Journal of Al-Azhar University Engineering Sector

Vol. 19, No. 70, January 2024, 80 - 87

DEVELOPMENT AND VALIDATION OF A FINITE ELEMENT MODEL FOR C2-C3 CERVICAL SPINE: ESTIMATING RANGE OF MOTIONS

K. Hussein [1,*], M. Elsayeh[2], M. Habib[1], N. Fatahalla[1]

[1] Department of Mechanical Engineering, Al-Azhar University, Cairo, Egypt
[2] Department Systems and Biomedical Engineering, Cairo Universit Cairo, Egypt
***Correspondence:** khalid.alolaa@gmail.com

Citation:

K. Hussein, M. Elsayeh, M. Habib and N. Fatahalla, " Development and Validation of A Finite Element Model For C2-C3 Cervical Spine: Estimating Range Of Motions ", Journal of Al-Azhar University Engineering Sector, vol. 19, pp. 80 - 87, 2024.

Received: 23 August 2023

Revised: 1 October 2023

Accepted: 8 October 2023

DOI:10.21608/auej.2023.240114.1435

ABSTRACT

In orthopedic surgery, Finite element analysis (FEA) is a very useful tool for the surgeon to predict the behaviour of different fixation systems of cervical vertebrae and cages implantation before surgery. The objective of this work is to establish the 3D re-construction, modelling and examine the validation of an intact C2-C3 level of cervical vertebrae in finite element (FE) software with respect to Range of Motions (ROMs). 3D re-construction of an intact C2-C3 cervical vertebrae was modeled and imported to ANSYS 2023 R1 STUDENT EDITION software. Ligaments are defined as rod connection. The 3D model then meshed with quadratic order of tetrahedron elements. The results showed that the Range of Motion of our model for flexion, extension, lateral bending right and axial rotation right is validated. Validation of the cervical vertebrae 3D model is an initial step that must be made before any study is carried out on the FE model. This validate model is going to be very helpful to evaluate the outcomes of different fixation systems of cervical vertebrae and cages implantation before surgeries.

KEYWORDS: intervertebral disc biomechanics, Cervical spine model, range of motion, Finite Element Analysis.

تطوير والتحقق من نمذجة الفقرتين C2-C3 من الفقرات العنقية : تقدير نطاق الحركات

خالد محمد حسين[1,*]، محمد محمود السايح [2]، محمد أحمد متولي حبيب [1]، نبيل كمال فتح الله [1]

[1] قسم الهندسة الميكانيكية – جامعة الأزهر - القاهرة – مصر
[2] قسم الأنظمة والهندسة الحيوية – جامعة القاهرة – القاهرة – مصر
***البريد الالكتروني للباحث الرئيسي :** khalid.alolaa@gmail.com

الملخص العربي

في جراحة العظام، تعد تحليل النمذجة (FEA) أداة مفيدة جدًا للجراح للتنبؤ بسلوك أنظمة التثبيت المختلفة للفقرات العنقية وزرع الأقفاص قبل الجراحة. الهدف من هذا العمل هو إعادة تطوير بناء ثلاثية الأبعاد ونمذجة وفحص التحقق من صحة مستوى C2-C3 السليم للفقرات العنقية في برنامج النمذجة (FE) فيما يتعلق بنطاق الحركات (ROMs). تم تصميم نموذج إعادة بناء ثلاثي الأبعاد للفقرات العنقية C2-C3 السليمة وادخالها

إلى برنامج ANSYS 2023 R1 STUDENT EDITION . تم تعريف تثبيت الأربطة على أنها قضبان اسطوانية. ثم تم دمج النموذج ثلاثي الأبعاد بترتيب تربيعي لعناصر رباعية السطوح. أظهرت النتائج أن مدى الحركة لنموذجنا للانثناء والبسط والانحناء الجانبي لليمين والدوران المحوري لليمين تم التحقق منه. يعد التحقق من صحة النموذج ثلاثي الأبعاد للفقرات العنقية خطوة أولية يجب إجراؤها قبل إجراء أي دراسة على النمذجة (FE). يكون نموذج التحقق هذا مفيدًا جدًا لتقييم نتائج أنظمة التثبيت المختلفة للفقرات العنقية والأقفاص قبل العمليات الجراحية.

الكلمات المفتاحية: الميكانيكا الحيوية للغضروف الفقري ، نمذجة الفقرات العنقية ، نطاق الحركة ، النمذجة.

1. INTRODUCTION

Intervertebral disc diseases of cervical vertebrae such as stenosis, herniation, deformity, trauma, degenerative disc disease and spondylolisthesis are treated by surgical procedures when conservative therapy failed [1, 2]. Discectomy [3], Laminectomy [2, 4-6], Total disc replacement [7- 9] and spinal fusion are the main surgical procedures employed.

Spinal fusion is the most common surgical procedure used. In this procedure, the disc is totally removed and placing instead of it a natural bone graft, autograft or allograft, or synthetic cage. Cage is usually made in a box shape with a cavity in its core so that autogenous bone, Allograft bone or synthetic bone [10] can be placed inside the cage to be act as a fused material between the vertebrae [11,12]. Currently, titanium (Ti) alloys and Poly-ether-ether-ketone (PEEK) are the most common materials used as a synthetic cage in cervical spine operations [13 - 17].

In orthopedic surgery, Finite element analysis (FEA) is a very useful tool for the surgeon to test different fixation systems of cervical vertebrae, i.e., pedicular screws, implanted cages compared with the dynamic ones. [18]. Additionally, FEA models help to find the intervertebral disc mechanics, injury mechanism and contribute to the diagnosis of cervical spine problems and treatment methodologies [19]. However, the results of FEA cannot be considered until the 3D model of the cervical vertebrae is validated. Validation of the 3D model of cervical vertebrae is occurred by comparing the ROMs of the 3D model with the ROM of intact cervical that obtained from in-vitro study [20, 21].

The objective of this study is to model an intact cervical vertebrae C2-C3 motion segment and investigate its validation by comparing the ROMs for the flexion, extension, lateral bending right, axial rotation right using FEA with the corresponding values in in-vitro studies.

2. MATERIALS AND METHODS

3D models of intact C2-C3 cervical vertebrae were constructed to simulate their mechanical behavior and evaluate the stresses applied on them.

2.1. 3D construction model of the C2-C3 cervical vertebrae

C2-C3 Cervical vertebrae model is downloaded from public on-line resource [31]. It was stated in the on-line resource that the 3D model of the spine is taken from male cadaver. The spine of the cadaver was CT-scanned and the resulted CT slices are converted to 3D construction by using mimics software. The model was suffered from geometry imperfections, such as boundary separation, unspecified faces, lost faces, and the presence of gabs. All these geometrical imperfections were repaired by importing the model into ANSYS space claim software and applying stitch, gaps, and missing faces commands. The surfaces in the model were connected and to analyze more specific portions of the model independently, faces should be segmented. Split command was used to segment different faces in the vertebra. To ensure successful meshing do not attempt to merge faces in any vertebra. The bony structure of C2-C3 cervical vertebrae bodies were modeled to be composed of cortical, cancellous, superior endplate and inferior endplate. Whereas the intervertebral disc was modeled to consist of annulus fibrosus, nucleus pulposus, superior cartilage and inferior cartilage endplates, **Fig.1**.

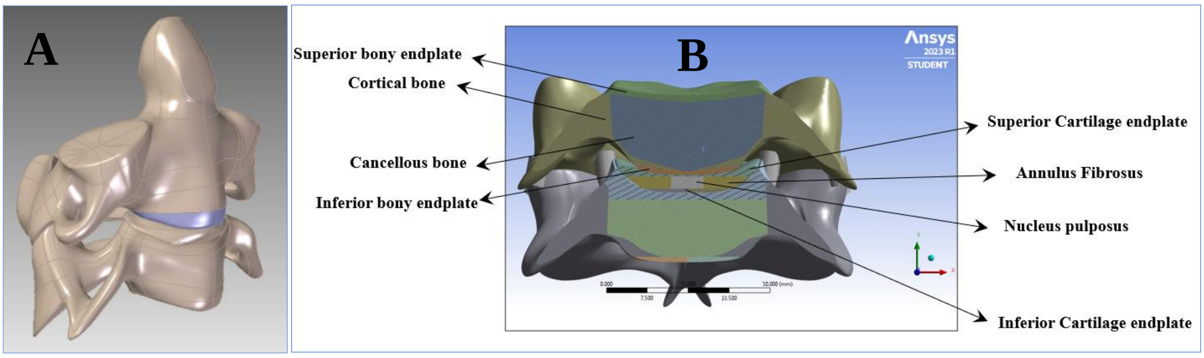

Fig. 1 3D model of C2-C3 vertebrae A) unsegmented model B) segmented model.

2.2 Finite element analysis (FEA) model establishment

3D model of C2-C3 cervical vertebrae after modelling was imported to ANSYS 2023 R1 STUDENT EDITION for meshing and FEA analysis. Tetrahedron mesh element with quadratic order was used. The element mesh size for FE model was 1.9 mm and the total elements of the model were 49786. Six major ligaments are included in the model at corresponding anatomical positions. These ligaments are anterior (ALL), posterior (PLL), flavum (LF), capsular (CL), spinous (SL), and interspinous (ISL) ligaments; **Fig. 2**. The ligaments are defined as rod connections. The material properties of bony structure of cervical vertebrae and interverbal disc are summarized in **Table 1**. Whereas the material properties of ligaments are listed in **Table 2**. In this study, to replicate the actual behavior of ligament tension only link elements were considered. To approximate anatomical and physiological properties of the facet joints, our model considered that the contact type is defined as no separation contact. Other adjacent parts were defined as bonded contact.

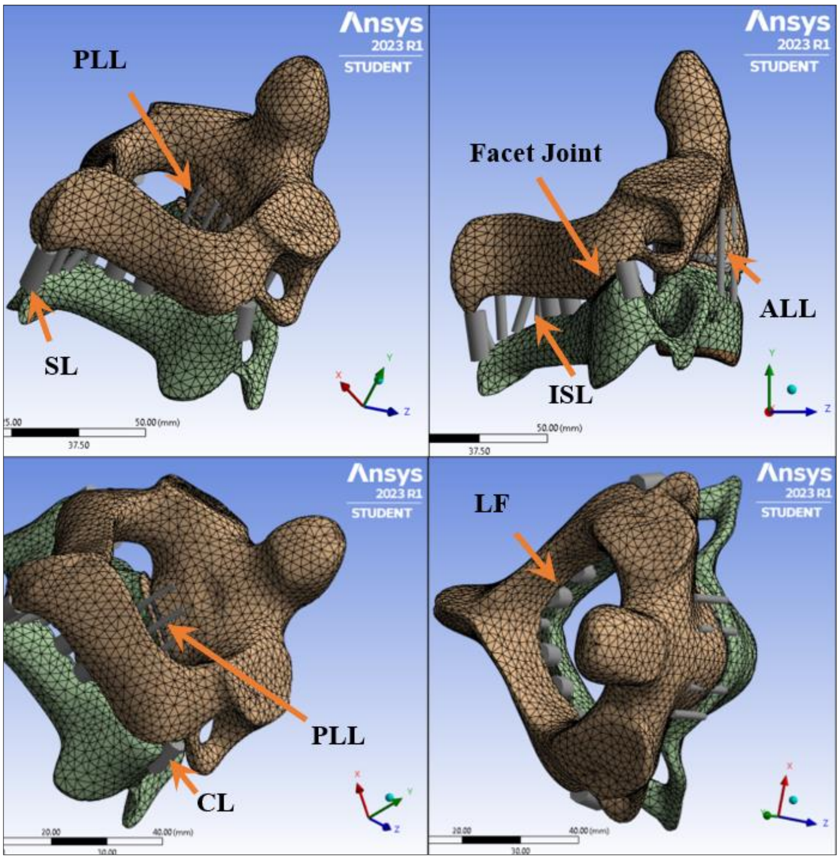

Fig. 2 Ligaments positions.

Table 1 Materials properties of bony structure of cervical vertebrae and intervertebral disc

	Component	Element type	Young's Modulus (MPa)	Poisson's ratio	Reference
Bony Structures	Cortical bone	Solid	**12000**	**0.3**	[22]
	Cancellous bone		**450**	**0.3**	[22]
	Superior bony endplate		**500**	**0.45**	[22]
	Inferior bony endplate		**500**	**0.45**	[22]
Intervertebral Disc	Annulus Fibrosus	Solid	**4.2**	**0.3**	[22]
	Nucleus pulposus		**3.4**	**0.45**	[22]
	Superior cartilage endplate		**2**	**0.45**	[22]
	Inferior cartilage endplate		**2**	**0.45**	[22]

Table 2 table properties of ligaments of C2-C3 cervical vertebrae

	Component	Element type	Young's Modulus (MPa)	Poisson's ratio	Cross Sectional area (mm^2)	Reference
Ligaments	ALL	Rod (tension only)	15	0.3	6.1	[23]
	PLL		10		5.4	[23]
	LF		5		50.1	[23]
	CL		10		46.6	[23]
	SL		1		13.1	[23]
	ISL		4		13.1	[23]

2.3. Boundary conditions and loadings

Static force analysis was performed by applying 1.0 Nm of flexion, extension, and lateral bending moments with 15 N of axial compression applied on the superior to C2. The boundary condition was simulated by fixing the inferior surface of the C3 vertebra under constraint of different degrees of freedom. The validity of the FE model was verified by comparing the predicted data with the results reported in the literature.

2.4. Calculation of range of motion

Vector dot product is the tool used to calculate the range of motion for any physiological motion. The following steps shall be followed to calculate the ROMs:

1- Assign two nodes at the outer boundary of the vertebra. These nodes should be in the plane of rotation.
2- Get the cartesian coordinate of each node from the 3D software
[Initial Nodes = (Y_{1i}, Z_{1i}) & (Y_{2i}, Z_{2i})]
3- Get the displacement values of each node from the output result of FE software.
4- Get the cartesian coordinates of each node after displacement
[Displacement Nodes = (Y_{1d}, Z_{1d}) & (Y_{2d}, Z_{2d})]
5- Calculate the magnitude value of each vector
$M_{vec1} = ((Y_{1i} - Y_{2i})^{\wedge}2 + (Z_{1i} - Z_{2i})^{\wedge}2)^{\wedge} 0.5$
$M_{vec2} = ((Y_{1d} - Y_{2d})^{\wedge}2 + (Z_{1d} - Z_{2d})^{\wedge}2)^{\wedge} 0.5$
6- From the cartesian coordinates before displacement, assign vec1 = (($Y_{1i} - Y_{2i}$), ($Z_{1i} - Z_{2i}$))
7- From the cartesian coordinates After displacement, assign vec2 = (($Y_{1d} - Y_{2d}$), ($Z_{1d} - Z_{2d}$))
8- The rotational angle = (M_{vec1} * M_{vec2}) / (**l** vec1**l** * **l** vec2**l**)

3. RESULT

FE model validation of the intact C2–C3 cervical vertebrae was analyzed under static loading condition and the estimated ROMs were compared with the results of the in vitro studies; **Fig. 3**. The ROMs of our FE model are 3.002, 3.7, 7.98 and 3.37 degree for flexion, extension, lateral bending right and axial rotation right respectively. The corresponding physiological motion of the model is shown in **Fig.4**.

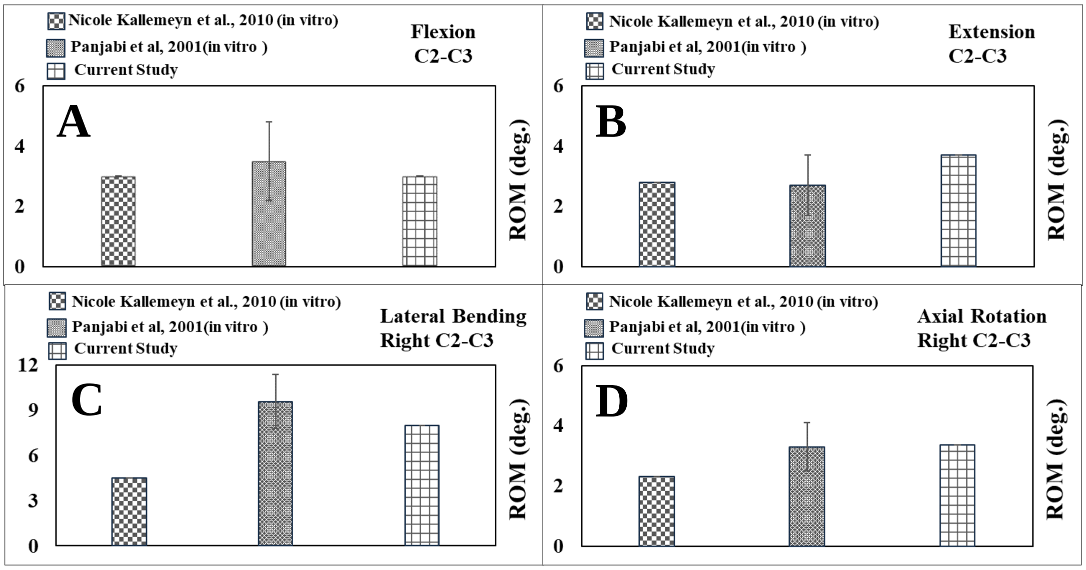

Fig. 3 Estimated ROMs is compared to experimental in-vitro studies A) Flexion B) Extension C) Lateral Bending Right D) Axial Rotation Right.

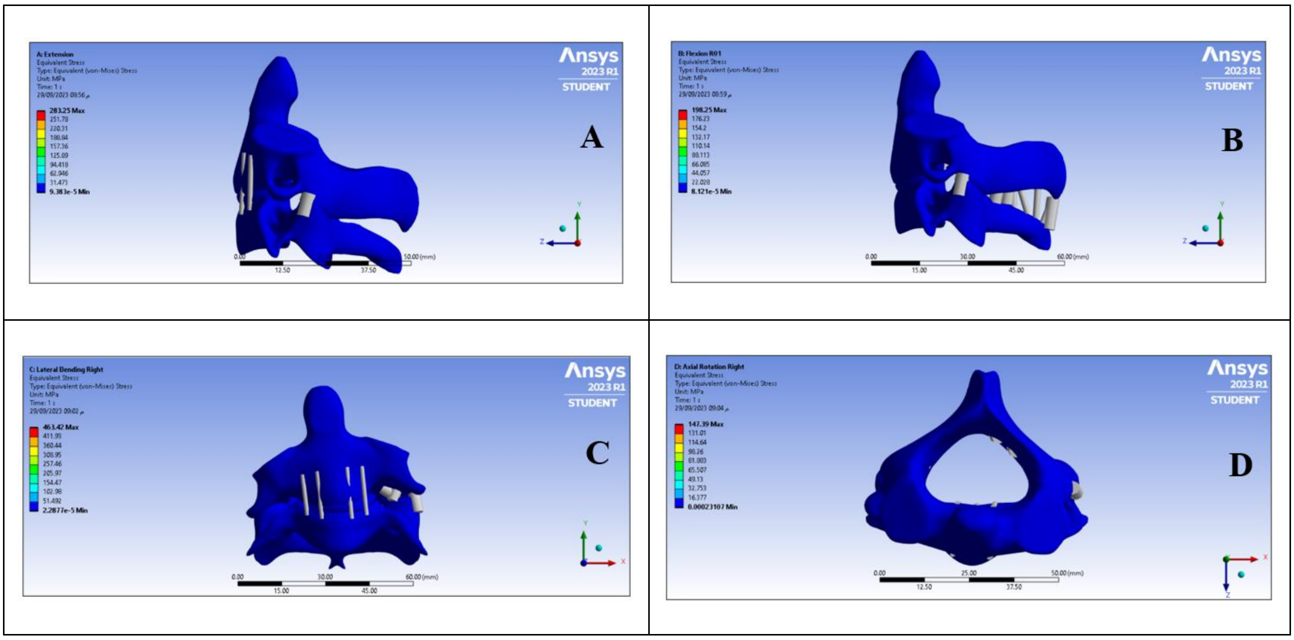

Fig. 4 The physiological motion of C2-C3 cervical vertebrae A) Extension B) Flexion C) Lateral bending Right D) Axial Rotation Right.

4. DISCUSSION

In this study, we examine the validation of 3D model of an intact C2-C3 cervical vertebrae by FE studies regarding the physiological motions. 3D model of C2-C3 cervical vertebrae is imported from the site [31] and the geometrical imperfections are treated by ANSYS space claim software. The model was modified to generate the main parts of intervertebral disc and vertebrae using solid edge software ST8. After that the model was imported to ANSYS 2023 R1 STUDENT EDITION. The ligaments of the FE model are constructed and defined as rod connection. Tetrahedron was selected to be the meshing element with quadratic order and size equal 1.9 mm. The results showed that our modified 3D model of an intact C2-C3 cervical vertebrae is validated with respect to in-vitro study of [20] but not validated with [21]. In comparison with average values of Panjabi et al. study, our FE model behaves 14% and 17% lower in flexion and lateral bending right. Whereas it behaves 2 % higher in axial rotation and reaches the maximum value of extension range. Our findings showed the validation of C2-C3 cervical vertebrae regarding the ROMs of the physiological motions after modelling the intervertebral disc, the vertebrae, and ligaments.

The goal of FE modeling of cervical vertebrae is to predict the biomechanical behavior of cervical vertebrae before performing the surgery. Additionally, FEA help to find the intervertebral disc mechanics, injury mechanism and contribute to the diagnosis of cervical spine problems and treatment methodologies. Thus, FE Model may help clinicians in decision making, surgery planning and better treatment for patients [19]. However, any study of FEA regarding human vertebrae will not be considered until the FE model is validated with respect to the ROMs of in-vitro studies [24 - 29].

The present study has a couple of limitations, first we have used rods to model the ligaments with a few numbers. The approximation of our FE model can be enhanced by increasing the number of ligaments. This is preferred as the ligaments in anatomical are spread over the entire connection [30]. However, the used number of rods in this study didn’t affect the validity of the model. The other limitation is that we cannot perform convergence test of the mesh because of the limitation associated with ANSYS 2023 R1 STUDENT EDITION.

Conclusions

The new contributions presented in this study are the commands used to repair the surfaces of cervical vertebrae and the procedure of calculating the Range of Motion of the vertebrae. Three-Dimensional FE model has been modeled using ANSYS 2023 R1 STUDENT EDITION. The FE model is validated with respect to the ROMs of the in-vitro study. Tension ligaments shall only be considered for any specific physiological motion. Our validated FE model can be used in further orthopedic or clinical applications.

References

[1] L. Tacconi, Lumbar discectomy: has it got any ill effects? Journal of Spine Surgery. 4 (2018) 677–680. https://doi.org/10.21037/jss.2018.07.05.

[2] R. Wang, X. Li, X. Zhang, D. Qin, G. Yang, G. Gao, H. Zhang, Microscopic decompressive laminectomy versus percutaneous endoscopic decompressive laminectomy in patients with lumbar spinal stenosis: protocol for a systematic review and meta-analysis, BMJ Open. 10 (2020) e037096. https://doi.org/10.1136/bmjopen-2020-037096.

[3] A. Blamoutier, Surgical discectomy for lumbar disc herniation: Surgical techniques, Orthopaedics and Traumatology: Surgery and Research. 99 (2013) S187–S196. https://doi.org/10.1016/j.otsr.2012.11.005.

[4] C. Whaley, Decompressive lumbar laminectomy: Indications and discussion, Tech Reg Anesth Pain Manag. 17 (2013) 39–42. https://doi.org/10.1053/j.trap.2014.01.006.

[5] J. Lundberg, J.-P. Langevin, Lumbar Microlaminectomy vs Traditional Laminectomy Lumbar microlaminectomy is associated with shorter hospitalization and lower cost within the VA system, n.d. www.fedprac.com.

[6] S.W. Wiesel, J.N. Delahay, Essentials of orthopedic surgery, Springer New York, 2010. https://doi.org/10.1007/978-1-4419-1389-0.

[7] J. Reeks, H. Liang, Materials and their failure mechanisms in total disc replacement, Lubricants. 3 (2015) 346–364. https://doi.org/10.3390/lubricants3020346.
[8] S.N. Salzmann, N. Plais, J. Shue, F.P. Girardi, Lumbar disc replacement surgery—successes and obstacles to widespread adoption, Curr Rev Musculoskelet Med. 10 (2017) 153–159. https://doi.org/10.1007/s12178-017-9397-4.
[9] A. Van Ooij, F.C. Oner, A.J. Verbout, Complications of Artificial Disc Replacement A Report of 27 Patients with the SB Charité Disc, 2003.
[10] Andrew R. Block, Robert J. Gatchel, William W. Deardorff, Richard D., M.D. Guyer - The Psychology of Spine Surgery (2003).
[11] F. Salamanna, M. Tschon, V. Borsari, S. Pagani, L. Martini, M. Fini, Spinal fusion procedures in the adult and young population: a systematic review on allogenic bone and synthetic grafts when compared to autologous bone, J Mater Sci Mater Med. 31 (2020). https://doi.org/10.1007/s10856-020-06389-3.
[12] A. Gupta, N. Kukkar, K. Sharif, B.J. Main, C.E. Albers, S.F. El-Amin, Bone graft substitutes for spine fusion: A brief review, World J Orthop. 6 (2015) 449–456. https://doi.org/10.5312/wjo.v6.i6.449.
[13] S.C. Yson, J.N. Sembrano, E.R.G. Santos, Comparison of allograft and polyetheretherketone (PEEK) cage subsidence rates in anterior cervical discectomy and fusion (ACDF), Journal of Clinical Neuroscience. 38 (2017) 118–121. https://doi.org/10.1016/j.jocn.2016.12.037.
[14] K. Schmieder, M. Wolzik-Grossmann, M. Engelhardt, M. Scholz, A. Harders, Subsidence of the Wing titanium cage after anterior cervical interbody fusion: 2-year follow-up study, 2006.
[15] K. Phan, M.H. Pelletier, P.J. Rao, W.J. Choy, W.R. Walsh, R.J. Mobbs, Integral Fixation Titanium/Polyetheretherketone Cages for Cervical Arthrodesis: Evolution of Cage Design and Early Radiological Outcomes and Fusion Rates, Orthop Surg. 11 (2019) 52–59. https://doi.org/10.1111/os.12413.
[16] O. Nemoto, T. Asazuma, Y. Yato, H. Imabayashi, H. Yasuoka, A. Fujikawa, Comparison of fusion rates following transforaminal lumbar interbody fusion using polyetheretherketone cages or titanium cages with transpedicular instrumentation, European Spine Journal. 23 (2014) 2150–2155. https://doi.org/10.1007/s00586-014-3466-9.
[17] T. V. Le, A.A. Baaj, E. Dakwar, C.J. Burkett, G. Murray, D.A. Smith, J.S. Uribe, Subsidence of polyetheretherketone intervertebral cages in minimally invasive lateral retroperitoneal transpsoas lumbar interbody fusion., Spine (Phila Pa 1976). 37 (2012) 1268–1273. https://doi.org/10.1097/brs.0b013e3182458b2f.
[18] A. Herrera, E. Ibarz, J. Cegoñino, A. Lobo-Escolar, S. Puértolas, E. López, J. Mateo, L. Gracia, Applications of finite element simulation in orthopedic and trauma surgery, World J Orthop. 3 (2012) 25–41. https://doi.org/10.5312/wjo.v3.i4.25.
[19] P.S. Manickam, S. Roy, The biomechanical study of cervical spine: A Finite Element Analysis, International Journal of Artificial Organs. 45 (2022) 89–95. https://doi.org/10.1177/0391398821995495.
[20] M.M. Panjabi, J.J. Crisco, A. Vasavada, T. Oda, J. Cholewicki, K. Nibu, E. Shin, Mechanical Properties of the Human Cervical Spine as Shown by Three-Dimensional Load-Displacement Curves. SPINE Volume 26, Number 24, pp 2692–2700 ©2001, Lippincott Williams & Wilkins, Inc.
[21] N. Kallemeyn, A. Gandhi, S. Kode, K. Shivanna, J. Smucker, N. Grosland, Validation of a C2-C7 cervical spine finite element model using specimen-specific flexibility data, Med Eng Phys. 32 (2010) 482–489. https://doi.org/10.1016/j.medengphy.2010.03.001.
[22] Q.H. Zhang, E.C. Teo, H.W. Ng, V.S. Lee, Finite element analysis of moment-rotation relationships for human cervical spine, J Biomech. 39 (2006) 189–193. https://doi.org/10.1016/j.jbiomech.2004.10.029.
[23] N. Yoganandan, S. Kumaresan, F.A. Pintar, Biomechanics of the cervical spine Part 2. Cervical spine soft tissue responses and biomechanical modeling, n.d. www.elsevier.com/locate/clinbiomech.
[24] J. won Kwon, S.H. Bang, T.H. Park, S.J. Lee, H.M. Lee, S. Bin Lee, B.H. Lee, S.H. Moon, Biomechanical comparison of cervical discectomy/fusion model using allograft spacers between anterior and posterior fixation methods (lateral mass and pedicle screw), Clinical Biomechanics. 73 (2020) 226–233. https://doi.org/10.1016/j.clinbiomech.2020.01.018.

[25] S.H. Lee, Y.J. Im, K.T. Kim, Y.H. Kim, W.M. Park, K. Kim, Comparison of cervical spine biomechanics after fixed- and mobile-core artificial sisc replacement: A finite element analysis, Spine (Phila Pa 1976). 36 (2011) 700–708. https://doi.org/10.1097/BRS.0b013e3181f5cb87.
[26] Z. Lei, X. Ji, N. Li, J. Yang, Z. Zhuang, D. Rottach, Simulated effects of head movement on contact pressures between headforms and n95 filtering facepiece respirators-Part 1: Headform model and validation, Annals of Occupational Hygiene. 58 (2014) 1175–1185. https://doi.org/10.1093/annhyg/meu051.
[27] X.F. Li, L.Y. Jin, C.G. Liang, H.L. Yin, X.X. Song, Adjacent-level biomechanics after single-level anterior cervical interbody fusion with anchored zero-profile spacer versus cage-plate construct: A finite element study, BMC Surg. 20 (2020). https://doi.org/10.1186/s12893-020-00729-4.
[28] G. Lewis, Finite Element Analysis Study of the Influence of Simulated Surgical Methods on Kinematics of a Model of the Full Cervical Spine, Spine Research. 02 (2016). https://doi.org/10.21767/2471-8173.100014.
[29] J. Sun, Q. Wang, D. Cai, W. Gu, Y. Ma, Y. Sun, Y. Wei, F. Yuan, A lattice topology optimization of cervical interbody fusion cage and finite element comparison with ZK60 and Ti-6Al-4V cages, BMC Musculoskelet Disord. 22 (2021). https://doi.org/10.1186/s12891-021-04244-2.
[30] Anne M. R. Agur, Arthur F. Dalley - Grant's Atlas of Anatomy-Lippincott Williams &amp_ Wilkins (2012).
[31] https://grabcad.com/liberary/human-spine-1