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Review article

In vivo cervical vertebrae kinematic studies based on dual fluoroscopic imaging system measurement: A narrative review

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ABSTRACT

Understanding the motion characteristics of cervical spine through biomechanical analysis aids in the identification of abnormal joint movements. This knowledge is essential for the prevention, diagnosis, and treatment of related disorders. However, the anatomical structure of the cervical spine is complex, and traditional medical imaging techniques have certain limitations. Capturing the movement characteristics of various parts of the cervical spine in vivo during motion is challenging. The dual fluoroscopic imaging system (DFIS) is able to quantify the motion and motion patterns of individual segments. In recent years, DFIS has achieved accurate non-invasive measurements of dynamic joint movements in humans. This review assesses the research findings of DFIS about the cervical spine in healthy and pathological individuals. Relevant study search was conducted up to October 2023 in Web of Science, PubMed, and EBSCO databases. After the search, a total of 30 studies were ultimately included. Among them, 13 studies focused on healthy cervical spines, while 17 studies focused on pathological cervical spines. These studies mainly centered on exploring the vertebral bodies and associated structures of the cervical spine, including intervertebral discs, intervertebral foramina, and zygapophyseal joints. Further research could utilize DFIS to investigate cervical spine motion in different populations and under pathological conditions.

1. Introduction

The anatomy and function of the cervical spine are intricate, often bearing high loads which elevate the risk of injury and degenerative changes. These changes can ultimately result in pain, functional disability, and/or neurological complications [1]. The normal distribution of loads and the proper functioning of various tissue structures are essential for maintaining its longevity and functionality [2,3]. The etiology of cervical degenerative changes is considered multifactorial, although the exact mechanisms remain

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unclear [4]. Most scholars tend to believe that degeneration results from the imbalanced mechanical stress distribution or excessive loading. Therefore, it is crucial to measure the cervical spine under dynamic loads [5,6].Quantitative analysis of cervical spine kinematics provides a comprehensive understanding of motion patterns, loading modes, and potential mechanisms of injury during movement. This analysis contributes to the improvement of surgical techniques and rehabilitation programs.

Existing traditional three-dimensional motion measurement methods have certain limitations when capturing cervical spine motion. For example, optical motion capture systems rely on tracking motion trajectories through reflective markers placed on the body surface. However, due to the thick, soft tissue covering in the cervical spine region and the absence of distinct bony landmarks. There may be significant errors when using optical motion capture systems to precisely capture cervical spine motion. Radiostereometric analysis (RSA) is an invasive method that requires the implantation of specific markers inside the body, mainly used for in vitro studies [7]. On the other hand, single-plane fluoroscopy imaging techniques may exhibit significant errors when capturing out-of-plane motion [8]. Finite element models rely on computer programming to simulate the 6 degrees of freedom (DOF) motion of joints, but their results may deviate from actual motion trajectories [9].

The dual fluoroscopic imaging system (DFIS) is a novel in vivo joint motion capture technology (Fig. 1). DFIS provides high-resolution real-time imaging of cervical spine motion, enabling precise tracking of three-dimensional cervical spine motion. Compared to traditional methods, DFIS offers significant advantages. Unlike optical motion capture systems, DFIS utilizes bone models and image registration techniques, not relying on surface markers, thus ensuring higher accuracy in measuring cervical spine kinematics. Additionally, DFIS is non-invasive and suitable for in vivo studies, eliminating the need for markers as required by RSA. Moreover, when measuring 6 DOF joint kinematics, DFIS demonstrates higher accuracy compared to single-plane fluoroscopy imaging. Compared to finite element model analysis, DFIS can more accurately reflect actual joint motion, reducing deviations from the true trajectory. In conclusion, DFIS is an effective alternative method for measuring three-dimensional cervical spine motion, addressing some limitations of existing methods.

DFIS combines dynamic orthogonal fluoroscopy with magnetic resonance imaging (MRI) or 3D computed tomography (CT) to obtain human body imaging information [10,11] (Fig. 2). This method overcomes the limitations of existing measurement techniques in terms of accuracy and ethics, enabling more precise in vivo measurements of cervical spine motion. Wang et al. pioneered the application of this technology to in vivo spinal kinematics research, validating its sub-millimeter accuracy and high repeatability in measuring spinal motion [12]. However, there is currently limited study reviewing the in vivo motion patterns of the cervical spine based on DFIS. This review aims to summarize and evaluate existing research, providing a reference for subsequent studies on the potential etiology, pathology, and biomechanics of cervical spine diseases.

2. Materials and methods

2.1. Search methodology

A standardized electronic study searches of electronic databases including Web of Science, PubMed and EBSCO databases was conducted on October 1, 2023. The search utilized keywords "cervical vertebrae" and the terms "dual fluoroscopy" or "biplane fluoroscopy" or "biplanar video radiography" or "biplanar video fluoroscopy" or "biplanar fluoroscopy" or "biplane radiography" or "biplane X-ray system" or "biplane X-ray fluoroscopy" in the topic field. All studies were imported into Citavi to eliminate duplicates.

2.2. Inclusion and exclusion criteria

The identified studies were required to meet the following inclusion criteria: (1) published in English peer-reviewed journals, (2) biomechanical studies on cervical vertebrae, (3) original research studies.

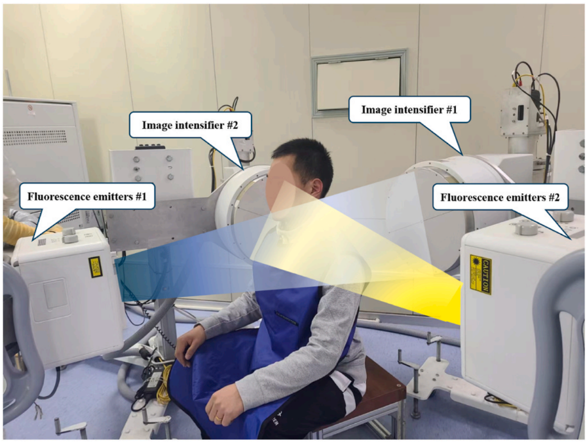

Fig. 1. The dual fluoroscopic imaging system.

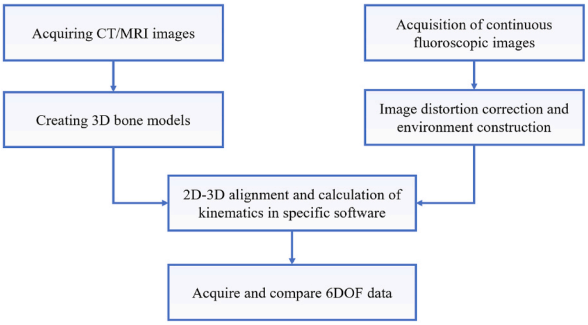

Fig. 2. Process of using dual fluoroscopic imaging system.

Studies were excluded if the studies met any of the following exclusion criteria: (1) were reviewed, case reports or case series, (2) non-DFIS, (3) studies that do not involve any head or neck motion, (4) in vitro studies.

2.3. Study selection

There was no disagreement among the authors regarding the selection of studies eligible for review. The initial search identified 133 studies. After pooling the results and removing duplicates, the titles and abstracts of 70 studies were screened. Additionally, the references of the 29 included studies were reviewed to identify any additional relevant studies. Finally, 30 studies successfully met the eligibility criteria (Fig. 3).

2.4. Data extraction and tabulation

A total of 13 studies focusing on healthy populations were ultimately included (Table 1). Among them, 8 studies investigated kinematics of cervical spine, such as the range of motion (ROM) of the vertebrae, coupled motion, and the quality of motion. The remaining 5 studies analyzed the kinematic anatomy of cervical spine, including intervertebral foramen and vertebral accessory structures. A total of 17 research studies related to non-healthy populations were included. These studies include 1 project describing pathological manifestations, 12 describing in vivo kinematic changes in the cervical spine after anterior cervical discectomy and fusion (ACDF) surgery, and 4 describing in vivo kinematics after artificial disc replacement (ADR) surgery, comparing them with the results of ACDF surgery (Table 2).

Information assessed included: (1) author(s), (2) publication date, (3) sample size, (4) participant condition (e.g., sex, age), (5) anatomical structure, (6) cervical spine movement, (7) type of parameters, and (8) biomechanical characteristics.

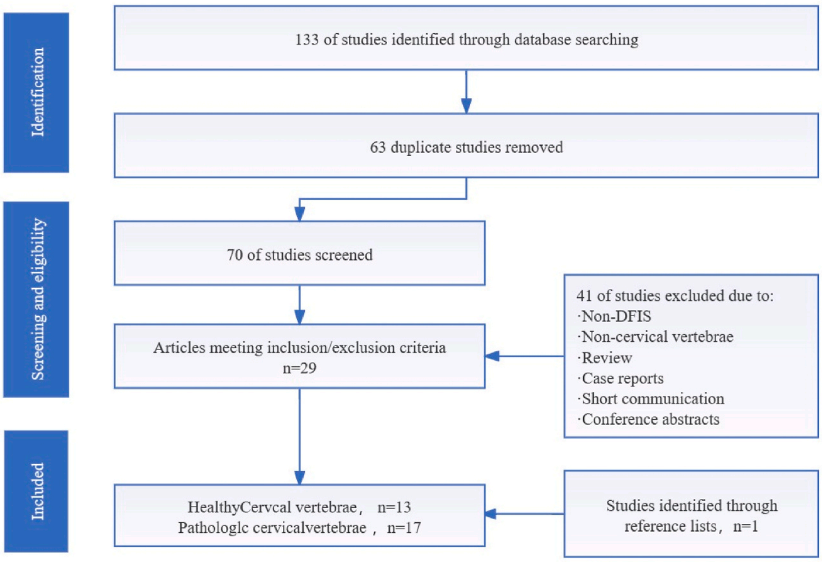

Fig. 3. Studies search methodology.

Table 1
Studies on the biomechanical characteristics in healthy individuals based on DFIS.

Reference	Participants Information: Sample Size, Sex, Age	Anatomical Structure	Cervical Spine Movement	Type of Parameters	Biomechanical Characteristics
Anderst et al., 2013 [13]	19(6 M, 13F), 45.6 ± 5.8	C2–C7 vertebral bodies	Flexion-Extension	Sagittal intervertebral angle	The position of the cervical spine during movement depends on the direction of head movement.
Lin et al., 2014 [14]	10(4 M, 6F), 22.6 ± 2.6	C3-T1 vertebral bodies	Lateral bending, Axial rotation	Coupled intervertebral motion	Interbody lateral bending accounts for a greater proportion of the coupled intervertebral motion that occurs during lateral bending and axial rotational movements of the cervical vertebrae
Anderst et al., 2015 [15]	29(15 M, 14F), 27.3 ± 4.4	C1–T1 vertebral bodies	Flexion-Extension, Lateral bending, Axial rotation	ROM	The contribution of different cervical segments to head movement is constantly changing and in full flexion or extension, reverse motion is generated by the C0–C1 segment.
Anderst et al., 2015 [16]	29(15 M, 14F), 27.3 ± 4.4	C1-T1 vertebral bodies	Flexion-Extension, Lateral bending, Axial rotation	ROMs, Helical axis of motion (HAM)	High inter-subject variability across motor segments
Mao et al., 2016 [17]	10(6 M, 4F), 40.3 ± 10.9	C3–C7 intervertebral foramen	Flexion-Extension	Dimensional Parameters (area, height, width)	The intervertebral foraminal area decreases by approximately 9 % in extension and increases by approximately 15 % in flexion.
Chang et al., 2017 [18]	5(3 M, 2 F), 27-31	C3–C7 intervertebral foramen	Extension, Axial rotation	Dimensional Parameters (height, width)	There is asymmetry between the two intervertebral foramina of the same segment
Yu et al., 2017 [19]	10(6 M, 4F), 40.3 ± 10.9	C3–C7 intervertebral disc	Flexion-Extension	Cervical Intervertebral Disc Deformation	The deformation of the cervical disc can be more than 70 %
Anderst et al., 2017 [20]	20(13 M, 7F), 28 ± 4.2	C1–C2 vertebral bodies	Axial rotation	ROM	C1–C2 rotation is linearly related to head rotation, with a ratio close to 1:1
Yu et al., 2019 [21]	10(6 M, 4F), 40.3 ± 10.9	C3–C7 vertebral bodies	Flexion-Extension, Axial rotation	Center of Rotation (COR), ROM	COR and ROM are related to cervical segmental level and vertebral motion
Kim et al., 2019 [22]	3(3 M, 0F), 31-33	C3–C7 vertebral bodies	Flexion-Extension	Instant Center of Rotation (ICR)	The cervical ICR showed a tendency to move forward and upward, except for the C5–C6 segment.
Zhou et al., 2020 [23]	8(0 M, 8F), 33.4 ± 5.7	C0-T1 vertebral bodies	Flexion-Extension, Lateral bending, Axial rotation	ROM	Significant differences in motion patterns exist between the superior and inferior cervical segments
Wang et al., 2020 [11]	18(7 M, 11F), 40.5 ± 10.9	C3–C7 intervertebral disc and zygapophyseal joint	Flexion-Extension, Lateral bending, Axial rotation	ROM	Vertebral motion is constrained by the intervertebral disc and guided by the zygapophyseal joint
Zhou et al., 2021 [24]	8F, (33.4 ± 5.7)	C0-1、C1-2、CCJ (C0-2)	Axial rotation, Flexion-Extension, Lateral bending	Segmental Kinematics, Ligament Deformations	C0–C1, C1–C2, and the entire cranio-cervical junction (C0–C2) exhibited complex coupled segmental motion, each component of the cruciform ligament was slightly deformed during head rotation

3. Results

3.1. Accuracy of DFIS measurements

Reliability and effectiveness are essential prerequisites for applying DFIS in cervical spine kinematics in vivo. Several papers have compared DFIS with the "gold standard" RSA. In a study by McDonald et al., tantalum beads were implanted in the vertebrae of sheep specimens to validate the accuracy of cervical spine kinematics measured by DFIS [42]. The study compared DFIS data with RSA data. The results indicated sub-millimeter and sub-degree measurement accuracy with DFIS, with translational precision within ±0.6 mm and rotational error of ±0.6° [42]. Similarly, Anderst et al. recruited three patients who underwent ACDF surgery [43]. Tantalum beads were implanted in the fused segments and adjacent vertebrae. Kinematic data were collected using DFIS and RSA six months post-surgery. The comparison revealed that utilizing DFIS for in vivo cervical spine kinematics research could achieve accurate measurements with good reproducibility [43]. The application of DFIS in three-dimensional cervical spine kinematic analysis is non-invasive and provides highly accurate results.

Table 2
Studies on the postoperative cervical biomechanical characteristics based on DFIS.

Reference	Participants Information; Sample; Size; sex; Age (years)	Anatomical structure	Activity	Type of Parameters	Biomechanical characteristics
Anderst et al., 2013 [25]	Healthy subjects, 20 (7 M, 13 F), 46 ± 6 Post C5–C6 ACDF surgery subjects, 12 (2 M, 10 F), 47 ± 10 Post C6–C7 ACDF surgery subjects, 5 (2 M, 3 F), 43 ± 8	C2–C7 vertebral bodies	Flexion-Extension	ICR	Single-segment fusion does not affect the quality of motion of adjacent segments
Anderst et al., 2013 [26]	Healthy subjects, 20 (7 M, 13 F), 46 ± 9 Post C5–C6 ACDF surgery subjects, 10 (2 M, 8 F), 45 ± 6 Post C6–C7 ACDF surgery subjects, 5 (2 M, 3 F), 43 ± 8	C2–C7 intervertebral disc	Flexion-Extension	ROM	Single-level ACDF surgery alters the compression–distraction deformation in the disc
Anderst et al., 2013 [27]	Healthy subjects, 18 (5 M, 13F), 45.6 ± 5.8 Post C5–C6 ACDF surgery subjects, 6 (1 M, 5F), 48.8 ± 6.9	C2–C7 vertebral bodies	Flexion-Extension, Axial rotation	ROM	Following ACDF, there is a significant increase in the contribution of adjacent motion segments, but there is no change in the motion pattern or overall activity.
Anderst et al., 2013 [28]	Healthy subjects, 20 (7 M, 13 F), 45.5 ± 5.8 Post C5–C6 ACDF surgery subjects, 10 (2 M, 8F), 45.3 ± 9.1	C2–C7 vertebral bodies	Flexion-Extension	ROM	Total ROM of adjacent vertebrae is unchanged after C5/C6 ACDF surgery
Anderst et al., 2014 [29]	Healthy subjects, 14 (5 M, 9F), 43.4 ± 5.2 Post C5–C6 ACDF surgery subjects, 9 (2 M, 7F), 45.9 ± 9.5	C2–C7 intervertebral disc and zygapophyseal joint	Flexion-Extension	ROM	Single-segment joint fusion affects the zygapophyseal joint motion of adjacent segments
McDonald et al., 2014 [30]	Post C5–C6 ACDF surgery subject, 10, 48 ± 10.8 Post C5–C6 ADR surgery subjects, 7, 47 ± 7.0	C3–C7 vertebral bodies and zygapophyseal joint	Flexion-Extension, Axial rotation	ROM	Compared to patients undergoing ADR, those undergoing ACDF show increased motion in non-operated segments.
Anderst et al., 2016 [31]	Healthy subjects, 6 (0 M, 6F), 47 ± 6 Post C5–C6 ACDF surgery subjects, 8 (1 M, 7F), 45 ± 9	C2–C7 vertebral bodies	Flexion-Extension, Axial rotation	ROM	C5/C6 arthrodesis had a significant effect on the mid-level motion of the adjacent segment, but not on the end-level motion.
Yeni et al., 2018 [32]	Post C5–C6 ACDF surgery subjects, 16 (4 M, 12F), 28-71 Post C5–C6 ADR surgery subjects, 7 (3 M, 4F), 38-57	C3–C7 intervertebral foramen	Extension, Axial rotation	ROM	Compared to patients undergoing ADR, those undergoing ACDF experience a greater reduction in foraminal area at the operated segment.
Azad et al., 2020 [33]	Post C5–C6 ACDF surgery subjects, 8 (4 M, 4F), 42.5 ± 10.1 Post C5–C6 ADR surgery subjects, 6 (2 M, 4F), 48.2 ± 7.5	C4–C7 intervertebral foramen	Extension, Axial rotation	ROM	Long-term kinematic studies post-surgery reveal a decrease in variability in foraminal area of adjacent segments after ACDF, while there is a slight increase after ADR.
Guo et al., 2021 [34]	Healthy subjects, 10 (4 M, 6F), 30-59 C5–C6 spondylotic subjects, 8 (4 M, 4F), 26-51	C3–C7 vertebral bodies	Flexion-Extension, Axial rotation	ROM	Preservation of motion therapy should further consider the preoperative spinal disease status to restore physiological segmental ROM.
Chen et al., 2021 [35]	Post ACDF surgery subjects59, (28 M, 31F), 47.9 ± 7.8.	C4–C7 vertebral bodies	Flexion-Extension, Axial rotation	ROM, postoperative segmental kyphosis, disc distraction ratio	The area of the lower cervical nerve foramen decreases with age and pathological changes. Surgical factors such as graft type and spinal lordotic angle are not associated with short-term

(continued on next page)

Table 2 (*continued*)

Reference	Participants Information; Sample; Size; sex; Age (years)	Anatomical structure	Activity	Type of Parameters	Biomechanical characteristics
					changes in kinematics of adjacent segments following ACDF.
LeVasseur et al., 2021 [36]	Young Healthy subjects, 30 (15 M, 15F), 26.7 ± 4.2 Middle-age Healthy subjects, 23 (8 M, 15F), 47.3 ± 5.9 Post ACDF surgery subjects, 36 (14 M, 22F), 47.8 ± 7.2	C1–C7 intervertebral foramen	Flexion-Extension	intervertebral disc height, neural foramen area	The entire cervical lower intervertebral foramen area decreases with age and pathological changes. In middle-aged controls, a moderate to strong correlation between foramen area and disc height is observed. Following ACDF surgery, no changes in the foramen area were observed.
Chen et al., 2022 [37]	Post ACDF surgery subjects, 55 (31 M, 32F), 48.7 ± 7.7	C4–C7 vertebral bodies	Flexion-Extension, Axial rotation	ROM, intervertebral disc height	The adjacent segment disc degeneration is correlated with a reduction in motion of adjacent segments following ACDF.
LeVasseur et al., 2022 [38]	Healthy subjects, 38 (15 M, 23F), 47.1 ± 6.7 Post ACDF surgery subjects, 62 (31 M, 31F), 47.3 ± 8.3	C1–C7 vertebral bodies	Flexion-Extension	Helical axis of motion (HAM)	ACDF does not alter the short-term kinematics of adjacent segments, thereby leading to the development of adjacent segment disease.
LeVasseur et al., 2022 [39]	Healthy subjects, 23 (8 M, 15F), 46.5 ± 6.7 Post ACDF surgery subjects,50 (29 M, 21F), 48.4 ± 7.6 One level (C5–C6) surgery subject, 19 (8 M, 11F) Two level (C5–C6–C7) surgery subjects, 19 (12 M, 8F) Two level (C4–C5–C6) surgery subjects, 11 (9 M, 2F)	C1–C7	Flexion-Extension, head rotation	ROM, Helical axis of motion (HAM)	There is no evidence to suggest that adjacent segment ROM increases more after two-level fusion surgery compared to single-level fusion surgery. Moderate-range joint motion tasks are more favorable than full-range motion tasks for assessing postoperative joint kinematic changes.
Oyekan et al., 2022 [40]	Healthy subjects 47 (23 M, 24F), 35 ± 12 Post C4–C5, C6–C7 ACDF surgery subjects 64 (32 M, 32F), 48 ± 8	C1–C7	neutral position	intervertebral disc height	Cervical motion segment alignment changes between supine and upright positioning, those changes differ among motion segments, and cervical pathology affects these changes.
Yeni.et al., 2022 [41]	Post ACDF surgery subjects 8 (4 M, 4F), 42.5 ± 10.1 Post ADR surgery subjects 6 (2 M, 4F), 48.2 ± 7.5	C3–C7	Axial rotation, Extension,	ROM	There is no increase in adjacent segment motion after fusion.

Anterior cervical discectomy and fusion (ACDF). Artificial disc replacement (ADR).

3.2. *Cervical spine kinematics based on DFIS studies in healthy populations*

3.2.1. *Studies on cervical motion segment contributions*

The head and neck are capable of axial rotation in the horizontal plane, flexion and extension in the sagittal plane, and lateral bending in the coronal plane. Various segments contribute differently to these motions. DFIS technology enables the analysis of complete cervical spine kinematics, providing precise assessments down to individual motion segments. Quantitative studies on the contribution of different motion segments to neck movements have revealed significant differences (Figs. 4–6).

Zhou et al. reported that C1–C2 accounted for 73.2 ± 17.3 % of axial rotation of the head [23], which contrasts with the findings of Anderst et al., who reported C1–C2 contributing to approximately half of the total head rotation [20]. However, it is noteworthy that Zhou et al. included only females (8 individuals) and focused on head movements, while Anderst et al. included both males and females (13 males, 7 females), suggesting potential kinematic differences between genders. The first half of the mobility could be attributed to the motion of the upper cervical spine (C0–C2). The contribution of the motion segments between C3-T1 steadily increased in the full ROM and was greatest at the end of the ROM. The cervical motion segments were found to be mirror images of each other in lateral bending and axial rotation motion but not in flexion and extension [16]. This is consistent with his subsequent research [20].

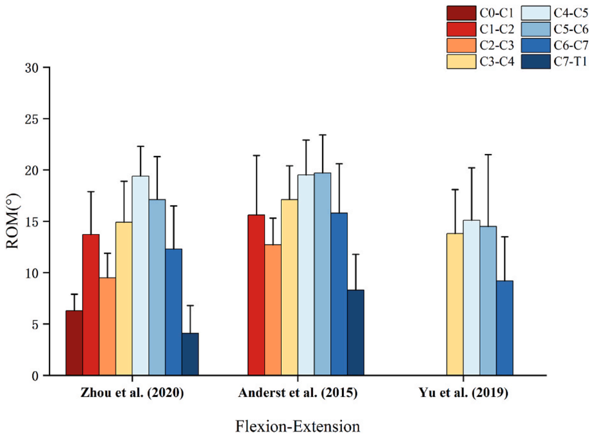

Fig. 4. Contribution of each segment to flexion-extension during cervical spine motion.

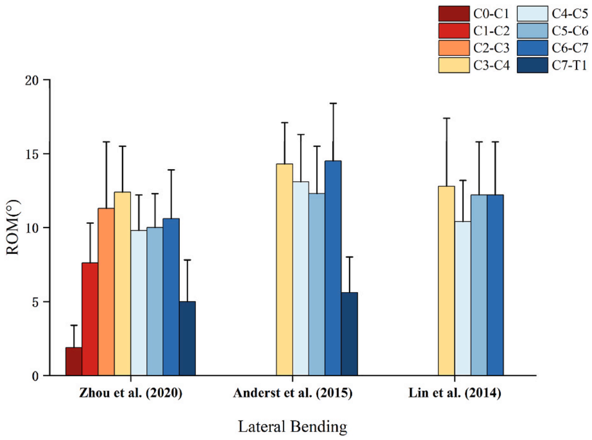

Fig. 5. Contribution of each segment to lateral bending during cervical spine motion.

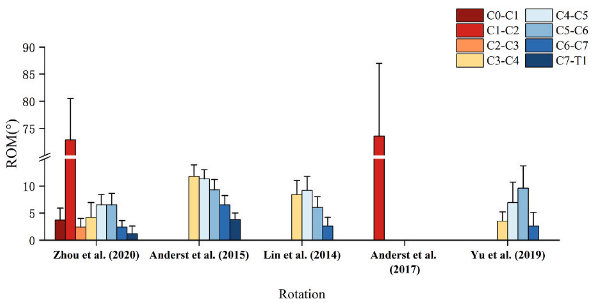

Fig. 6. Contribution of each segment to rotation during cervical spine motion.

Significant differences were found in the intervertebral angles of the vertebrae during flexion and extension movements in the same head direction [13]. Regarding the contribution of each segment in the subaxial spine (C2-T1) during these motions. Several studies consistently concluded that the C4–C5 intervertebral segment contributes the most to cervical spine motion followed by C3–C4 or C5–C6 [23,16,14,21,44]. This feature may be attributed to the resting case C4–C5 segments are in a smaller extension in the static neutral position relative to the upper and lower moving segments [16]. Considering the different characteristics of each segment during motion. Dynamic observational methods often provide a better reflection of the kinematics of the cervical spine than static image measurements.

3.2.2. Studies of coupled motion

The normal physiological movement of the spine is accompanied by coupled motion. This means that movement in any given plane usually automatically results in movement in another plane. Some scholars believe that this coupling significantly influences the function of the cervical spine. Observations of coupled motion in different directions using DFIS indicate that during flexion and extension, except for the C1–C2 motion segment (average rotation of 8.5° ROM), the out-of-plane motion of each active cervical spine segment averages no more than 3° [14]. However, during lateral bending and axial rotation of the cervical spine, there is a relatively significant amount of coupled motion, with the activity of lateral bending coupling being greater than rotational coupling [14]. This result may be attributed to the orientation of the articular facets of the zygapophyseal joints [16]. Zhou et al. found that during axial rotation of the head, C0–C1, C1–C2, and the entire cranio-cervical junction (C0–C2) exhibited complex coupled segmental motion [24].

3.2.3. Other characteristics for quality of motion

Anderst et al. believes that ROM only describes information about the quantity of intervertebral motion, which is not sufficient [25]. Therefore, some scholars have started to characterize the quality of motion and many have chosen to use the helical axis of motion (HAM), center of rotation (COR), or the instant center of rotation (ICR) to indicate motion quality and to evaluate the abnormal ROM (e.g., the stability of the motion) [45,46]. The HAM and the COR define how the motion occurs in each motion segment, while the ICR is a parameter to describe instant motion. Studies on cervical vertebrae movements have shown a tendency for the ICR to move in the forward and upward direction from C2–C3 to C6–C7 segments during flexion and extension movements [22]. This is consistent with the results reported in 2015 [16]. However, the findings of studies by Anderst et al. and Yu et al. are different. They reported no change or only a slight posterior translation in the anterior-posterior translation of the ICR from the C3-4 segment to the C6-7 segment [44,21]. In lateral bending and axial rotational motion, each motor segment moves in a slightly different direction [16]. The location of the COR is segment-specific and dependent on neck motion [21]. Yu et al. also found that the COR of C4-5 and C5-6 was closer to the intervertebral centers compared to the segments of C3-4 and C6-7 [21]. This corroborates the greater contribution of C4–C5 segments to mobility. These differences in the quality-of-motion studies are most likely due to differences in the loads applied to the motion segments during the measurements [16].

3.3. Cervical spine kinematic anatomy based on DFIS studies in healthy populations

3.3.1. Intervertebral foramen

Previous methods only assessed all cervical spine neural foramina from the same angle. The DFIS technique can reconstruct and overlay the upper and lower vertebral arches that form the neural foramen to identify differences between segments and positions. Wang et al. proposed the application of DFIS technology for reconstructing a three-dimensional model of the cervical spine accurately determines the cross-sectional area of each intervertebral foramen [11]. LeVasseur et al. found that age, disc protrusion or degenerative changes, and cervical fusion surgery all affect the area of the cervical neural foramen [36]. Mao et al. used DFIS to investigate spatial parameters (area, height and width) of the intervertebral foramen during dynamic flexion and extension of the cervical spine [17]. This study revealed that almost all geometric parameters of the lower cervical neural foramina exhibited a decreasing trend from the neutral position to the extended position and an increasing trend from the neutral position to the flexed position [17]. The wide variation in the C3–C4 and C4–C5 segments was significantly greater than that in the C5–C6 and C6–C7 segments, while the intervertebral foramen area of C5–C6 and the height of C6–C7 remained relatively constant [17].

These findings of the intervertebral foramen corroborate the greatest contribution of the C4/C5 segment to motion, which may be related to the trajectory and intervertebral kinematics of the cervical ICR [17,19]. Chang et al. proposed that the movement in the lower cervical vertebrae is relatively smaller and less variable, possibly adapting to its load-bearing function [18]. The higher prevalence of diseases in the lower segments may be attributed to their lower tolerance to changes in intervertebral foramen width of the lower cervical vertebrae during motion. Additionally, during cervical extension, there is greater variability in the intervertebral foramen height in the lower cervical segments. DFIS could effectively assess the condition of the cervical neural foramina, particularly during motion, suggesting potential applications in the future.

3.3.2. Cervical joint accessory structures

Joint auxiliary structures exert varying degrees of influence on joint motion. Previous research has predominantly relied on static structural imaging from MRI and single-plane X-rays in static positions. There is a dearth of relevant studies on dynamic changes during motion, and the assessment of motion loads is often limited to modeling and simulation [47,47–51]. DFIS allows non-invasive measurements of in vivo motion of deep bone-related structures such as intervertebral discs, zygapophyseal joints, ligament, and vertebral arch roots. Research on intervertebral discs reveals that during flexion and extension movements, the maximum compression of the C2–C3 segment is observed. The lower motion segments exhibit smaller compression deformation, with compression deformation significantly greater than tensile deformation [26]. This is consistent with in vitro studies [52]. The peak deformation in the posterior lateral cervical region was found to be 47.8 ± 4.4 % greater than that in the anterior cervical region (24.6 ± 2.7 %) during flexion and extension compared with the resting condition in the sitting position [26]. Compared to the lying position, in the C3–C7 segments deformation in the anterior part of the intervertebral disc is greater than in the middle and posterior parts for each disc. On average, the deformation is greatest in the C4–C5 segment and smallest in the C6–C7 segment [17,19]. Wang et al. indicated that intervertebral discs and the zygapophyseal joints translation mainly occurs in the sagittal plane with zygapophyseal joints having greater in-plane translation than intervertebral discs [11]. Researchers have utilized DFIS to study the characteristics of cervical ligaments during motion. Zhou et al. found that during head rotation, each component of the transverse atlanta ligament, including the superior longitudinal band and inferior longitudinal band undergoes slight deformation [24]. The ipsilateral alar ligaments significantly lengthen, while the contralateral alar ligaments are compressed. The contralateral accessory ligaments significantly lengthen, while the ipsilateral accessory ligaments are compressed.

3.4. The application of DFIS in pathological conditions

The data from these studies on the intradiscal motion of pathological cervical spine are of significant reference value for assessing surgical quality, predicting patient prognosis, and guiding postoperative rehabilitation. Previous studies on the adjacent segment motion after cervical spine surgery typically used full flexion and extension X-ray images for clinical assessment [53–55]. However, research has shown that static images cannot represent the dynamic cervical spine kinematics [25]. Therefore, applying DFIS technology to study the biomechanics of the cervical spine before or after surgery helps analyze the reasons for adjacent segment degenerative changes.

3.4.1. Biomechanical characteristics after ACDF surgery

ACDF is a surgical procedure that combines spinal decompression and spinal fusion and is the most common surgical method for treating radiculopathy of the cervical spine. The success rate of this surgery exceeds 90 % and has a good short-term prognosis. However, studies have shown that degeneration of the vertebral bodies adjacent to the surgical segment often accelerates postoperatively [56–58]. Fusion may lead to increased motion in adjacent vertebrae, which is one of the causes of degenerative changes in adjacent segments [59–61]. Adjacent segment degeneration (ASD) refers to the degenerative changes that occur in the adjacent intervertebral discs or vertebrae following spinal fusion surgery. This includes degenerative deformities, reduced intervertebral disc height, and osteophyte formation. These are generally considered as one of the outcomes of postoperative cervical spine kinematic and biomechanical alterations. Stephen et al. found that approximately 25 % of patients will experience symptomatic ASD within 10 years after ACDF surgery and will require further surgery [35]. Postoperative segmental kyphosis and intervertebral disc distraction have the strongest correlation with the development of ASD [62].

Previous studies have shown that following C5–C6 ACDF surgery, there was no change in the total ROM of adjacent vertebral bodies, but there was a change in the motion pattern [13,44,25,26,27]. The increased posterior shift in motion of the two adjacent segments, with the largest percentage change in motion contribution observed at the C6–C7 motion segment (8.9 %), followed by the C4–C5 segment (5.1 %). This suggests that there is a more significant potential mechanical mechanism for adjacent segment degeneration at C6–C7 following C5–C6 joint fusion surgery [27]. This is consistent with epidemiological study results [59,27]. The impact of surgery on adjacent segment motion is primarily in the middle of the motion [31]. Additionally, the C4–C5 segment exhibited a trend of more extension and less flexion motion [27]. The impact on the intervertebral disc is a compression-traction pattern change in the disc above the fused segment, while there is no impact below the fused segment [26]. According to the research by LeVasseur et al., after ACDF surgery, there is a significant increase in the ROM within the adjacent segments, and this effect is exacerbated by two-level joint fusion surgery [39]. Additionally, when assessing early changes in adjacent segment motion following cervical spine fusion surgery, mid-ROM appears to be more useful than long-term ROM [39].

After fusion surgery, the deformation of the fused segment and the adjacent facet joints significantly decreases during the extension motion but not as significant in the flexion direction [29]. Overall, the average ICR position and the change in ICR position in the asymptomatic group did not differ significantly compared to the fusion group [25]. This can be interpreted as the motion quality of the adjacent segments not being affected. However, there are also studies showing that the ROM and angles of adjacent segments after ACDF surgery do not significantly differ from preoperative values [35]. The surgery itself does not significantly increase the motion of adjacent segments [35]. This inconsistency in results may be related to sample size, age range of subjects, and surgical techniques. The changes in motion of adjacent segments after surgery are complex. When evaluating the impact of fusion surgery on the motion of adjacent facet joints and segments, differences in different motion directions and symptomatic groups need to be considered. Further research is needed to better understand the impact of surgery on the biomechanics of the cervical spine.

3.4.2. Biomechanical characteristics after ADR surgery

With advancements in technology, artificial disc replacement surgery (ADR) has been developed as an alternative treatment method [63]. ADR involves the replacement of a pathological intervertebral disc with an artificial one, avoiding the need for additional bone grafting and the use of titanium plates for anterior cervical fixation. It is designed to avoid the drawbacks of ACDF surgery and theoretically reduce adjacent segment degeneration. Previous reports have indicated that ADR surgery can reduce degeneration in adjacent segments, resulting in a lower rate of secondary surgeries in adjacent segments postoperatively [64]. Some studies suggest that ADR does not significantly reduce the incidence of postoperative complications [65].

In order to investigate the potential biomechanical differences between ACDF and ADR surgeries, kinematics of postoperative patients were measured using DFIS technology. The conclusion indicates that two years postoperatively, there was no difference in the total cervical ROM during neck rotation and extension between the two surgical methods. However, the ACDF group exhibited higher mobility in the non-operated segments compared to the ADR group [30,32], particularly at the C6–C7 level. It is worth noting that there was considerable variability in the motion performance of the operated segment at C5–C6 disc replacement among subjects [30]. This suggests that the retained motion after disc replacement may not fully replicate the in vivo motion of the original disc. At 6.5 years postoperatively, Azad et al. found a decrease in the variability of the foraminal area of the adjacent segment after ACDF surgery and a slight increase after ADR surgery [33]. Meanwhile Yeni et al. found minimal differences in the ROM between the two surgical procedures [41]. Post-ACDF, cervical motion exhibited a greater range of flexion and lateral bending angles, while post-ADR patients exhibited a larger range of rotational angles [41].

Changes in the geometric shape of intervertebral foramen and ROM in adjacent segments were observed. Following ACDF surgery, the width of the intervertebral foramen in the fused and adjacent segments decreased, whereas such changes were not observed in the ADR group. However, an increase in the height range of the intervertebral foramen in the caudal adjacent segments was noted in the ADR group. Intervertebral disc height showed no differences in surgical approach, time points, or interactions. The authors pointed out that cervical extension is a more sensitive test for detecting surgery-related changes in intervertebral foramen motion [33,34]. The latest research suggests that the cervical motion pattern in the cervical fusion group is more rigid, while the cervical motion pattern in the ADR group is closer to the physiological pattern of normal cervical motion [41].

4. Perspectives

4.1. Individual differences

There are partial variations in studies involving healthy individuals. These differences may arise from various factors such as different physiological curvatures of the cervical spine, variations in participant age (reflecting different degrees of degeneration) [16], and differences in participant gender [24]. Scholars suggest that age and gender significantly impact cervical spine anatomy and kinematics [66]. In future research, it is essential to recruit participants of diverse ages and genders to elucidate the influence of individual variables on the anatomical and kinematic aspects of cervical spine structures.

4.2. Motion design for assessment

Various participant positioning (supine vs. sitting) [19,26,40], motion speed during data collection (potential differences in muscle forces applied to the vertebrae), initial head position at the start of motion, and variations in applied loads during motion [26] can all have varying degrees of impact on study results.

Additionally, current research is confined to single-plane movements such as flexion and extension, lateral bending, and axial rotation and has not yet extended to more complex combined head movements [44]. The scope or limitations of the DFIS in terms of the ROM it can capture may restrict researchers' choices when it comes to selecting specific motions for their studies. Apart from intricate head movements, activities occurring at the distal ends of the limbs may also influence cervical spine kinematics. However, DFIS has limited capture range. During data acquisition, capturing certain movement phases may exceed the imaging range. This can result in the loss of partial target information, reducing the accuracy of the registration process.

Therefore, there is a need for further research into a variety of motion designs considering different factors. Simultaneously, when making comparisons between different populations, it is crucial to ensure consistency in body position, speed, load, and limb movements to minimize errors.

4.3. Radiation safety

DFIS technology possesses non-invasive and high-precision characteristics, playing an irreplaceable role in monitoring cervical spine in vivo movements. However, since its imaging relies on X-ray imaging technology, there is a possibility of subjecting participants to a certain dose of ionizing radiation during the measurement process (0.08–4 ms). These places higher demands on researchers to accurately calculate sample sizes and optimize experimental designs, including the number of collections and total duration, while ensuring radiation safety.

4.4. Clinical applications and technical challenges

Cervical spine motion measurements can enhance understanding of cervical spine structure and function. These studies serve as a benchmark for postoperative spinal kinematics, guide patient rehabilitation, prevent hazardous activities, and inform the design of artificial intervertebral discs. In clinical guidance, Anderst et al. proposed that the C6–C7 motion segment continues to have a greater impact near the end of the ROM [44]. Clinicians can advise patients to avoid end-range positions to reduce the demand on the intervertebral discs in the lower motion segments [44]. However, the equipment required for DFIS is unique, with limited commercial availability and fewer institutions possessing the corresponding hardware. Future research in the technology should focus on improving the acquisition range of the device as well as improving its ease of use.

Research on cervical spine pathology is currently focused on post-ACDF and post-ADR, conservative treatment, with relatively fewer studies on other surgical techniques. At the same time, there is a lack of preoperative kinematic data and symptom presentation in studies of cervical spine patients. Some authors have pointed out that this lack of information is due to the high variability in preoperative ROM caused by pain, thus reducing the reference value of such data [54,27]. Additionally, most authors have not differentiated patients based on preoperative symptoms, time interval from surgery to measurement, postoperative rehabilitation, or other postoperative care factors. Epidemiological reports indicate a higher prevalence of postoperative complications in patients undergoing multi-level fusion [67]. Furthermore, the differences in research results may be attributed to variations in the age and pathological characteristics of the study population. Therefore, when studying the postoperative kinematic characteristics of the cervical spine, it is important to comprehensively consider multiple factors such as age, preoperative pathology, and surgical approach.

5. Limitation

This study has the following limitations. Firstly, despite meticulous search and screening, there remains an issue of limited scope and low consistency of evaluated indicators in the retrieved studies. As a result, meta-analysis could not be conducted, thus restricting the evidence level of this review. Secondly, due to variations in the principles of different evaluation methods and inconsistent evaluation indicators. This paper did not directly compare other assessment methods of cervical spine motion with DFIS. However, the study still included 30 relevant studies, providing a preliminary analysis and review of the research methods and application outcomes of DFIS in the cervical spine from various perspectives. This can be used as a reference for relevant researchers.

6. Conclusions

DFIS offers a novel solution for accurately capturing in vivo cervical spine motion, preliminarily meeting both clinical and research needs. This technology can be applied to various joints in the human body, particularly advantageous for the cervical spine, which features rich soft tissue and complex internal skeletal structures. In research, DFIS has been utilized to quantify the kinematics of intervertebral discs, intervertebral foramina, and zygapophyseal joints during motion. Furthermore, DFIS has been employed in further analyses to determine the kinematic characteristics of joint structures such as transverse processes, intervertebral discs, and ligaments. Particularly in recent years, scholars have utilized DFIS to assess the biomechanical features of cervical spines after ACDF and ADR surgeries. This has provided a basis for evaluating the effects of surgery on adjacent joints and differences between surgical methods. Future applications may consider employing DFIS to further explore cervical spine motion in different populations and pathological conditions. To provide evidence for assessing surgical indications, evaluating surgical outcomes, and predicting long-term prognosis of cervical spine issues. Future technological research could consider improvements to DFIS to enhance its user-friendliness in clinical settings.

Data availability statement

Data included in study/supplementary material/referenced in study.

Ethical statement

The ethical statement is not applicable in this study as this is a review paper, and we are using secondary published information.

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CRediT authorship contribution statement

Yuanbiao Luo: Supervision, Methodology, Conceptualization. **Xinwei Huang:** Resources, Formal analysis. **Yongda Yue:** Resources, Formal analysis. **Xiande Lin:** Writing – original draft. **Guoxian Chen:** Writing – original draft. **Kun Wang:** Writing – review & editing, Visualization, Validation, Funding acquisition. **Ye Luo:** Writing – original draft, Validation, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] A. Nouri, L. Tetreault, A. Singh, S.K. Karadimas, M.G. Fehlings, Degenerative cervical myelopathy: epidemiology, genetics, and pathogenesis, Spine 40 (2015) E675–E693, https://doi.org/10.1097/BRS.0000000000000913.
[2] M. Gallucci, N. Limbucci, A. Paonessa, A. Splendiani, Degenerative disease of the spine, Neuroimaging Clin. 17 (2007) 87–103, https://doi.org/10.1016/j.nic.2007.01.002.
[3] N.V. Jaumard, W.C. Welch, B.A. Winkelstein, Spinal facet joint biomechanics and mechanotransduction in normal, injury and degenerative conditions, J. Biomech. Eng. 133 (2011) 071010, https://doi.org/10.1115/1.4004493.
[4] F. Akter, M. Kotter, Pathobiology of degenerative cervical myelopathy, Neurosurg. Clin. 29 (2018) 13–19, https://doi.org/10.1016/j.nec.2017.09.015.
[5] T. Ishii, Y. Mukai, N. Hosono, H. Sakaura, R. Fujii, Y. Nakajima, S. Tamura, K. Sugamoto, H. Yoshikawa, Kinematics of the subaxial cervical spine in rotation in vivo three-dimensional analysis, Spine 29 (2004) 2826–2831, https://doi.org/10.1097/01.brs.0000147806.31675.6b.
[6] T. Ishii, Y. Mukai, N. Hosono, H. Sakaura, R. Fujii, Y. Nakajima, S. Tamura, M. Iwasaki, H. Yoshikawa, K. Sugamoto, Kinematics of the cervical spine in lateral bending: in vivo three-dimensional analysis, Spine 31 (2006) 155–160, https://doi.org/10.1097/01.brs.0000195173.47334.1f.
[7] A. Humadi, S. Dawood, K. Halldin, B. Freeman, RSA in spine: a review, Global Spine J. 7 (2017) 811–820, https://doi.org/10.1177/2192568217701722.
[8] J. Novosad, F. Cheriet, Y. Petit, H. Labelle, Three-dimensional (3-D) reconstruction of the spine from a single X-ray image and prior vertebra models, IEEE Trans. Biomed. Eng. 51 (2004) 1628–1639, https://doi.org/10.1109/TBME.2004.827537.
[9] J.D. John, G. Saravana Kumar, N. Yoganandan, Cervical spine morphology and ligament property variations: a finite element study of their influence on sagittal bending characteristics, J. Biomech. 85 (2019) 18–26, https://doi.org/10.1016/j.jbiomech.2018.12.044.

[10] Z. Li, D.-J. Chen, Z. Liu, B. Tang, Y. Zhong, G. Li, Z. Wan, Motion characteristics of the lower lumbar spine in individuals with different pelvic incidence: an in vivo biomechanical study, Clin. Biomech. 88 (2021) 105419, https://doi.org/10.1016/j.clinbiomech.2021.105419.
[11] H. Wang, C. Zhou, Y. Yu, C. Wang, T.-Y. Tsai, C. Han, G. Li, T. Cha, Quantifying the ranges of relative motions of the intervertebral discs and facet joints in the normal cervical spine, J. Biomech. 112 (2020) 110023, https://doi.org/10.1016/j.jbiomech.2020.110023.
[12] S. Wang, P. Passias, G. Li, G. Li, K. Wood, Measurement of vertebral kinematics using noninvasive image matching method-validation and application, Spine 33 (2008) E355–E361, https://doi.org/10.1097/BRS.0b013e3181715295.
[13] W.J. Anderst, W.F. Donaldson, J.Y. Lee, J.D. Kang, Cervical spine intervertebral kinematics with respect to the head are different during flexion and extension motions, J. Biomech. 46 (2013) 1471–1475, https://doi.org/10.1016/j.jbiomech.2013.03.004.
[14] C.-C. Lin, T.-W. Lu, T.-M. Wang, C.-Y. Hsu, S.-J. Hsu, T.-F. Shih, In vivo three-dimensional intervertebral kinematics of the subaxial cervical spine during seated axial rotation and lateral bending via a fluoroscopy-to-CT registration approach, J. Biomech. 47 (2014) 3310–3317, https://doi.org/10.1016/j.jbiomech.2014.08.014.
[15] W.J. Anderst, Bootstrap prediction bands for cervical spine intervertebral kinematics during in vivo three-dimensional head movements, J. Biomech. 48 (2015) 1270–1276, https://doi.org/10.1016/j.jbiomech.2015.02.054.
[16] W.J. Anderst, W.F. Donaldson III, J.Y. Lee, J.D. Kang, Three-dimensional intervertebral kinematics in the healthy young adult cervical spine during dynamic functional loading, J. Biomech. 48 (2015) 1286–1293, https://doi.org/10.1016/j.jbiomech.2015.02.049.
[17] H. Mao, S.J. Driscoll, J.-S. Li, G. Li, K.B. Wood, T.D. Cha, Dimensional changes of the neuroforamina in subaxial cervical spine during in vivo dynamic flexion-extension, Spine J. 16 (2016) 540–546, https://doi.org/10.1016/j.spinee.2015.11.052.
[18] V. Chang, A. Basheer, T. Baumer, D. Oravec, C.P. McDonald, M.J. Bey, S. Bartol, Y.N. Yeni, Dynamic measurements of cervical neural foramina during neck movements in asymptomatic young volunteers, Surg. Radiol. Anat. : SRA 39 (2017) 1069–1078, https://doi.org/10.1007/s00276-017-1847-6.
[19] Y. Yu, H. Mao, J.-S. Li, T.-Y. Tsai, L. Cheng, K.B. Wood, G. Li, T.D. Cha, Ranges of cervical intervertebral disc deformation during an in vivo dynamic flexion-extension of the neck, J. Biomech. Eng. 139 (2017), https://doi.org/10.1115/1.4036311.
[20] W. Anderst, B. Rynearson, T. West, W. Donaldson, J. Lee, Dynamic in vivo 3D atlantoaxial spine kinematics during upright rotation, J. Biomech. 60 (2017) 110–115, https://doi.org/10.1016/j.jbiomech.2017.06.007.
[21] Y. Yu, J.-S. Li, T. Guo, Z. Lang, J.D. Kang, L. Cheng, G. Li, T.D. Cha, Normal intervertebral segment rotation of the subaxial cervical spine: an in vivo study of dynamic neck motions, Journal of Orthopaedic Translation 18 (2019) 32–39, https://doi.org/10.1016/j.jot.2018.12.002.
[22] S.H. Kim, D.W. Ham, J.I. Lee, S.W. Park, M.J. Ko, S.-B. Koo, K.-S. Song, Locating the instant center of rotation in the subaxial cervical spine with biplanar fluoroscopy during in vivo dynamic flexion-extension, Clin. Orthop. Surg. 11 (2019) 482–489, https://doi.org/10.4055/cios.2019.11.4.482.
[23] C. Zhou, H. Wang, C. Wang, T.-Y. Tsai, Y. Yu, P. Ostergaard, G. Li, T. Cha, Intervertebral range of motion characteristics of normal cervical spinal segments (C0-T1) during in vivo neck motions, J. Biomech. 98 (2020) 109418, https://doi.org/10.1016/j.jbiomech.2019.109418.
[24] C. Zhou, R. Guo, C. Wang, T.Y. Tsai, Y. Yu, W. Wang, G. Li, T. Cha, Ligament deformation patterns of the craniocervical junction during head axial rotation tracked by biplane fluoroscopes, Clin. Biomech. 88 (2021) 105442, https://doi.org/10.1016/j.clinbiomech.2021.105442.
[25] W. Anderst, E. Baillargeon, W. Donaldson, J. Lee, J. Kang, Motion path of the instant center of rotation in the cervical spine during in vivo dynamic flexion-extension: implications for artificial disc design and evaluation of motion quality after arthrodesis, Spine 38 (2013) E594–E601, https://doi.org/10.1097/BRS.0b013e31828ca5c7.
[26] W. Anderst, W. Donaldson, J. Lee, J. Kang, Cervical disc deformation during flexion-extension in asymptomatic controls and single-level arthrodesis patients, J. Orthop. Res. 31 (2013) 1881–1889, https://doi.org/10.1002/jor.22437.
[27] W.J. Anderst, W.F. Donaldson III, J.Y. Lee, J.D. Kang, Cervical motion segment percent contributions to flexion-extension during continuous functional movement in control subjects and arthrodesis patients, Spine 38 (2013) E533–E539, https://doi.org/10.1097/BRS.0b013e318289378d.
[28] W.J. Anderst, J.Y. Lee, W.F. Donaldson III, J.D. Kang, Six-Degrees-of-Freedom cervical spine range of motion during dynamic flexion-extension after single-level anterior arthrodesis comparison with asymptomatic control subjects, Journal of Bone and Joint Surgery-American 95A (2013) 497–506, https://doi.org/10.2106/JBJS.K.01733.
[29] W.J. Anderst, W.F. Donaldson III, J.Y. Lee, J.D. Kang, In vivo lenCervical facet joint capsule deformation during flexion-extension, Spine 39 (2014) E514–E520, https://doi.org/10.1097/BRS.0000000000000235.
[30] C.P. McDonald, V. Chang, M. McDonald, N. Ramo, M.J. Bey, S. Bartol, Three-dimensional motion analysis of the cervical spine for comparison of anterior cervical decompression and fusion versus artificial disc replacement in 17 patients: clinical study, J. Neurosurg. Spine 20 (2014) 245–255, https://doi.org/10.3171/2013.11.SPINE13392.
[31] W. Anderst, Narrative review of the in vivo mechanics of the cervical spine after anterior arthrodesis as revealed by dynamic biplane radiography, J. Orthop. Res. 34 (2016) 22–30, https://doi.org/10.1002/jor.23042.
[32] Y.N. Yeni, T. Baumer, D. Oravec, A. Basheer, C.P. McDonald, M.J. Bey, S.W. Bartol, V. Chang, Dynamic foraminal dimensions during neck extension and rotation in fusion and artificial disc replacement: an observational study, Spine J. 18 (2018) 575–583, https://doi.org/10.1016/j.spinee.2017.08.248.
[33] S. Azad, D. Oravec, T. Baumer, A. Schildcrout, P. White, A. Basheer, M.J. Bey, S.W. Bartol, V. Chang, Y.N. Yeni, Dynamic foraminal dimensions during neck motion 6.5 Years after fusion and artificial disc replacement, PLoS One 15 (2020) e0237350, https://doi.org/10.1371/journal.pone.0237350.
[34] T. Guo, Y. Yu, C.-C. Zhou, K. Khan, H.-M. Wang, G.-A. Li, T. Cha, In vivo ranges of motion of cervical segments in patients with cervical spondylosis during dynamic neck motions, Chin. Med. J. 134 (2021) 478–480, https://doi.org/10.1097/CM9.0000000000001209.
[35] S.R. Chen, C.M. LeVasseur, S. Pitcairn, A.S. Kanter, D.O. Okonkwo, J.D. Shaw, W.F. Donaldson, J.Y. Lee, W.J. Anderst, Surgery-related factors do not affect short-term adjacent segment kinematics after anterior cervical arthrodesis, Spine 46 (2021) 1630–1636, https://doi.org/10.1097/BRS.0000000000004080.
[36] C.M. LeVasseur, S. Pitcairn, J. Shaw, W.F. Donaldson, J.Y. Lee, W.J. Anderst, The effects of age, pathology, and fusion on cervical neural foramen area, J. Orthop. Res. 39 (2021) 671–679, https://doi.org/10.1002/jor.24663.
[37] S.R. Chen, C.M. LeVasseur, S. Pitcairn, M.A. Munsch, B.K. Couch, A.S. Kanter, D.O. Okonkwo, J.D. Shaw, W.F. Donaldson, J.Y. Lee, et al., In vivo evidence of early instability and late stabilization in motion segments immediately superior to anterior cervical arthrodesis, Spine 47 (2022) 1234–1240, https://doi.org/10.1097/BRS.0000000000004388.
[38] C.M. LeVasseur, S.W. Pitcairn, J.D. Shaw, W.F. Donaldson, J.Y. Lee, W.J. Anderst, The effects of pathology and one-level versus two-level arthrodesis on cervical spine intervertebral helical Axis of motion, J. Biomech. 133 (2022), https://doi.org/10.1016/j.jbiomech.2022.110960. N.PAG-N.PAG.
[39] C.M. LeVasseur, S.W. Pitcairn, D.O. Okonkwo, A.S. Kanter, J.D. Shaw, W.F. Donaldson, J.Y. Lee, W.J. Anderst, In vivo changes in dynamic adjacent segment motion 1 Year after one and two-level cervical arthrodesis, Ann. Biomed. Eng. 50 (2022) 871–881, https://doi.org/10.1007/s10439-022-02964-7.
[40] A.A. Oyekan, C.M. LeVasseur, J.D. Shaw, W.F. Donaldson, J.Y. Lee, W.J. Anderst, Changes in intervertebral sagittal alignment of the cervical spine from supine to upright, J. Orthop. Res. (2022), https://doi.org/10.1002/jor.25500.
[41] Y.N. Yeni, S. Azad, D. Oravec, A. Schildcrout, A. Basheer, M.J. Bey, S.W. Bartol, V. Chang, Intervertebral kinematics during neck motion 6.5 Years after fusion and artificial disc replacement, Clin. Biomech. 99 (2022) 105756, https://doi.org/10.1016/j.clinbiomech.2022.105756.
[42] C.P. McDonald, C.C. Bachison, V. Chang, S.W. Bartol, M.J. Bey, Three-dimensional dynamic in vivo motion of the cervical spine: assessment of measurement accuracy and preliminary findings, Spine J. 10 (2010) 497–504, https://doi.org/10.1016/j.spinee.2010.02.024.
[43] W.J. Anderst, E. Baillargeon, W.F. Donaldson, J.Y. Lee, J.D. Kang, Validation of a noninvasive technique to precisely measure in vivo three-dimensional cervical spine movement, Spine 36 (2011) E393–E400, https://doi.org/10.1097/BRS.0b013e31820b7e2f.
[44] W.J. Anderst, W.F. Donaldson, J.Y. Lee, J.D. Kang, Cervical motion segment contributions to head motion during Flexion\extension, lateral bending, and axial rotation, Spine J. : official journal of the North American Spine Society 15 (2015) 2538–2543, https://doi.org/10.1016/j.spinee.2015.08.042.
[45] C. Barrey, S. Champain, S. Campana, A. Ramadan, G. Perrin, W. Skalli, Sagittal alignment and kinematics at instrumented and adjacent levels after total disc replacement in the cervical spine, Eur. Spine J. : official publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society 21 (2012) 1648–1659, https://doi.org/10.1007/s00586-012-2180-8.

[46] N. Bogduk, S. Mercer, Biomechanics of the cervical spine. I: normal kinematics, Clin. BioMech. 15 (2000) 633–648, https://doi.org/10.1016/S0268-0033(00)00034-6.
[47] B. Aour, N. Damba, Finite element investigation of the intervertebral disc behaviour, Comput. Methods Biomech. Biomed. Eng. 17 (Suppl 1) (2014) 58–59, https://doi.org/10.1080/10255842.2014.931113.
[48] A.P. Del Palomar, B. Calvo, M. Doblaré, An accurate finite element model of the cervical spine under quasi-static loading, J. Biomech. 41 (2008) 523–531, https://doi.org/10.1016/j.jbiomech.2007.10.012.
[49] M. Hussain, R.N. Natarajan, H.S. An, G.B.J. Andersson, Progressive disc degeneration at C5-C6 segment affects the mechanics between disc heights and posterior facets above and below the degenerated segment: a flexion-extension investigation using a poroelastic C3-T1 finite element model, Med. Eng. Phys. 34 (2012) 552–558, https://doi.org/10.1016/j.medengphy.2011.08.014.
[50] 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.
[51] F. Kolstad, G. Myhr, K.A. Kvistad, O.P. Nygaard, G. Leivseth, Degeneration and height of cervical discs classified from MRI compared with precise height measurements from radiographs, Eur. J. Radiol. 55 (2005) 415–420, https://doi.org/10.1016/j.ejrad.2005.02.005.
[52] N. Yoganandan, S. Kumaresan, F.A. Pintar, Biomechanics of the cervical spine Part 2. Cervical spine soft tissue responses and biomechanical modeling, Clin. Biomech. 16 (2001) 1–27, https://doi.org/10.1016/S0268-0033(00)00074-7.
[53] W. Frobin, G. Leivseth, M. Biggemann, P. Brinckmann, Sagittal plane segmental motion of the cervical spine. A new precision measurement protocol and normal motion data of healthy adults, Clin. BioMech. 17 (2002) 21–31, https://doi.org/10.1016/S0268-0033(01)00105-X.
[54] C.A. Reitman, J.A. Hipp, L. Nguyen, S.I. Esses, Changes in segmental intervertebral motion adjacent to cervical arthrodesis: a prospective study, Spine 29 (2004) E221–E226, https://doi.org/10.1097/00007632-200406010-00022.
[55] S.-K. Wu, L.-C. Kuo, H.-C.H. Lan, S.-W. Tsai, C.-L. Chen, F.-C. Su, The quantitative measurements of the intervertebral angulation and translation during cervical flexion and extension, Eur. Spine J. : official publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society 16 (2007) 1435–1444, https://doi.org/10.1007/s00586-007-0372-4.
[56] M.A. Hansen, H.J. Kim, E.M. van Alstyne, A.C. Skelly, M.G. Fehlings, Does postsurgical cervical deformity affect the risk of cervical adjacent segment pathology? A systematic review, Spine 37 (2012) S75–S84, https://doi.org/10.1097/BRS.0b013e31826d62a6.
[57] P. Kraemer, M.G. Fehlings, R. Hashimoto, M.J. Lee, P.A. Anderson, J.R. Chapman, A. Raich, D.C. Norvell, A systematic review of definitions and classification systems of adjacent segment pathology, Spine 37 (2012) S31–S39, https://doi.org/10.1097/BRS.0b013e31826d7dd6.
[58] J.M. Lombardi, A.C. Vivas, M.F. Gornet, T.H. Lanman, J.R. McConnell, R.F. Dryer, J.K. Burkus, K.D. Riew, The effect of ACDF or arthroplasty on cervicogenic headaches: a post hoc analysis of a prospective, multicenter study with 10-year follow-up, Clinical spine surgery 33 (2020) 339–344, https://doi.org/10.1097/BSD.0000000000001087.
[59] A.S. Hilibrand, G.D. Carlson, M.A. Palumbo, P.K. Jones, H.H. Bohlman, Radiculopathy and myelopathy at segments adjacent to the site of a previous anterior cervical arthrodesis, J. Bone Jt. Surg. Am. Vol. 81 (1999) 519–528, https://doi.org/10.2106/00004623-199904000-00009.
[60] J.S. Schwab, D.J. DiAngelo, K.T. Foley, Motion compensation associated with single-level cervical fusion: where does the lost motion go? Spine 31 (2006) 2439–2448, https://doi.org/10.1097/01.brs.0000239125.54761.23.
[61] K.-J. Song, B.-W. Choi, T.-S. Jeon, K.-B. Lee, H. Chang, Adjacent segment degenerative disease: is it due to disease progression or a fusion-associated phenomenon? Comparison between segments adjacent to the fused and non-fused segments, Eur. Spine J. : official publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society 20 (2011) 1940–1945, https://doi.org/10.1007/s00586-011-1864-9.
[62] W. Xiong, J. Zhou, C. Sun, Z. Chen, X. Guo, X. Huo, S. Liu, J. Li, Y. Xue, 0.5- to 1-fold intervertebral distraction is a protective factor for adjacent segment degeneration in single-level anterior cervical discectomy and fusion, Spine 45 (2020) 96–102, https://doi.org/10.1097/BRS.0000000000003209.
[63] T.F. Fekete, F. Porchet, Overview of disc arthroplasty-past, present and future, Acta Neurochir. 152 (2010) 393–404, https://doi.org/10.1007/s00701-009-0529-5.
[64] Y. Hu, G. Lv, S. Ren, D. Johansen, Mid- to long-term outcomes of cervical disc arthroplasty versus anterior cervical discectomy and fusion for treatment of symptomatic cervical disc disease: a systematic review and meta-analysis of eight prospective randomized controlled trials, PLoS One 11 (2016) e0149312, https://doi.org/10.1371/journal.pone.0149312.
[65] K. Verma, S.D. Gandhi, M. Maltenfort, T.J. Albert, A.S. Hilibrand, A.R. Vaccaro, K.E. Radcliff, Rate of adjacent segment disease in cervical disc arthroplasty versus single-level fusion: meta-analysis of prospective studies, Spine 38 (2013) 2253–2257, https://doi.org/10.1097/BRS.0000000000000052.
[66] M. Matsumoto, E. Okada, D. Ichihara, K. Watanabe, K. Chiba, Y. Toyama, H. Fujiwara, S. Momoshima, Y. Nishiwaki, T. Hashimoto, et al., Age-related changes of thoracic and cervical intervertebral discs in asymptomatic subjects, Spine 35 (2010) 1359–1364, https://doi.org/10.1097/BRS.0b013e3181c17067.
[67] J.D. Stull, D.K.C. Goyal, J.J. Mangan, S.N. Divi, J.C. McKenzie, D.S. Casper, K. Okroj, C.K. Kepler, A.R. Vaccaro, G.D. Schroeder, et al., The outcomes of patients with neck pain following ACDF: a comparison of patients with radiculopathy, myelopathy, or mixed symptomatology, Spine 45 (2020) 1485–1490, https://doi.org/10.1097/BRS.0000000000003613.