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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 Following Arthrodesis

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Abstract

Study Design—Case-control.

Objective—To characterize the motion path of the instant center of rotation (ICR) at each cervical motion segment from C2 to C7 during dynamic flexion-extension in asymptomatic subjects. To compare asymptomatic and single-level arthrodesis patient ICR paths.

Summary of Background Data—The ICR has been proposed as an alternative to range of motion (ROM) for evaluating the quality of spine movement and for identifying abnormal midrange kinematics. The motion path of the ICR during dynamic motion has not been reported.

Methods—20 asymptomatic controls, 12 C5/C6 and 5 C6/C7 arthrodesis patients performed full ROM flexion-extension while biplane radiographs were collected at 30 Hz. A previously validated tracking process determined three-dimensional vertebral position with sub-millimeter accuracy. The finite helical axis method was used to calculate the ICR between adjacent vertebrae. A linear mixed-model analysis identified differences in the ICR path among motion segments and between controls and arthrodesis patients.

Results—From C2/C3 to C6/C7, the mean ICR location moved superior for each successive motion segment ($p < .001$). The AP change in ICR location per degree of flexion-extension decreased from the C2/C3 motion segment to the C6/C7 motion segment ($p < .001$). Asymptomatic subject variability (95% CI) in the ICR location averaged ± 1.2 mm in the SI direction and ± 1.9 mm in the AP direction over all motion segments and flexion-extension angles. Asymptomatic and arthrodesis groups were not significantly different in terms of average ICR position (all $p > .091$) or in terms of the change in ICR location per degree of flexion-extension (all $p > .249$).

Conclusions—To replicate asymptomatic in vivo cervical motion, disc replacements should account for level-specific differences in the location and motion path of ICR. Single-level anterior arthrodesis does not appear to affect cervical motion quality during flexion-extension.

Keywords

adjacent segment degeneration; kinematics; finite helical axis; Anterior cervical fusion; disc replacement

Introduction

Cervical spine kinematics are most often assessed through static lateral radiographs collected in the full-flexion and full-extension positions^{1–3}. Intervertebral range of motion (ROM) is the most common measurement acquired from these static end-range images. However, ROM is highly variable among subjects^{1,2,4–6} and ROM measurements fail to characterize mid-range motion where the majority of our activities of daily living occur^{7,8}. Furthermore, ROM only provides information about the *quantity* of intervertebral motion (i.e. total translation and total rotation), while failing to characterize the *quality* of motion (i.e. how the motion occurs).

The instant center of rotation (ICR) has been proposed as an alternative to ROM for evaluating the quality of spine movement and for identifying abnormal cervical spine kinematics⁹. The location of the ICR between two adjacent cervical vertebrae reflects the combined relative translation and rotation that occur during flexion-extension (Figure 1). It has been proposed that the location of the ICR has clinical significance, as specific abnormalities in the ICR may correspond to specific pathologies¹⁰. Additionally, ICRs may be useful in diagnosing deviations of normal segmental motion in the sagittal plane¹¹ and in diagnosing whiplash injuries¹². The ICR has recently been used to evaluate cervical adjacent segment motion quality following arthrodesis and arthroplasty^{13–15}.

The location of the center of rotation for each cervical motion segment has traditionally been measured using radiographs collected at the ends of the ROM^{13,14,16–18}, although one study reported an average center of rotation by using a sequence of radiographs collected during the flexion-extension motion¹¹. These single locations for the center of rotation, calculated from end-range radiographs or from averaged data, fail to account for the fact that the ICR may change location during dynamic motion and may not be fully described by a single point¹⁹.

Correctly identifying the in vivo path of the center of rotation between adjacent cervical vertebrae is clinically significant due to the recent FDA approval of several cervical disc replacement devices in the United States^{20–22}. These disc replacements have either fixed or variable centers of rotation, and it is not clear how well these designs mimic in vivo cervical spine movement. Additionally, an abnormal motion path of the ICR in motion segments adjacent to arthrodesis may reflect altered adjacent segment loading, potentially leading to adjacent segment degeneration.

The first objective of this study was to characterize the movement path of the ICR at each cervical motion segment from C2 to C7 during dynamic in vivo flexion-extension in asymptomatic subjects. It was hypothesized that the ICR location would undergo significant translation in the anterior-posterior direction, but not in the superior-inferior direction, during flexion-extension. It was also hypothesized that the path of the ICR would be unique for each motion segment in asymptomatic spines. The second objective of this study was to perform a preliminary comparison of ICR paths in asymptomatic subjects and single-level arthrodesis patients during flexion-extension. It was hypothesized that the ICR path in motion segments adjacent to the arthrodesis would be significantly different in arthrodesis patients when compared to corresponding motion segments in asymptomatic subjects.

Materials and Methods

All subjects provided informed consent prior to participating in this Institutional Review Board-approved study. Participants included 20 asymptomatic subjects (7 M, 13 F, average age 46±6 yrs.), 12 C5/C6 single-level anterior arthrodesis patients (2 M, 10 F, average age 47±10 yrs., 7±1 months post surgery, 9 autograft, 3 allograft) and 5 C6/C7 single-level

anterior arthrodesis patients (2 M, 3 F, average age 43 ± 8 yrs., 7 ± 1 months post surgery, 1 autograft, 4 allograft). Surgical indications were spondylotic radiculopathy due to disc herniation or stenosis. All surgeries included fusion instrumentation, and patients were placed in a cervical collar for 3 weeks post-surgery. Radiographic union was confirmed prior to dynamic movement testing. Pregnant women, patients diagnosed with osteoporosis, and patients with any other injury or disease that interferes with spine function were excluded. Healthy asymptomatic subjects were recruited through an employee newsletter to approximately match the age and sex distribution of the arthrodesis patients.

High-resolution CT scans (GE Lightspeed 16) ($0.29 \text{ mm} \times 0.29 \text{ mm} \times 1.25 \text{ mm}$ voxels) of the cervical spine (C2–C7) were acquired on each participant. Bone tissue was segmented from the CT volume using a combination of commercial software (Mimics software, Materialise, Leuven, Belgium) and manual segmentation²³. A three-dimensional (3D) model of each vertebra was generated from the segmented bone tissue. Eight markers were interactively placed on the 3D bone models to define bone-specific anatomic coordinate systems (4 on each endplate: most anterior, most posterior, left edge and right edge). The origin of the anatomic coordinate system for each bone was defined as the average of the most anterior and most posterior points on the superior and inferior endplates.

Subjects were seated within a biplane X-ray system and directed to continuously move their head and neck through their entire range of flexion-extension. A metronome set at 40 to 44 beats per minute was used to ensure the participants moved at a continuous, steady pace to complete each full movement cycle in 3 seconds or less. Biplane radiographs were collected simultaneously at 30 images per second for 3 seconds for each trial of continuous flexion-extension (X-ray parameters: 70 KV, 160 mA, 2.5 ms X-ray pulses, source-to-subject distance 140 cm). Radiographs were recorded for 2 or 3 trials for each subject, resulting in a total of 96 movement trials analyzed for this study. A static trial with the subject looking forward with the head in the neutral position was also collected for each participant. The effective radiation dose for each dynamic flexion-extension motion trial was estimated to be 0.16 mSv (determined using PCXMC simulation software, STUK, Helsinki, Finland). In comparison, the effective dose of a cervical spine CT scan has been reported to be between 3.0 mSv and 4.36 mSv^{24,25}.

A previously validated model-based tracking process was used to determine three-dimensional vertebral position with sub-millimeter accuracy²⁶ for all static and dynamic trials (Figure 2). Details describing the volumetric model-based tracking process, including hardware and software specifications, calibration and distortion correction procedures, and computational algorithms have been described previously^{26–29}.

Tracked data was smoothed using a 1.0 Hz fourth-order, low-pass Butterworth filter³⁰. The intervertebral flexion-extension angle in each frame of the continuous dynamic trial was normalized to the static neutral trial for each subject. The C2 vertebra was not sufficiently captured in the CT scan and/or in the biplane radiographs for several arthrodesis patients. Therefore, ICR data at the C2/C3 motion segment was not included in the analysis for arthrodesis patients.

The finite helical axis method³¹ was used to calculate the three-dimensional axis of rotation between adjacent vertebrae for each 2° change in intervertebral flexion-extension. The ICR was defined as the point at which this three-dimensional axis of rotation vector intersected the sagittal anatomical plane of the inferior vertebra. The anterior-posterior (AP) and superior-inferior (SI) location of each ICR was defined with respect to the inferior bone anatomic coordinate system and expressed as a percentage of the inferior bone size. The path of ICR positions during flexion-extension was interpolated at 1° increments of

intervertebral flexion-extension to allow for comparison among trials and participants. Multiple trials from the same subject were averaged to yield a single average dataset for each subject used for statistical analysis. The instant center of rotation was not calculated for the motion segment included in the arthrodesis.

The ICR calculation is highly sensitive to a number of factors, including the amount of rotation that occurs between start and end images (i.e. the step size), tracking (or digitizing) error, and the distance from the moving body to its center of rotation^{32–35}. We previously completed a parametric analysis of factors affecting ICR accuracy and precision during in vivo flexion-extension³⁶. Processing the data as described above, the within-subject reliability in ICR path location was 0.5 mm in the SI direction and 1.0 mm in the AP direction. A computational experiment demonstrated the in vivo accuracy in ICR location was between 1.1 mm and 3.1 mm³⁶. This parametric analysis also indicated there was no significant difference between ICR locations calculated during the flexion and extension movement. Therefore, ICRs calculated during the flexion movement were averaged with ICRs calculated at corresponding angles during the extension movement for the present analysis.

A previous study that calculated cervical motion segment ICRs indicated inter-subject variability in the ICR location would range between 1.0 mm and 2.2 mm¹⁵. Setting power to 80%, with an estimated inter-subject variability of 1.0 to 2.2 mm, the sample size calculation³⁷ indicated that between 6 and 21 subjects would be required per group (for inter-subject variability of 1.0 and 2.2 mm, respectively) in order to identify a difference between groups of 2 mm in ICR location.

A linear mixed-model analysis was performed to characterize differences in the path of the center of rotation according to motion segment in control subjects. Additionally, the length of the ICR path in the SI and AP directions was quantified. In order to normalize the path lengths among motion segments with different amounts of flexion-extension, the change in location of the ICR per degree of intervertebral flexion-extension was determined by fitting a line through the ICR location versus intervertebral angle paths for each motion segment of each subject. The change in ICR location per degree of flexion-extension was compared across motion segments using repeated measures analysis of variance. Differences in ICR paths between control subjects and arthrodesis groups were identified using linear mixed-model analysis. Significance was set at $p < .05$ for all tests, and the Bonferroni correction was applied to adjust for multiple comparisons in all cases.

Results

ICR data were available over different ranges of intervertebral flexion-extension for each participant due to inter-subject variability in flexion and extension range of motion at each motion segment. Therefore, analysis was restricted to flexion-extension angles that contained a sufficient number of participants in each group (n = at least 6 in the control group, at least 4 in the C5/C6 arthrodesis group and at least 3 in the C6/C7 arthrodesis group) (Table 1). For example, for the C4/C5 motion segment in the control group, the number of subjects available for each 1° increment of flexion from neutral to 10° of flexion was 19, 20, 19, 19, 18, 14, 11, 7, 5, 4, 2. Therefore, ICR values were included in the analysis up to +7° of flexion (7 participants) at the C4/C5 motion segment for the controls (Table 1).

Control Group

The mean SI location of the ICR became progressively more superior from the C2/C3 motion segment to the C6/C7 motion segment (Figure 3, Figure 4, Table 2). Significant differences in the mean SI location of the ICR were found between all motion segments (all

$p < .001$ after correction for multiple comparisons) except the C3/C4 and C4/C5 levels ($p = 1.000$). The average SI location of the ICR did not change significantly with intervertebral flexion-extension angle ($p = .747$). The interaction between flexion-extension angle and motion segment level also was not significant ($p = .844$), indicating the effect of flexion-extension angle on SI ICR location was not significantly different among motion segments.

The average AP location of the ICR path was posterior to the geometric center of the inferior vertebral body and not significantly different among levels (Figure 4, Figure 5, Table 2). The AP ICR location was significantly affected by the angle of intervertebral flexion-extension, indicating significant translation of the ICR in the AP direction during flexion-extension ($p < .001$). Furthermore, there was a significant interaction between intervertebral flexion-extension angle and motion segment level ($p < .001$), indicating differences among motion segments in the relationship between AP location of the ICR and intervertebral flexion-extension angle.

The change in ICR location in the AP direction per degree of flexion-extension generally decreased from the C2/C3 motion segment to the C6/C7 motion segment (Table 3). The change in ICR location in the AP direction per degree of flexion-extension was significantly different among all motion segments (all $p \leq .021$), with the exception of the C6/C7 motion segment, which was not different from the C4/C5 and C5/C6 motion segments (both $p = 1.000$) (Table 3).

The inter-subject variability in the ICR location in asymptomatic subjects, defined by the 95% CI of the mean at each intervertebral flexion-extension angle, averaged ± 1.2 mm in the SI direction and ± 1.9 mm in the AP direction across all intervertebral flexion-extension angles and all motion segments (Figure 4, Figure 5).

Asymptomatic vs. Arthrodesis

No significant differences between the control and arthrodesis groups were identified when comparing the average location of the ICR paths in the SI (all $p \geq .528$) or AP direction (all $p \geq .579$) (Table 4). The average 95% confidence interval of the difference in ICR location between asymptomatic and C5/C6 or C6/C7 arthrodesis patients was ± 1.4 mm and ± 2.0 mm, respectively. No significant differences were observed when comparing the control and arthrodesis groups in terms of the change in ICR location in the AP direction per degree of flexion-extension (all $p \geq .249$) (Table 5). The average 95% confidence intervals for the differences in the change in the AP ICR location per degree of flexion-extension between asymptomatic and arthrodesis groups was ± 0.6 mm/deg.

Discussion

This is believed to be the first report of the motion path of the ICR in the cervical spine during in vivo functional movement. This study has revealed important kinematic differences among motion segments during functional mid-range motion in asymptomatic subjects. These level-dependent differences include the average location of the ICR in the SI direction and the amount of AP translation in the ICR per degree of intervertebral flexion-extension. These findings clearly illustrate that if the goal of cervical disc replacements is to replicate in vivo motion, they should be designed to account for level-specific differences in the location and motion path of ICR. For example, although the average ICR in the AP direction was located posterior to the geometric center of each inferior vertebra, it is clear that the ICR translates significantly in the AP direction with flexion-extension, and that the amount of this translation varies by motion segment. Furthermore, although the SI position of the ICR did not change significantly within motion segments during flexion-extension, there were clear differences among motion segments in the average SI location of the ICR.

The center of rotation in the SI direction was located near the center of C3 for C2/C3 and moved progressively closer to the disc for each motion segment until C6/C7, where the ICR was located near the top endplate of C7 (Figure 3). This variation in the SI location of the ICR with respect to motion segment is in agreement with previous studies that have reported single ICR locations for each cervical motion segment^{11,16–18}.

In the current study, the inability to detect significant differences between the asymptomatic and arthrodesis groups was influenced by the sample size and by the effect size of the treatment. First, the relatively small sample sizes of the arthrodesis groups limited the statistical power of the study. However, the 95% confidence intervals of the differences between groups were quite small, indicating the ICR motion paths were consistent between control and surgical groups. Second, the effect size of the treatment (i.e. the differences between asymptomatic and arthrodesis groups) was small. For example, the mean difference between asymptomatic and arthrodesis groups was 0.6 mm for average ICR location and 0.2 mm/deg for ICR translation per degree of flexion-extension. The combination of narrow confidence intervals and small effect size provides preliminary evidence to suggest that single-level anterior arthrodesis does not appear to affect cervical motion quality during flexion-extension.

While the current results suggest that single-level arthrodesis does not affect the quality of motion in adjacent segments, the effects of single-level disc arthroplasty on adjacent segment motion quality remain unknown. Previous results investigating adjacent segment ICR following arthroplasty or fusion have been contradictory. While two studies have indicated arthroplasty¹³ and arthroplasty or fusion¹⁵ do not affect adjacent segment center of rotation, another study found arthroplasty shifted the center of rotation in the superior motion segment in comparison to fusion¹⁴. These studies, however, were performed using only full-flexion and full-extension radiographs to calculate a single, stationary center of rotation. Further investigation will be necessary to compare adjacent segment effects on the motion path of the ICR following arthroplasty or fusion. It is possible a poorly designed disc replacement could lead to significant alterations in adjacent segment motion quality. This may be the case with current disc replacement designs that have a fixed center of rotation and/or fail to allow for vertebral level differences in motion. The mechanical benefits of increased ROM associated with total disc replacements may be negated by poor motion quality, leading to no significant reduction in adjacent segment degeneration in comparison to arthrodesis^{38,39}.

A limitation of the current study was the relatively narrow, yet clinically important, age range of the subjects. ICR motion paths may differ in young and older spines, given the degenerative changes that occur with age^{40–43}. A second limitation was the fact that the arthrodesis subjects were tested approximately 7 months after surgery. This time frame is earlier than adjacent segment disease generally occurs⁴⁴. Therefore, while the present results provide valuable information regarding the short-term effects of arthrodesis, the results may not be representative of longer-term effects. Furthermore, the current data only assesses adjacent segment motion quality in single-level arthrodesis patients. The effects of multi-level arthrodesis on the quality of adjacent segment motion remain unknown.

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Key Points

1. If the objective of cervical disc replacements is to replicate in vivo motion, the disc replacements should account for level-specific differences in the location and motion path of ICR.
2. The center of rotation between adjacent vertebrae in asymptomatic control subjects was generally fixed in the superior-inferior (SI) direction, but it translated in the anterior-posterior (AP) direction during flexion-extension. The center of rotation in the SI direction was located near the center of C3 for C2/C3 and moved progressively superior (closer to the intervertebral disc) for each motion segment until C6/C7, where the ICR was located near the top endplate of C7.
3. Single-level anterior arthrodesis does not appear to affect adjacent segment motion quality during flexion-extension 7 months post-surgery.

Figure 1.

The effects of relative translation and rotation on the location of the instant center of rotation (ICR). A) The ICR is calculated using the perpendicular bisectors method as the top bone moves from position 1 to position 2 (light blue to dark blue) relative to the bottom bone. B) Increased anterior translation leads to a small anterior and large inferior shift in the ICR. C) Increased flexion leads to a large superior shift in the ICR.

Figure 2.

An illustration of the virtual X-ray system for model-based tracking. A 3D CT reconstruction of the bone was placed in a computer-generated reproduction of the X-ray system. Simulated X-rays were then passed through the 3D CT reconstruction to generate digitally reconstructed radiographs (DRRs). Bone position and orientation was determined by a computer algorithm that optimized the correlation between the DRRs (green in image) and the edge-enhanced radiographs (red in figure).

Figure 3.

Asymptomatic group average ICR paths during flexion-extension in the cervical spine. Black crosses denote ICR location at each motion segment for each 1° increment of flexion-extension at the motion segment, with the colored background denoting relative extension (blue) and flexion (red) at each motion segment. ICR locations were expressed relative to anatomic coordinate systems with origins at the geometric center of each vertebral body (red, green, blue arrows).

Figure 4.

The mean superior-inferior (SI) motion path of the ICR at each motion segment in asymptomatic controls at 1° increments of intervertebral flexion-extension. Error bars represent 95% confidence interval of the mean at each flexion-extension angle. ICR locations on the vertical axis are measured relative to the geometric center of the inferior vertebral body.

Figure 5.

The mean anterior-posterior (AP) motion path of the ICR at each motion segment in asymptomatic controls at 1° increments of intervertebral flexion-extension. Error bars represent 95% confidence interval of the mean at each flexion-extension angle. ICR locations on the vertical axis are measured relative to the geometric center of the inferior vertebral body.

Table 1

Flexion-extension range of motion included in the ICR analysis for each group and each motion segment. Negative (and positive) angles indicate extension (and flexion) range of motion relative to the neutral position at each motion segment.

		Group		
		Control	C5/C6 Arthrodesis	C6/C7 Arthrodesis
Motion Segment	C2/C3	-3° to +5°	N/A	N/A
	C3/C4	-5° to +6°	-5° to +5°	-2° to +4°
	C4/C5	-8° to +7°	-9° to +2°	-4° to +4°
	C5/C6	-5° to +6°	N/A	-6° to +4°
	C6/C7	-4° to +7°	-4° to +5°	N/A

Mean ICR location and 95% confidence interval (CI) of the mean location in the superior-inferior and anterior-posterior directions in asymptomatic subjects. Mean locations and 95% CI values are provided in millimeters (mm) from the center of the inferior vertebral body for each motion segment, with positive values denoting the superior and anterior directions and negative values denoting inferior and posterior directions. Significant SI differences were found between all motion segments (all $p < .001$ after adjusting for multiple comparisons) except the C3/C4 and C4/C5 levels ($p = 1.000$). No significant AP differences were found between any motion segments (all $p > .075$ after adjusting for multiple comparisons).

Table 2

Motion Segment	Lower 95% CI (mm)	Mean Superior-Inferior Location (mm)	Upper 95% CI (mm)	Lower 95% CI (mm)	Mean Anterior-Posterior Location (mm)	Upper 95% CI (mm)
C2/C3	-1.1	-0.3	0.5	-3.9	-2.8	-1.8
C3/C4	0.7	1.5	2.2	-2.7	-1.8	-0.8
C4/C5	0.9	1.6	2.3	-2.9	-1.9	-0.9
C5/C6	2.5	3.2	3.9	-3.1	-2.0	-1.0
C6/C7	5.1	5.9	6.7	-3.1	-2.0	-1.0

Table 3

Mean change in the AP location of the ICR per degree of intervertebral flexion-extension and 95% confidence interval (CI) of the change in AP location per degree of intervertebral flexion-extension in asymptomatic subjects. All units are millimeters per degree (mm/deg). Significant differences were found between all levels (all $p < .021$ after adjusting for multiple comparisons) except the C6/C7 level and the C4/C5 and C5/C6 levels (both $p = 1.000$).

Motion Segment	Lower 95% CI (mm/deg)	Change in AP ICR Location Per Degree of Flexion-Extension (mm/deg)	Upper 95% CI (mm/deg)
C2/C3	3.2	3.9	4.7
C3/C4	1.0	1.4	1.7
C4/C5	0.5	0.7	0.9
C5/C6	0.1	0.3	0.5
C6/C7	0.1	0.5	0.8

Difference in mean ICR location between groups (Asymptomatic - Arthrodesis) and 95% confidence interval (CI) of the difference in the superior-inferior (SI) and anterior-posterior (AP) directions. All units are millimeters (mm). None of the mean differences were statistically significant (all SI p .528; all AP p .579).

Table 4

Motion Segment ICR		Asymptomatic vs. C56 Arthrodesis			Asymptomatic vs. C67 Arthrodesis		
		Lower 95% CI	Mean Difference	Upper 95% CI	Lower 95% CI	Mean Difference	Upper 95% CI
C3/C4	SI	-1.8	-0.3	1.1	-0.9	1.1	3.1
	AP	-1.5	0.2	1.9	-4.1	-1.5	1.2
C4/C5	SI	-2.4	-1.0	0.5	-1.5	0.2	2.0
	AP	-1.2	0.2	1.6	-3.5	-1.4	0.7
C5/C6	SI	N/A	N/A	N/A	-1.9	0.2	2.3
	AP	N/A	N/A	N/A	-1.3	0.2	1.8
C6/C7	SI	-1.0	0.4	1.8	N/A	N/A	N/A
	AP	-0.6	0.7	2.0	N/A	N/A	N/A

Difference between groups (Asymptomatic – Arthrodesis) in change in ICR location per degree of intervertebral flexion-extension and 95% confidence interval (CI) of the difference in the anterior-posterior direction. All units are millimeters per degree (mm/deg). None of the mean differences were statistically significant (all p > .249).

Table 5

Motion Segment ICR	Asymptomatic vs. C56 Arthrodesis			Asymptomatic vs. C67 Arthrodesis		
	Lower 95% CI	Mean Difference	Upper 95% CI	Lower 95% CI	Mean Difference	Upper 95% CI
C3/C4	-1.4	-0.5	0.4	-0.1	0.7	1.5
C4/C5	-0.5	-0.1	0.2	-0.5	0.0	0.5
C5/C6	N/A	N/A	N/A	-0.3	0.1	0.5
C6/C7	-0.9	-0.3	0.3	N/A	N/A	N/A