Biomechanical behaviour of tension-band-reconstruction titanium plate in open-door laminoplasty: a study based on finite element analysis

Hanpeng Xu1†, Jincheng Wu1†, Hongru Xie1†, Wangqiang Wen2, Haoxiang Xu3, Juan Du4* and Jun Miao5*

Abstract

Objective: To investigate and evaluate the biomechanical behaviour of tension-band-reconstruction (TBR) and ordinary titanium plates in open-door laminoplasty by finite element (FE) analysis.

Methods: TBR titanium plate and ordinary titanium plate were implanted into a validated finite element model of healthy adult cervical vertebrae. Among them, 5 ordinary titanium plate were used in model A, 2 TBR titanium plates and 3 ordinary titanium plates were used in model B, and 5 TBR titanium plates were used in model C. The same loading conditions was applied identically to all models. Range of motion (ROM) of the vertebral body, stress distribution of the titanium plate and intradiscal pressure (IDP) were compared in flexion, extension, lateral bending and rotation.

Results: The ROM of model B and C was similar in flexion and extension, and both were smaller than that of model A. The highest von Mises stress in the titanium plate appears is in model C. The IDP in C2/3 was significantly higher than that in other segments in flexion. There was no significant difference in IDP among three models in left lateral bending and left axial rotation.

Conclusion: Application of TBR titanium plate in open-door laminoplasty can reduced ROM in flexion, extension and axial rotation of the cervical vertebrae. But the increase of stress in TBR titanium plate could lead to higher risk of adverse events such as titanium plate deformation. Moreover, compared with complete TBR titanium plate, the combination of TBR titanium plate for C3 and C7 with ordinary titanium plate for the other vertebrae largely reduce the stress of the titanium plates by ensuring stability. The proposed FE model (C2-T1) exhibits a great potential in evaluating biomechanical behaviour of TBR titanium plate for open-door laminoplasty.

Keywords: Cervical spine, Open-door laminoplasty, Titanium plate, Finite element analysis

Introduction

Cervical spondylotic myelopathy (CSM) is a degenerative spinal disease with clinical symptoms such as limb weakness and numbness [1]. Open-door laminoplasty is currently recognized as a classic surgical treatment for severe multisegment cervical spinal stenosis. In recent years, micro-titanium plate fixation has become widely recognized and used in Open-door laminoplasty [2]. Excellent biocompatibility, biomechanical...
performance, and most importantly simple operation procedure have been proofed by many surgeons [3].

In C3-C7 open-door laminoplasty, to fully expose the upper edge of the C3 lamina, the cervical semispinous muscle should be partially dissected at the C2 spinous process, and the spinous process of the operative segment together with the interspinous ligament (ISL) will be completely removed. The posterior cervical muscle-ligament complex (MLC) is an important structure for stability of the cervical vertebrae and mainly includes the spinous process, ISL and muscle tissue attached to the spinous process [4, 5]. When the MLC is seriously damaged, patients will experience symptoms of cervical weakness or even difficulty supporting the head in the short term; in the long term, this change is likely to lead to changes in the cervical curvature and atrophy of the posterior cervical muscles. Lin et al. [6] compared 53 patients with preservation of MLC and 37 patients with traditional open-door laminoplasty, and concluded that preserving MLC plays an important role in maintaining sagittal balance of cervical vertebra. Studies have shown that retaining one side of the MLC can reduce the incidence of axial symptoms (AS) [7]. Therefore, many studies continued to try to improve open-door laminoplasty.

Cheng et al. [8] removed the top of the C2 spinous process together with the attached muscles and then refixed the truncated tendon–bone structure to the spinous process after opening the lower lamina. This method provides greater strength than the method of fixing the muscle to the C2 spinous process with silk thread. Takeuchi et al. [9] applied C3 laminectomy combined with C4–7 open-door laminoplasty to eliminate the influence of the superimposed laminae without affecting the effect of spinal cord decompression. To preserve the C7 spinous process, Konig et al. [10] applied titanium plates for support and fixation on both sides of the lamina to reconstruct the integrity of the spinous process after laminectomy and decompression of the spinal cord and create conditions for muscle attachment.

Although retaining the C3 spinous process increases the attachment point, opening too few segments will limit the spinal cord decompression that can be achieved, and a new site of compression may easily form at the posterior and inferior border of the C3 lamina. Removal of the C3 lamina can avoid the dissection of muscle from the superior spinous process, but the integrity of the spinal canal is lost, and postoperative scar formation can lead to compression again. To the author’s knowledges, a simple operation method with decent postoperative effect is still under investigation.

A tension-band-reconstruction (TBR) titanium plate for open-door laminoplasty was introduced for the first time (Fig. 1). The novel titanium plate has an innovative structure. The length of the titanium plate on the laminar side is appropriately extended, and an additional screw hole (three holes in total) is present at the distal end. During the operation, only the two inner holes are used for laminar fixation, while the remaining hole is used to suture the dissected muscle. This new type of titanium plate not only increases the stability of the door structure but also provides an attachment point for extensor reconstruction. From our previous clinical observation, the cross-sectional area of posterior cervical muscles was not significantly reduced after modified titanium microplate reconstruction, and the incidence of axial symptoms was 11.5%, which was lower than ordinary titanium plate (16.7%) [11]. However, the biomechanical behaviour of the new designed titanium plate, which can be the potential reason for this phenomenon is still unclear.

The aim of this study is to investigate the biomechanical behaviour of TBR titanium plate in open-door laminoplasty, generate reliable data for different spinal implants, and provide a potential tool to evaluate spinal implants.

Materials and methods
FE model of healthy adult cervical vertebrae (C2-T1)
In this study, a FE model of cervical spine (C2-T1) was build based on a healthy 26-year-old male volunteer.
The absence of spinal lesions was confirmed on X-ray with no history of trauma or fracture. The volunteer was recruited from Tianjin Hospital in November 2020 and signed the volunteer’s informed consent form. The study was approved by the Ethics Committee of Tianjin Hospital. We used a 64-slice spiral CT scanner (Siemens, Erlangen, Germany) to obtain DICOM images of the C2-T1 vertebrae of the subject. The DICOM images were then imported into Mimics 20.0 (Materialise, Inc., Leuven, Belgium) to create a 3D vertebral surface model of C2-T1 and generate an STL file. Then, 3-matic 12.0 (Materialise, Inc.) was used to construct the posterior structures, intervertebral discs, nucleus pulposus and facet joints [12]. After these data were imported into the reverse engineering software Geomagic Studio 12.0 (Geomagic, Inc., USA) and materialized using smoothing, construction patches and grilles. Bones, discs and ligaments was meshed using Hypermesh2017 (Altair Engineering, Troy, Michigan, USA). Finally, the model was imported into Abaqus 2020 (Abaqus, Inc., USA) for FE analysis [13]. Tetrahedral mesh was used on the vertebral body, and hexahedral mesh was used on the intervertebral disc (Fig. 2). The cortical bone, facet joint surface and cartilage endplate were meshed by shell elements, with thickness of 1.5 mm, 0.2 mm and 0.4 mm [14], respectively. The intervertebral disc was divided into the nucleus pulposus and the annulus fibrosus, with the nucleus pulposus accounting for 1/3 of the intervertebral volume [15]. The annulus fibrosus consists of an annulus fibrosus matrix and fibres. The inclination of the annular fibres relative to the horizontal plane is between 15° and 45°. The model simulated five ligaments: the anterior longitudinal ligament (ALL), posterior longitudinal ligament (PLL), ligamentum flavum (LF), interspinous ligament (ISL) and articular capsule ligament (CL). The annulus fibrosus and all intervertebral ligaments were modelled as tension-only truss elements. The contact between facet joints was designated as frictionless sliding [16]. The material properties used in the FE model (Table 1) were derived from the relevant literature [17–19].

Model validation
The maximum von Mises stress of the model with element size of 1 mm, 1.5 mm and 2 mm is calculated and compared with the model with element size of 0.5 mm. When the difference is less than 5%, the element is considered to be convergent. In terms of the load and calculation accuracy, the element size of 1 mm is selected. In this case, the percentage error is 4.60%. The complete C2-T1 FE model had a total of 514,952 elements. Boundary conditions were applied to the lower surface of T1, and six degrees of freedom were fixed. The odontoid surface of C2 was coupled with the reference point at the upper 2 mm. A torque of 2.0 N·m was applied at this reference point to simulate flexion, extension, lateral bending and rotation of the cervical vertebrae. The range of motion (ROM) of each segment was measured and compared with previously reported results [20–23].
C3-C7 laminectomy models

**FE model of all ordinary titanium plates (model A)**

In 3-matic, the spinous processes and laminae of C3-C7 of the verified normal adult cervical vertebral model were removed and opened, respectively. The operation to remove the spinous process is designed not to impede the degree of opening the door. After rematerialization, titanium plates and screws were implanted between the lateral mass and the lamina in Hypermesh; at the same time, the ISL and the LF were removed selectively. This completed the C2-T1 FE model of laminectomy (C3-C7) [7, 24], as shown in Fig. 3.

**FE model of tension band titanium plate reconstruction for C3 and C7 (model B)**

The TBR titanium plate based on the ordinary titanium plate features a long end loop; after the titanium plate was fixed behind the lamina and lateral mass with screws, the dissected cervical semispinalis muscle and multifidus muscle were sutured to the end loop of the C3 titanium plate, as shown in Fig. 3. During the operation, the cranial and caudal levels of the open-door segment can be reconstructed with a TBR titanium plate to achieve the effect of MLC reconstruction and increase stability of the cervical spine after the operation.

Using the FE model mentioned in the previous section, the ordinary titanium plates at C3 and C7 were replaced by TBR titanium plates. These plates were fixed with screws, and the end loops of the two titanium plates were connected by T3D4 elements and assigned muscle properties. This completed the FE model of laminectomy with partial TBR titanium plate [25], as shown in Fig. 3.

**FE model of all tension band titanium plates (model C)**

In open-door laminoplasty, TBR titanium plates can also be used at each level of the operative segment. After the titanium plate was fixed, the dissected cervical semispinalis muscle and multifid muscle were sutured to the end loop of the C3 titanium plate, and the rest of the posterior cervical muscle group was sutured to the end loop of the other titanium plate.

All the ordinary titanium plates in the FE model above were replaced with TBR titanium plates, as shown in Fig. 3, which were connected one by one with a T3D4 element and assigned muscle properties. After the screws and titanium plates were attached to the vertebral bodies,
the FE model of open-door laminoplasty with five TBR titanium plates was completed.

**Biomechanical performance analysis**
We applied the same load to the above three models and used a moment of 2.0 N·m to simulate the flexion, extension, lateral bending and axial rotation of cervical vertebrae. According to the simulation in ABAQUS, the ROM of each cervical segment and the stress distribution contour of each titanium plate were recorded. Because only one subject was modelled, there was no statistical analysis in this study.

**Results**

**Validation of the healthy adult C2-T1 FE model**
ROM was calculated for each cervical segment of the FE model in six directions in flexion, extension, lateral bending and rotation with a 2.0 N·m moment (Fig. 4). Compared with previous in vitro experiments and FE studies, ROM obtained from our model were in the same range of those reported by Wheeldon et al. [22], Yoganandan et al. [26] for all flexion, extension and lateral bending. In rotation, the intact model predicted motions that were comparable to the experimental data for the majority of loading modes [18, 21, 27, 28]. Thus, a reliable healthy adult C2-T1 FE model was obtained in accordance with human physiological conditions.

**Biomechanical behaviour of TBR titanium plate**

**ROM of the cervical spine**
At the same moment, the overall ROM in model B and C with TBR titanium plate in flexion was smaller than that in model A, and the ROM in model B was the lowest for all three types of models. (Fig. 5). The ROM in model B in flexion was 35.97% lower than that in model A, while that in model C was 31.76% lower than that in model A. Similarly, three models showed the same trend in extension. The ROM in model B was 46.99% lower than that in model A, while the ROM in model C was 36.77% lower than that in model A. The ROM of the three models were 28.61°, 27.5°, and 25.92° in right lateral bending. However, both model B and C were smaller than model A in axial rotation. There was little difference in axial rotation between model B and model C.

**Stress distribution of the titanium plates**
The maximum stress in the titanium plates in the three models in each motion showed an increasing trend. Among them, the greatest increase in stress was observed in flexion and extension (Fig. 6). In flexion, the stress in model B reached 259.1 MPa, while that in model C reached 318.9 MPa. In extension, the stress in model B reached 320.7 MPa, while that in model C reached 414.2 MPa. In flexion and extension in model B, the stress of titanium plates located at C4, C5 and C6 was lower than that of plates at C3 and C7 (Fig. 7). In lateral bending, the maximum stress of the titanium plates in model C was 34% higher than that in model B, while it was 26% higher in axial rotation. The maximum von-Mises stress of each titanium plate during flexion, extension, lateral bending and rotation was presented in the Additional file 1: Appendix 1.

**Intradiscal pressure**
The intradiscal pressure (IDP) at C2/3 of model A, B and C were 1.55 MPa, 1.89 MPa, and 1.89 MPa in flexion...
While the IDPs of model B and C were smaller than that of model A at C3/4, C4/5, C5/6 and C6/7. The three models showed the same trend in extension. The corresponding IDPs at C2/3 were 0.37 MPa, 0.46 MPa, and 0.46 MPa. There is little difference among the three models in left lateral bending and left axial rotation. The IDPs of model B and C at C2/3 were higher than that of model A in right lateral bending and right axial rotation. The IDPs of model A, B and C at C2/3 in right lateral bending were 0.43 MPa, 0.84 MPa and 0.83 MPa, respectively. The IDPs of model A, B and C at C2/3 in right axial rotation were 0.46 MPa, 0.76 MPa and 0.73 MPa, respectively. The IDPs of three models during flexion, extension, lateral bending and rotation were presented in the Additional file 1: Appendix 2.
Discussion

In this study, FE models of three different combinations of titanium plates in cervical spine open-door laminoplasty were built to evaluate their biomechanical behaviour. We found TBR titanium plates yielded better stability in flexion, extension and axial rotation. Comparing with model A, the ROM of model B in flexion and extension was 35.97 and 46.99% lower; while 31.76 and 36.77% lower in model C than in model A, respectively. At the same time, the stress of the titanium plates was largely increased when too many TBR titanium plates were used. The IDP and titanium plate stress showed the same trend. The IDP of C2/3 and C7/T1 in model B and C in flexion and extension were slightly higher than that in model A, while IDP in the middle segment decreased. Thus, in model B which used a combination of
TBR titanium plates for C3 and C7 and ordinary titanium plates for the other vertebrae, showing less burden on the titanium plates, but ensure good stability and reduced the stress of the titanium plates and IDPs in the middle of the segment.

It has been widely approved that the semispinalis cervicalis is the most important extensor muscle in the posterior cervical muscles. Its proximal end mainly stops at the C2 spinous process, and the posterior extension force generated during contraction accounts for 37% of the total contraction force of the posterior cervical muscles [29]. Therefore, the mechanical stabilization device composed of cervical semispinalis muscle and C2 spinous process plays an extremely important role in maintaining the posterior tension and physiological kyphosis of the cervical spine. The results of FEA show that due to the fact that the TBR titanium plate provides an extra hole to reconstruct the muscle attachment point, the muscle separated during the operation is re-attached to C3. This increases the stability of the cervical spine in the
direction of flexion, extension and rotation analysis after open-door operation. Because the motion plane of the cervical vertebrae during lateral bending is not consistent with the direction of the reconstructed muscles, the use of TBR titanium plate has little effect on the ROM of lateral bending. The inconsistency in the ROM of three models during right lateral bending may be related to the opening angle of the lamina.

The stress distribution of titanium plate in three models shows substantial different patterns. As the new titanium plate provides muscle attachment points, the titanium plate stress rises. In model B, the stress of the titanium plates in the middle of the segment was partially transferred to the cranial and caudal ends of the segment. However, model C applied five TBR titanium plates, and the stress of the titanium plate increased significantly, which may be related to the increase of the force arm. It is worth noting that the new titanium plate has stress concentration near the newly added hole, which may lead to a negative effect on the durability of the titanium plate. Therefore, the fatigue test of the new titanium plate needs to be further studied.

The IDP of C2–3 increased significantly in the three models during flexion. This may be due to the removal of the LF in C2–3 and most of the ISL, and the lack of posterior structural stress during flexion, resulting in stress concentration in the anterior column of the vertebral body. This suggests a clinical risk of disease at this level. This study, however, simulated only a portion of the muscle, which may have magnified the phenomenon. In lateral bending and axial rotation, the inconsistency between left and right of IDP may be related to the opening direction of open-door laminoplasty.

It is particularly important to preserve or reconstruct the muscle attachment point and ligament complex in posterior cervical open-door laminoplasty [30–32]. However, every attempt to retain or reconstruct the attachment point and ligament complex may potentially increase the difficulty of opening the lamina and the complexity of the surgical operation. TBR titanium plate adopts a simple method to achieve MLC reconstruction without increasing the operative duration or intraoperative blood loss.

This study compared the biomechanical performance of different plates, which provide a non-invasively tool to evaluate their mechanical performance during human movement. However, there are still some limitations: first, follow-up promotion is still needed to be confirmed by a multicentre controlled large-sample size. In addition, we didn’t take muscle into account during validation. However, the three models are not compared with the complete model when they are compared with each other. Model B and model C used TBR titanium plate and simulated muscle, while model A did not. The comparison of the three models can show the difference between TBR titanium plate and ordinary titanium plate. And there is a lack of corroborative research in vitro to improve the simulation model and establishing finer muscle simulations. In our future research plan, in vitro biomechanical experiments will also be included. At last, the model created in this study shown a great potential in evaluating mechanical performance of different types of fixators.

**Conclusion**

In this study, a healthy adult cervical spine (C2-T1) FE model and corresponding open-door laminoplasty (C3-C7) FE models were established and used for further biomechanical analysis. FE analysis showed better stability using TBR titanium plate in open-door laminoplasty. But the increase of stress in TBR titanium plate could lead to a higher risk of adverse events such as titanium plate deformation. Compared with complete TBR titanium plate, the combination of TBR titanium plates for C3 and C7 with ordinary titanium plates for the other vertebrae largely reduce the stress of the titanium plates by ensuring stability.

**Abbreviations**

FE: Finite element; TBR titanium plate: Tension-band-reconstruction titanium plate; ROM: Ranges of motion; IDP: Intradiscal pressure; MLC: Muscle-ligament complex; ISL: Interspinous ligament.

**Supplementary Information**

The online version contains supplementary material available at https://doi.org/10.1186/s12891-022-05804-w.

**Additional file 1: Appendix1.** The maximum von stress (MPa) of the titanium plate on each segment. **Appendix2.** The intradiscal pressure (MPa) of three groups.

**Acknowledgements**

Not applicable.

**Authors' contributions**

Hanpeng Xu performed all the experiments and wrote the manuscript. Jincheng Wu and Hongru Xie participated in the collection of experimental data. Wangqiang Wen and Haoxiang Xu are responsible for image production. Jun Miao and Juan Du conceived and designed the study. The author(s) read and approved the final manuscript.

**Funding**

This work was supported by the National Natural Science Foundation of China (81472140) and the Natural Science Foundation of Tianjin City (S20ZDD484).

**Availability of data and materials**

The datasets generated and/or analyzed during the current study are not publicly available due the requirements of patent protection but are available from the corresponding author on reasonable request.
Declarations

Ethics approval and consent to participate
This study was approved by the Ethics Committee of Tianjin Hospital. All subjects signed informed consent by each patient. All clinical investigations had been conducted according to the principles expressed in the Declaration of Helsinki.

Consent for publication
Written informed consent for publication was obtained from all participants.

Competing interests
The authors declare that they have no competing interests.

Author details
1Graduate School, Tianjin Medical University, Tianjin, China. 2The First Affiliated Hospital of Hainan Medical University, Haikou, Hainan, China. 3The second people’s hospital of Hefei, Hefei, Anhui, China. 4Academy of Medical Engineering and Translational Medicine, Tianjin University, Tianjin, China. 5Department of Spine Surgery, Tianjin Hospital, Jiefangnanlu 406, Hexi District, Tianjin 300210, China.

Received: 24 June 2022 Accepted: 5 September 2022
Published online: 08 September 2022

References
1. Chen T, Zhang X, Meng F, Zhang T, Zhao Y, Yan J, et al. Open-door versus French-door Laminoplasty for patients with multisegmental cervical Spondylotic myelopathy: a systematic review and meta-analysis. World Neurosurg. 2021;155:82–93.
2. Yeh KT, Yu TC, Chen IH, Peng CH, Liu KL, Lee RP, et al. Expansive open-door laminoplasty secured with titanium miniplates is a good surgical method for multiple-level cervical stenosis. J Orthop Surg Res. 2014;9:49.
3. Rhee JM, Register B, Hamasaki T, Franklin B. Plate-only open door laminoplasty preserves the semispinalis cervicis inserted into axis. Spine (Phila Pa 1976). 2011;36(1):9–14.
4. Healy AT, Lubelski D, West JL, Mageswaran P, Colbrunn R, Mozr TE. Biomechanics of open-door laminoplasty with and without preservation of posterior structures. J Neurosurg Spine. 2016;24(5):746–51.
5. Chen C, Yang C, Yang S, Gao Y, Zhang Y, Wu X, et al. Clinical and radiographic outcomes of modified unilateral open-door Laminoplasty with posterior muscle-ligament complex preservation for cervical Spondylotic myelopathy. Spine (Phila Pa 1976). 2019;44(21):1697–704.
6. Lin S, Zhou F, Sun Y, Chen Z, Zhang F, Pan S. The severity of operative invasion to the posterior muscle-ligament complex influences cervical sagittal balance after open-door laminoplasty. Eur Spine J. 2015;24(1):127–35.
7. Hosono N, Sakaura H, Mukai Y, Fujii R, Yoshikawa H. C3-6 laminoplasty takes over C3-7 laminoplasty with significantly lower incidence of axial neck pain. Eur Spine J. 2006;15(9):1375–9.
8. Cheng Z, Chen W, Yan S, Li W, Qian S. Expansive open-door cervical laminoplasty: in situ reconstruction of extensor muscle insertion on the C2 spinous process combined with titanium miniplates internal fixation. Medicine (Baltimore). 2015;94(28):e171.
9. Takeuchi K, Yokoyama T, Aburakawa S, Saito A, Numasawa T, Iwasaki T, et al. Axial symptoms after cervical laminoplasty with C3 laminectomy compared with conventional C3-C7 laminoplasty: a modified laminoplasty preserving the semispinalis cervicis inserted into axis. Spine (Phila Pa 1976). 2005;30(22):2544–9.
10. Konig SA, Spetzger U. Modified open-door laminoplasty for the surgical treatment of cervical spondylotic myelopathy in elderly patients. Acta Neurochir. 2014;156(6):1225–30.
11. Miao J, Liu YC, Lan J, Ji JT, Han Y, Hu YC, et al. Application of modified micro titanium plate for extensor attachment point reconstruction in open-door laminoplasty. Zhonghua Yi Xue Za Zhi. 2019;99(17):1312–6.
12. OuYang P, Liu H, He X, Gao Z, Cai X, Jin Z. Biomechanical comparison of integrated fixation cage versus anterior cervical plate and cage in anterior cervical Corpectomy and fusion (ACCF): a finite element analysis. Med Sci Monit. 2019;25:1489–98.
13. Chai H, Purushothaman Y, Baiden J, Yoganandan N. Unique biomechanical signatures of Bryan, Prodisc C, and prestige LP cervical disc replacements: a finite element modelling study. Eur Spine J. 2020;29(11):2631–9.
14. Zhang Y, Li C, Li L, Sun Y, Li Z, Mei Y, et al. Design a novel integrated screw for minimally invasive atlantoaxial anterior transarticular screw fixation: a finite element analysis. J Orthop Surg Res. 2020;15(1):244.
15. Kallemsen N, Gandhi A, Kode S, Shivanna K, Smucker J, Grosland N. Validation of a C2-C7 cervical spine finite element model using specimen-specific flexibility data. Med Eng Phys. 2010;32(5):482–9.
16. Garbati D, Kim YM, Kim K, Jin YJ, Park WM. Effect of mechanical loading on heterotropic ossification in cervical total disc replacement: a three-dimensional finite element analysis. Biomech Model Mechanobiol. 2016;15(5):1191–9.
17. Mo Z, Li Q, Jia Z, Yang J, Wong DW, Fan Y. Biomechanical consideration of prosthesis selection in hybrid surgery for bi-level cervical disc degenerative diseases. Eur Spine J. 2017;26(6):1181–90.
18. Zhang QH, Teo EC, Ng HW, Lee VS. Finite element analysis of moment-rotation relationships for human cervical spine. J Biomech. 2006;39(1):189–93.
19. Ha SK. Finite element modeling of multi-level cervical spinal segments (C3-C6) and biomechanical analysis of an elastomer-type prosthetic disc. Med Eng Phys. 2006;28(6):534–41.
20. Zhang QH, Teo EC, Ng HW. Development and validation of a CO-C7 FE model for biomechanical study. J Biomech Eng. 2005;127(5):729–35.
21. Panjabi MM, Crisco JJ, Yasavas A, Oda T, Cholewicki J, Nibu K, et al. Mechanical properties of the human cervical spine as shown by three-dimensional load-displacement curves. Spine (Phila Pa 1976). 2001;26(24):2692–700.
22. Wheeldon JA, Pintar FA, Knoblos S, Yoganandan N. Experimental flexion/extension data corridors for validation of finite element models of the young, normal cervical spine. J Biomech. 2006;39(2):375–80.
23. Moroney SP, Schultz AB, Miller JA, Andersson GB. Load-displacement properties of lower cervical spine motion segments. J Biomech. 1998;31(9):769–79.
24. Park AE, Heiber JG. Cervical laminoplasty: use of a novel titanium plate to maintain canal expansion—surgical technique. J Spinal Disord Tech. 2004;17(4):265–71.
25. Sadegh AM, Tchako A. Vertebral stress of a cervical spine model under dynamic load. Technol Health Care. 2000;8(2):143–54.
26. Yoganandan N, Pintar FA, Stemer BD, Wolfa CE, Shender BS, Paskoff G. Level-dependent coronal and axial moment-rotation corridors of degeneration-free cervical spines in lateral flexion. J Bone Joint Surg Am. 2007;89(5):1066–74.
27. Nightingale RW, Carol CV, Ottaviano D, Luck JF, Tran L, Prange M, et al. Flexion and extension structural properties and strengths for male cervical spine segments. J Biomech. 2007;40(3):535–42.
28. Liu Y, Lewis G. Influence of surgical treatment for disc degeneration disease at C5-C6 on changes in some biomechanical parameters of the cervical spine. Med Eng Phys. 2010;32(6):595–603.
29. Vasavada AN, Li S, Delp SL. Influence of muscle morphology and moment arms on the moment-generating capacity of human neck muscles. Spine (Phila Pa 1976). 1998;23(4):412–22.
30. Barbieri C, Molina M, Ponce I, Tothova M, Cattinelli I, Iton TJ, et al. An international observational study suggests that artificial intelligence for clinical decision support optimizes anemia management in hemodialysis patients. Kidney Int. 2016;90(2):422–9.
31. Secer HI, Harman F, Aytar MH, Kahraman S. Open-door laminoplasty with preservation of muscle attachments of C2 and C7 for cervical Spondylotic myelopathy: retrospective study. Turk Neurosurg. 2018;28(2):257–62.
32. Riew KD, Raich AL, Dettori JR, Heller JG. Neck pain following cervical laminoplasty: does preservation of the C2 muscle attachments and/or C7 matter? Evid Based Spine Care J. 2013;4(1):42–53.

Publisher’s Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.