Journal of Orthopaedic Translation 23 (2020) 107–112

Contents lists available at ScienceDirect

Journal of Orthopaedic Translation

journal homepage: www.journals.elsevier.com/journal-of-orthopaedic-translation

Original Article

Comparative analysis of the biomechanics of the adjacent segments after minimally invasive cervical surgeries versus anterior cervical discectomy and fusion: A finite element study

Chao Chen [a,☆], Chen-Xi Yuchi [b,☆], Ziwei Gao [c,a], Xinlong Ma [a], Dong Zhao [a], Jun-Wei Li [b], Baoshan Xu [a], Chun-Qiu Zhang [b], Zheng Wang [d,***], Cheng-Fei Du [b,**], Qiang Yang [a,*]

[a] Department of Spine Surgery, Tianjin Hospital, Tianjin University, No. 406 Jiefangnan Road, Hexi District, Tianjin 300211, China
[b] Tianjin Key Laboratory for Advanced Mechatronic System Design and Intelligent Control, School of Mechanical Engineering, Tianjin University of Technology, Tianjin 300384, China
[c] Tianjin Medical University, Tianjin 300070, China
[d] Department of Orthopedics, No.1 Medical Center of Chinese PLA General Hospital, No. 28 Fuxing Road, Haidian District, Beijing 100853, China

A R T I C L E I N F O

Keywords:
Anterior cervical discectomy and fusion
Biomechanics
Finite element
Percutaneous full-endoscopic anterior cervical discectomy
Posterior cervical foraminotomy

A B S T R A C T

Purpose: Percutaneous full-endoscopic anterior cervical discectomy (PEACD) and posterior cervical foraminotomy (PCF) as alternatives to anterior cervical discectomy and fusion (ACDF) are extensively used in the treatment of patients with cervical spondylotic radiculopathy. The possibility of avoiding the risk of accelerated degeneration of the adjacent segments caused by fusion is claimed to be the theoretical advantage of these approaches; however, there is a paucity of supportive evidence from biomechanical data. Therefore, this study investigated and compared the effects of PCF, PEACD, and ACDF on the adjacent segments and operative segments of the cervical spine from a biomechanical standpoint.
Method: A normal and intact three-dimensional finite element digital model of C4–C7 was constructed and validated, and the finite element models of PEACD, PCF, and ACDF were obtained by modifying the C4–C7 model. All models were exposed to identical conditions of load during flexion, extension, axial rotation, and lateral bending. We calculated the range of motion (ROM), intervertebral disc pressure (IDP), and facet joint contact force (FJCF) of the operative segment and the adjacent segment in different motion conditions.
Result: The conventional ACDF had a remarkable influence on the ROM and IDP of the operative segment and the adjacent segments. In the PEACD model, the change of ROM was not noticeable; the IDP of the operative segment was significantly smaller, whereas the change of IDP of the adjacent segment was insignificant. In the PCF model, the ROM and IDP of all segments remained unaffected.During extension, the facet joint contact force changed significantly after ACDF, and it changed slightly after PECAD and PCF.
Conclusion: By comparatively analyzing the biomechanical changes of the cervical spine after PCF, PEACD, and ACDF using the finite element method, we suggested that PCF and PEACD were more suitable for surgical intervention of cervical spondylotic radiculopathy than ACDF from a biomechanical point of view and PCF may outperform PEACD.

* Corresponding author. Department of Spine Surgery, Tianjin Hospital, Tianjin University, No. 406 Jiefangnan Road, Hexi District, Tianjin 300211, China.
** Corresponding author. Tianjin Key Laboratory for Advanced Mechatronic System Design and Intelligent Control, School of Mechanical Engineering, Tianjin University of Technology, Tianjin 300384, China.
*** Corresponding author. Department of Orthopedics, No.1 Medical Center of Chinese PLA General Hospital, No. 28 Fuxing Road, Haidian District, Beijing 100853, China.
E-mail addresses: wangzheng301@hotmail.com (Z. Wang), ddccffb31@hotmail.com (C.-F. Du), yangqiang1980@126.com (Q. Yang).
☆ Chao Chen and Chen-Xi Yuchi contributed equally to this work.

https://doi.org/10.1016/j.jot.2020.03.006
Received 6 February 2020; Received in revised form 9 March 2020; Accepted 10 March 2020
Available online 2 April 2020

Introduction

Cervical spondylotic radiculopathy (CSR) is a highly prevalent chronic degeneration of the vertebrae and discs of the neck [1–3]. CSR is characterized by neck pain and numbness of the neck and arm with restricted neck movement and is associated with depression and insomnia, which significantly impact the quality of life of the patients [4–8]. According to the Global Burden of Diseases, Injuries, and Risk Factors Study 2016, neck pain is one of the top ten leading causes contributing to a rapid increase in years lost due to disability among 301 diseases and injuries in 188 countries of the world [9]. Besides, the ageing population will cause a significant increase in the economic and social burden attributed to CSR. Owing to the important anatomical location of the cervical spine, CSR not only adversely affects the quality of life but also reduces the social participation and labour force. The anterior cervical discectomy and fusion (ACDF) has been considered as the gold standard for the treatment of CSR. With the fusion rate of up to 95%, this established surgical technique can provide satisfactory postoperative neural decompression and good stabilization [10]. However, ACDF is limited by accelerated adjacent level degeneration and restricted cervical mobility, which are major causes of degeneration of the adjacent intervertebral discs and facet joints [10,11]. With the emergence of minimally invasive surgical procedure, the minimally invasive posterior cervical foraminotomy (MI-PCF) and percutaneous full-endoscopic anterior cervical discectomy (PEACD) have been increasingly adopted for treatment of CSR. However, studies comparing the therapeutic efficacy of MI-PCF and PEACD are still lacking; thus, there is no consensus on the better procedure for treating CSR, which can reduce the adverse effects on the adjacent segments.

PCF provides a standardized approach for the effective treatment of CSR. A recent systematic review compared the effects of CSR treatment using ACDF and PCF and reported that there was no significant difference in clinical efficacy, the incidence of complications, and reoperation rate [12]. Furthermore, MI-PCF can reduce the risk of adjacent segmental cervical spondylopathy. A recent retrospective analysis by Skovrlj et al. [13] indicated that a low rate (0.9% per adjacent segment per year) of cervical spondylopathy in the adjacent segments after MI-PCF surgery required surgical intervention. Besides, as an alternative to ACDF, PCF exhibits a good therapeutic effect and averts adverse effects on the adjacent segments. However, there is a paucity of studies comparing the therapeutic efficacy of MI-PCF and ACDF on the adjacent cervical segments from a biomechanical point of view.

With the development of endoscopic techniques in the field of orthopedics, PEACD has gained increased attention and has been progressively used in the treatment of CSR and other spinal diseases [14–17]. PEACD removes the degenerative intervertebral disc through minimally invasive endoscopic surgery to relieve the impact of the diseased intervertebral disc on the surrounding tissue structure. Besides, PEACD does not need implants and has several advantages compared with ACDF such as it is associated with less iatrogenic injury, lower bleeding, shorter hospital stay, and faster postoperative recovery [18]. Notably, Ahn et al. [19] performed PEACD through the anterior intervertebral disc approach in 17 patients with pain caused by intervertebral disc degeneration. During the follow-up, 88.2% of the patients exhibited significant improvement in postoperative symptoms. However, further studies are needed to investigate the effects of PEACD on the stability of the cervical spine compared with ACDF, the biomechanical properties of the intervertebral disc and facet joint, and the effect of the decompression channel on the adjacent segments.

Therefore, this study was initiated to simulate and test the biomechanical characteristics of the three surgical procedures, including ACDF, PCF, and PEACD, by the finite element method. We also compared the biomechanical indexes of these procedures and analyzed the intrinsic mechanical mechanism. We wish to add some more evidence for surgeons when they try to select a more rational surgical plan.

Methods

Establishment of the finite element model

The geometric characteristics of the finite element model were constructed from a computed tomography (CT) scan image of a 30-year-old healthy man (height = 175 cm, weight = 75 Kg, in supine position) who had no history of cervical spondylosis. The CT digital image was imported into Mimics 10.01 software (Materialise Technologies, Leuven, Belgium), transformed into a geometric solid model, and then imported into Geomagic Studio 2012 (Geomagic Inc., North Carolina, USA) for optimization. Based on the previous anatomical structure, the geometric appearance of the cervical vertebra model was optimized and converted into a nonuniform rational B-spline geometric surface.

Next, the optimized cervical geometric model was imported into Hypermesh 11.0 (Altair Engineering Corp, Michigan, USA) for the preprocessing of the finite element. Initially, the geometric model was divided into the vertebral body and the posterior structure, in which the vertebral body was composed of cancellous bone, the surrounding cortical bone, and upper and lower end plates, and the intervertebral disc was composed of nucleus pulposus, annulus fibrosus matrix, and annulus fibrosus. The components were meshed separately. After the C3–C7 mesh division was completed, according to the anatomical literature, five main ligaments were established in the appropriate position: anterior longitudinal ligament, posterior longitudinal ligament, ligament flavum, articular capsule ligament, and interspinous ligament [20]. The characteristics of the material of each part were summarized in Table 1. After validation of the intact C3–C7 model, the intercepted C4–C7 segment model was constructed. One coupling node was placed below the centre position of the upper end plate, and another one was arranged below the centre position of the lower end plate and was connected with the connector elements. As shown in the Fig. 1, 7 connector elements have been established; subsequently, a load of 50 N was applied on each of them (only the first connector load is marked in the picture). A moment of 1 N·m was applied on the sagittal plane, coronal plane, and horizontal plane at the coupling point of the end plate on C4, as is shown in Fig. 1, and the fully constrained boundary conditions were applied to the inferior end plate of C7. The displacement of the intact model at 1 N•m was calculated, and the calculated displacement load was applied to the surgical models instead of the moment. All the simulation works were conducted in a commercial finite element package (Abaqus 6.11; Dassault Systèmes Simulia Corporation, Pennsylvania, USA).

Calibration and validation

The intact cervical spine model was subjected to the calibration process to include the ligamentum flavum, articular capsule ligament, and interspinous ligament. Subsequently, the coefficient of ligaments was calibrated as described in a previously published article [22]. As presented in the author's previous study [27], the outcomes were compared

Table 1
Material properties of cervical vertebra components.

Component	Young's modulus (MPa)	Poisson's ratio	Element type
Cortical	10,000 [21,22]	0.3 [21,22]	Hexahedron
Cancellous	450 [22,23]	0.23 [26]	Pentahedron and tetrahedron
End plate	500 [23]	0.4 [23]	Hexahedron
Posterior	3500 [21]	0.25 [21, 22]	Pentahedron and tetrahedron
Annulus fibrosus matrix	2.0 [24]	0.45 [21]	Hexahedron
Annulus fibrosus	110 [24]	0.3 [21]	Tension-only truss
Nucleus	1 [23]	0.49 [23]	Hexahedron
Facet	10 [25]	0.4 [24]	Hexahedron
Ligaments	Nonlinear [22]	—	Connector

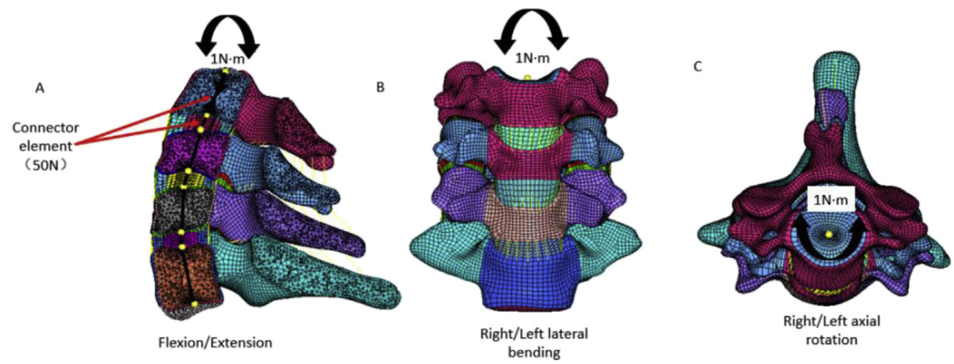

Figure 1. (A) Loads of flexion/extension applied in the intact model; (B) right/left lateral bending applied in the intact model; (C) right/left axial rotation applied in the intact model.

with the previously reported *in vitro* experimental data to validate the cervical finite element model [28–31], and the validation results of the calibrated model were in agreement with the *in vitro* experimental results. Taken together, the findings indicated that the intact model can effectively reflect the movement of the human cervical spine and accurately perform the simulation analysis.

Establishment of surgical models

Next, we modified the C5/6 segments of the validated intact model to construct ACDF, PEACD, and PCF models. For the ACDF model, the nucleus pulposus of the C5/6 segment was removed, and the annulus fibrosus was partially removed. The cage was placed between the upper end plate of C6 and lower end plates of the C5; then, the C5/6 segment was fixed with anterior plates and screws. For the PEACD model, a tunnel was established on the C5/6 intervertebral disc from anterior to oblique posterior to simulate the surgical process of full-endoscopic discectomy from the anterior approach. For the PCF model, half of the right facet joint of the C5/6 segment and part of the articular capsule ligament were removed. The operative models and corresponding schematic are shown in Fig. 2.

Results

The range of motion (ROM) of different surgical models and intact models under flexion, extension, lateral bending, and axial rotation is presented in Fig. 3. During flexion, the ROM of the operative segment in the ACDF model was significantly lower than that of the normal model. In contrast, the ROM of the adjacent segment was noticeably larger than that of the normal model. Overall, compared with the intact model under different postures, the ROM of several operations revealed that the traditional ACDF operation exhibited an apparent effect on the ROM of the surgical segment and adjacent segments, whereas the minimally invasive surgical interventions exhibited a relatively lower effect on the ROM.

The comparison of intervertebral disc pressure (IDP) between different surgical models and intact models under flexion, extension, lateral bending, and axial rotation is shown in Fig. 4. In the ACDF model, owing to the removal of the nucleus pulposus in the surgical segment, the IDP of the C5/6 segment was zero, whereas the IDP of the adjacent segments increased under most of the conditions. In the PEACD model, the IDP of the operated segments decreased significantly; however, the changes in the IDP of the adjacent segments were not evident. Notably, the IDP of all segments almost remained unchanged in the PCF model.

The comparison of facet joint contact force (FJCF) between different surgical models and intact models under extension, lateral bending, and axial rotation is shown in Fig. 5. During extension, the FJCF changed significantly after ACDF, and it changed slightly after PECAD and PCF. The tendency of the left lateral bending was similar to that of the extension. During right lateral bending, the FJCD of ACDF and PCF changed significantly, and PEACD was the closest to the intact model.

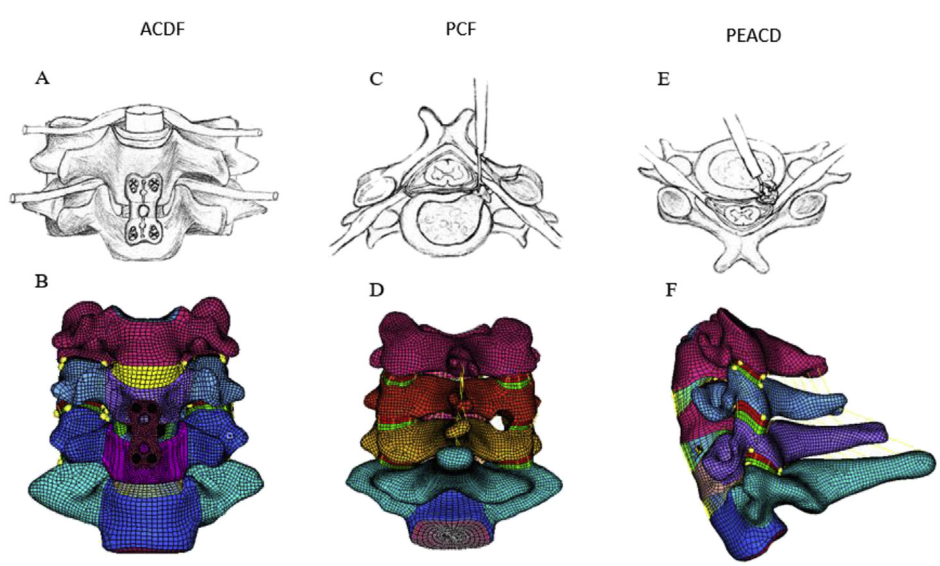

Figure 2. (A and B) The C4–C7 operation models and diagram of ACDF; (C and D) the C4–C7 operation models and diagram of PCF; (E and F) the C4–C7 operation models and diagram of PEACD. ACDF = anterior cervical discectomy and fusion; PEACD = percutaneous full-endoscopic anterior cervical discectomy; PCF = posterior cervical foraminotomy.

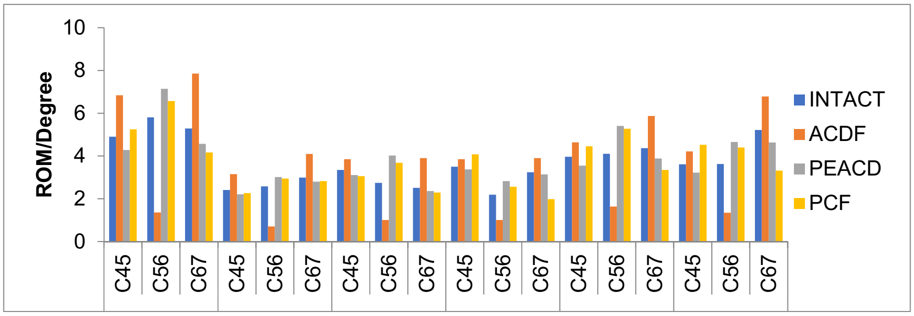

Figure 3. Comparison of range of motion (ROM) between different surgical models and intact models under flexion, extension, lateral bending, and axial rotation. ACDF = anterior cervical discectomy and fusion; LLATERAL = left lateral bending; LROTATION = left axial rotation; PEACD = percutaneous full-endoscopic anterior cervical discectomy; PCF = posterior cervical foraminotomy; RLATERAL = right lateral bending; RROTATION = right axial rotation.

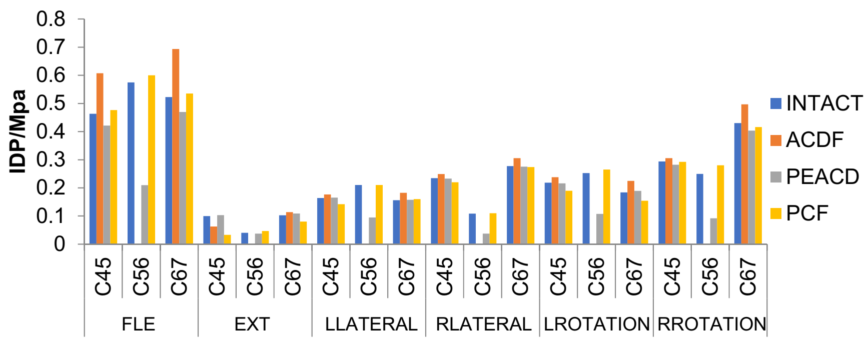

Figure 4. Comparison of IDP between different surgical models and intact models under flexion, extension, lateral bending, and axial rotation. ACDF = anterior cervical discectomy and fusion; IDP = intervertebral disc pressure; LLATERAL = left lateral bending; LROTATION = left axial rotation; PEACD = percutaneous full-endoscopic anterior cervical discectomy; PCF = posterior cervical foraminotomy; RLATERAL = right lateral bending; RROTATION = right axial rotation.

FJCF had obvious asymmetry during axial rotation. During left axial rotation, the FJCF on the right side was obviously greater than that on the left side. Right axial rotation was exactly the opposite.

Discussion

ACDF is considered as the gold standard surgery for CSR, which is most often associated with a high fusion rate, but may leading to an increased risk of accelerated degeneration of the adjacent segments. With recent technological advances, PEACD and PCF have increasingly gained attention in the treatment of CSR. However, there is a paucity of evidence for surgeons to select a more appropriate approach. Thus, this study simulated and tested the biomechanical characteristics of the three surgical procedures, including ACDF, PCF, and PEACD, by the finite element method and provided some more evidence for surgeons to select rational surgical plans.

Previously, studies have investigated the biomechanical properties of ACDF and suggested that spinal fusion increases the probability of intervertebral disc degeneration in the adjacent segments [32,33]. As an alternative to ACDF, it is not explicit whether minimally invasive surgery PCF and PEACD can reduce degeneration in the adjacent segments or not. Therefore, in this study, a multisegmental cervical vertebra model was presented to compare the biomechanical properties of the three surgical models. Generally, boundary conditions and loads are applied to both

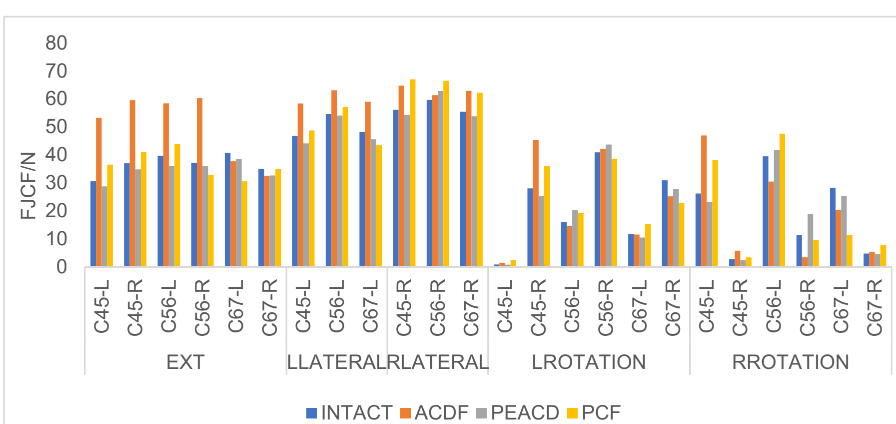

Figure 5. Comparison of FJCF between different surgical models and intact models under extension, lateral bending, and axial rotation. ACDF = anterior cervical discectomy and fusion; FJCF = facet joint contact force; LLATERAL = left lateral bending; LROTATION = left axial rotation; PEACD = percutaneous full-endoscopic anterior cervical discectomy; PCF = posterior cervical foraminotomy; RLATERAL = right lateral bending; RROTATION = right axial rotation.

end plates of the surgical segment by creating a single-segment finite element model. Subsequently, biomechanical calculation and analysis are performed [34]. In this study, boundary conditions were applied to the lower end plate of C7, and loads were applied to the end plate of C4 by establishing a C4–C5–C6–C7 multisegmental cervical vertebra model. The forces and boundary conditions of the operative segments were separately transmitted from the surrounding intervertebral discs, facet joints, ligaments, and other tissues. Recently, Maiman et al. [11] asserted that the multisegmental cervical vertebra model can simulate the physiological conditions of the cervical vertebra more accurately. This was one of the major characteristics of this investigation.

As validation plays an essential role in predicting the biomechanics of the cervical spine, this model was cut off from a validated C3–C4–C5–C6–C7 model. The validation results indicated that the ROM was in accordance with the *in vitro* experimental results reported previously. Therefore, we anticipated that this model can simulate the movement of the cervical spine accurately. The analysis of ACDF demonstrated that the surgery limited the movement of the operative segment; however, it caused excessive movement of the adjacent segment. Mechanistically, the plate fixation of the ACDF operation segment led to the reduction of its flexibility. Thus, to achieve the same mobility effect, the adjacent segments exhibited a compensatory movement. Consequently, this raised ROM caused greater deformation of the soft tissue of the cervical spine and induced changes in the IDP of the adjacent segments. A similar phenomenon was observed in the *in vitro* experiment of Eck et al. [10], indicating that ACDF may cause adjacent segment degeneration.

The findings from the two minimally invasive surgeries revealed that the ROM of the adjacent segments decreased significantly after PEACD, whereas the flexibility of operative segments increased. The IDP of surgical segments declined, and the change of IDP in the adjacent segments was not evident. Possibly, the anterior nucleus pulposus and annulus fibrosus were damaged to a certain extent when the working channel was established through the intervertebral disc, which caused irreversible damage to the residual intervertebral disc after surgery. Besides, the stress load on the intervertebral disc caused the intervertebral disc cells to be stimulated by compression stress, tensile stress, hydrostatic pressure, osmotic pressure shear stress, and other stress, which damaged the intervertebral disc to a large extent, which raised the change of ROM and the abnormal pressure in the intervertebral disc. Long-term follow-up investigation indicated that MI-PCF is a safe and effective cervical decompression method [35]. Finite element analysis also indicated that the ROM of PCF was not significantly changed with the intervertebral pressure, which was consistent with the related literature. Conceivably, when the resection of the facet joint does not exceed 50%, the IDP and ROM of the segment do not augment significantly [36].

Furthermore, the results of FJCF demonstrated that it increased under most of the conditions after PCF operation, which may be ascribed to the fact that there was a stable triangular structure on the horizontal plane consisting of the two facet joints of a spinal motion segment and the anterior intervertebral disc. The asymmetrical triangular columnar structure was formed from the point to surface, which restricted each other and maintained the stability of the spine. However, destruction of the right facet joint may lead to cervical segmental instability and more pressure load by facet joints. During flexion, there was a large gap between the upper and lower facet joints, so facet joints forces at that time were negligible. During right lateral bending, the gap between the facet joints on the right side became larger, and the FJCF on the right side was insignificant at this time; similar phenomena also occur during left lateral bending. Therefore, this study did not record FJCF during flexion, the right FJCF during right lateral bending, and the left FJCF during left lateral bending. Similar findings have been reported in the literature [37].

One of the major limitations of finite element simulation is model simplification. In this study, the model was based on CT-scanned images of a healthy 30-year-old adult man. The main purpose of this study was to investigate the mechanical effect of the destructive cervical spine on the structure of each part of the cervical vertebra after surgery. Considering the effect of age and gender on the movement of the cervical spine relatively negligible than that of structural destruction, this study did not take the changes of age and gender into account. Further studies are warranted based on the demographic characteristics of patients. Therefore, the aforementioned investigated models and variables are the major objectives, which we intended to probe into intensely.

Overall, by comparing the effects of the three operations on the ROM, IDP, FJCA, and FJCF, the present study indicated that MI-PCF and PEACD exhibited less impact on the operative and adjacent segments than ACDF. Consequently, after surgery, PCF and PEACD are more approximate to the state of a normal cervical vertebra.

Conclusion

Collectively, the findings of this study indicated that ACDF had a significant impact on the biomechanical indexes of the operative and adjacent segments; explicitly, PCF and PEACD can better approximate the physiological state of normal cervical vertebrae. Therefore, we believe that the intrinsic biomechanical mechanisms of the three surgeries can be effectively analyzed and compared using the finite element method. Thus, minimally invasive surgeries are more suitable in the treatment of CSR than traditional surgery from a biomechanical point of view, and PCF may outperform PEACD.

Author contributions

C.C., Z.W., C.-F.D., and Q.Y. contributed to conception and design of the study. C.-X.Y. and J.-W.L. contributed to acquisition of data. C.C., C.-X.Y., C.-F.D., and Q.Y. contributed to analysis or interpretation of data. C.C., C.-X.Y., Z.G., and D.Z. contributed to drafting the manuscript. X.M., B.X., C.-Q.Z., Z.W., Q.Y., and C.-F.D. contributed to revising the manuscript critically for important intellectual content. C.C., C.-X.Y., Z.G., X.M., D.Z., J.-W.L., B.X., C.-Q.Z., Z.W., C.-F.D., and Q.Y. contributed to approval of the version of the manuscript to be published.

Conflict of Interest

The authors have no conflicts of interest to disclose in relation to this article.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (81871782, 11602172, 31670983), Tianjin Science Foundation (18ZXSGSY00010, 18YFZCSY00890), the Tianjin Science Fund for Distinguished Young Scholars (18JCJQJC47900), and the National Key Research and Development Program of China (2019YFC0120600, 2019YFC110005).

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