted group vs TAL+ LL disrupted group.

Range of three-dimensional movement for C1–C2

The range of three-dimensional motion (flexion, extension, left and right bending, and rotation) increased after TAL was transected and it was further increased while the LL was also resected (Table 2). There were significant differences in flexion and extension between TAL and intact groups while the loading was 10 N or ⩾100 N ($P<0.05$), but not while the loading was 10–100 N. A significant difference was only observed between the TAL and intact groups in left and right lateral bending, and axial rotation when the loading was increased to 150 N. TAL+LL group presented significantly more range of motion compared with TAL or intact group under the same loading in flexion, extension, left and right lateral bending, and axial rotation ($P<0.001$; Table 2).

DISCUSSION

Unlike the lower cervical spine (C2–C7), the UCS (C0, C1 and C2) does not contain intervertebral discs and the ligament complex is the main structure to maintain the atlantoaxial stability. The ligament complex comprises TAL and LL. Traditionally, the TAL has been considered to be the one with the maximum volume, thickness and strength, and thus has the most important roles in maintaining atlantoaxial stability.[20–22] The TAL is connected to the lateral masses of atlas and works together with anterior arch to restrict odontoid and prevent anterior dislocation of the atlas. For unstable atlas fracture that associates with the TAL injuries, most clinicians advocate C1–C2 or C0–C2 fusion for fear of the TAL rupture and C1-sagittal plane instability. However, C0–C2 and C1–C2 fusion sacrifices the functions of UCS, which subsequently greatly affects the quality of life for patients.[8–10,23]

Haus and Harris[20] apply a cervical collar to successfully treat an unstable Jefferson fracture and consider that the intact alar ligaments and/or portions of facet capsules, as well as scarring of the avulsed TAL are sufficient to maintain the stability without conducting C1–C2 fusion. Nevertheless, the conservative treatment is difficult to maintain the C1 lateral mass stability, leading to reduction loss and reduced tension of the LL. Subsequently, several researchers have adopted direct C1 fixation for treatment of unstable atlas fracture and obtained good outcomes.[11,12] In 2011, we proposed the 'buoy hypothesis' to explain the importance to recovery the LL height and tension in maintaining UCS stability.[14] When the TAL is ruptured due to the lateral mass displacement, the atlas becomes unstable, but LL still remains intact because of loss of C0–C2 height (similar to the rope connecting the buoy to the water bottom will become lax, but not broken with the drop of water level), thus LL still has the capacities to provide a second line of the defense in preventing anterior displacement of the atlas under physiological loading. However, TAL rupture leads to concomitant failure of the vertical ligamentous tension, weakening the function of the vertical ligaments in the long-term and making the vertical ligaments lack of the capacities to maintain UCS stability. Therefore, it is essential to restore the C0–C2 height and recreate LL tension by fixation of the displaced C1 lateral mass using screws (similar to the rope connecting the buoy to the water bottom will get stable with the rise of water level). In this study, we tried to validate the roles of LLs in stabilizing atlas by sequentially disrupting TAL and LL. As expected, tension between C0 and C2 still remained when only the TAL was transected.

Previous studies point out that moment of 1.53 Nm can bring in the maximum range of physiological motion,[24] not only reflecting the changes in three-dimensional movement, but also imposing little damage on the specimens. Koller *et al.*[22] regard that 100 N is the maximum physiological loading for atlas. These parameters were adopted in our experiment to evaluate the changes in the stability of atlas. As anticipated, the results showed that the stability of atlas declined after the TAL was transected. In the beginning of loading (10 N), TAL group presented a significantly larger ADI and range of motion compared with the intact group. We speculate that the TAL has certain initial tension, which guarantees the coordinated motion of C1–C2. When the TAL is disrupted, initial tension disappears, leading to uncoordinated motion and even lateral displacement. However, no significant difference was observed when the loading was in the range of 10–100 N (mid-term loading), which may result from the reason that the LL starts to function during this stage. As the loading was $\geqslant$100 N that has exceeded the physiological loading, a significant difference appeared again, suggesting that LL is not sufficient to maintain the stability anymore. Although both TAL and LL were disrupted, atlantoaxial instability occurred with significantly increased ranges of motion compared with TAL or intact group in any loading.

ADI is a generally accepted indicator for assessing the atlantoaxial stability. When the ADI is >3 mm on flexion radiographs, the atlantoaxial instability is considered to be present.[25,26] In our study, the ADI was 1.95 mm in the intact group, 2.90 mm in TAL group and 4.32 mm in TAL + LL group under 100 N loading, suggesting that the LL is sufficient for atlantoaxial stability under physiological loading. The calculated ADI may be consistent with the actual measurement value by imaging technology. However, our measured values are smaller than that by Koller *et al.*,[22] which may result from different ways of loading. They adopt horizontal loading from back to forth, but we used eccentric loading, which is more close to the physiological condition. The eccentric force may cause tilt and rotation of C1 and thus generates relatively small ADI values.

Similarly, the TAL group showed no significant differences in lateral bending and axial rotation under physiological loading compared with the intact group. This may be explained by the fact that the alar ligament has a more important role in lateral bending, rotation and lateral subluxation.[27,28]

However, there are still some limitations in our study: (1) although our results provide a theoretical basis for direct C1 reduction and fixation for physiological restorative treatment of unstable atlas fractures, this study does not guide unstable atlas fractures treatment because this treatment strategy is not necessarily suitable for all types of atlas fractures. The indication for this method is still undefined. (2) It is unclear to select the anterior or posterior approach for reduction of C1. Considering the LL functions in flexion while anterior arch of the atlas serves in extension, we suggest that an anterior surgical reconstruction of the anterior arch should be taken into consideration when the anterior arch double fractures with free bones. (3) Each specimen was tested repeatedly because of small number of specimens, loading/unloading cycle was not adopted in experiment and ADI was not measured directly. These procedures may lead to some deviations between the testing results and actual value under the actual stress. Therefore, more studies, such as construction of finite element models are necessary to further verify this hypothesis.

DATA ARCHIVING

There were no data to deposit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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