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In Vivo Cervical Facet Joint Capsule Deformation During Flexion-Extension

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Abstract

Study Design—Non-randomized controlled cohort.

Objective—To characterize subaxial cervical facet joint kinematics and facet joint capsule (FJC) deformation during *in vivo*, dynamic flexion-extension. To assess the effect of single-level anterior arthrodesis on adjacent segment FJC deformation.

Summary of Background Data—The cervical facet joint has been identified as the most common source of neck pain and it is thought to play a role in chronic neck pain related to whiplash injury. Our current knowledge of cervical facet joint kinematics is based on cadaveric mechanical testing.

Methods—14 asymptomatic controls and 9 C5-C6 arthrodesis patients performed full range of motion (ROM) flexion-extension while biplane radiographs were collected at 30 Hz. A volumetric model-based tracking process determined 3D vertebral position with sub-millimeter accuracy. FJC fibers were modeled and grouped into anterior, lateral, posterior-lateral, posterior, and posterior-medial regions. FJC fiber deformations (total, shear and compression-distraction) relative to the static position were determined for each cervical motion segment (C2-C3 through C6-C7) during flexion-extension.

Results—No significant differences in the rate of fiber deformation in flexion were identified among motion segments ($p = .159$), however, significant differences were observed among fiber regions ($p < .001$). Significant differences in the rate of fiber deformation in extension were identified among motion segments ($p < .001$) and among fiber regions ($p = .001$). The rate of FJC deformation in extension adjacent to the arthrodesis was 45% less than in corresponding motion segments in control subjects ($p = .001$).

Conclusion—In control subjects, facet joint capsule deformations are significantly different among vertebral levels and capsule regions when vertebrae are in an extended orientation. In a

flexed orientation, FJC deformations are only different among capsule regions. Single-level anterior arthrodesis is associated with significantly less FJC deformation adjacent to the arthrodesis when the spine is in an extended orientation.

Keywords

Adjacent segment; whiplash; arthrodesis; fusion; kinematics; zygapophysial; cervical; spine

Introduction

The cervical facet joint has been identified as the most common source of neck pain^{1,2} and it is thought to play a role in chronic neck pain related to whiplash injury^{3,4-6}. Long-term symptoms are common following whiplash, with approximately half of those affected remaining symptomatic one year after the injury⁷. The precise site of injury within the facet joint capsule (FJC) has yet to be identified, however, facet joint injury mechanisms may include excessive compression of the facet joint^{8,9} and/or capsular ligament strain beyond physiological limits^{9,10}.

Our current knowledge of cervical facet joint kinematics is based on mechanical testing of cadaver specimens subjected to loading conditions designed to simulate “physiologic”^{3,9,11}, “whiplash”⁹⁻¹¹, and “catastrophic”^{3,10} conditions. Given our inability to accurately estimate *in vivo* cervical spine loads during dynamic movement, it is not clear how well these *in vitro* tests, performed under “physiologic loading”, replicate *in vivo* spine loading and kinematics. As a result, our current perception of *in vivo* facet kinematics may be mistaken.

The primary aim of the current study was to characterize subaxial cervical facet joint kinematics and FJC deformation during *in vivo*, dynamic flexion-extension in a group of asymptomatic control subjects. It was hypothesized that FJC deformation is significantly different among motion segments and that FJC deformation is dependent upon anatomic region of the facet joint (e.g. anterior vs. lateral vs. posterior facet). A secondary objective was to assess the effect of single-level anterior arthrodesis on FJC deformation during the flexion-extension motion. It was hypothesized that FJC deformation adjacent to the arthrodesis would be significantly greater than in corresponding facet joints of age-matched control subjects.

Materials and Methods

This study was approved by our Institutional Review Board (IRB) and all participants provided informed consent prior to participating in this study.

Subjects

Data from 14 asymptomatic control subjects (average age 43.4 ± 5.2 yrs, 5 M, 9 F) and 9 single-level (C5-C6) anterior arthrodesis patients (average age 45.9 ± 9.5 yrs.; 2 M, 7 F; 6.9 ± 1.3 mo. post-surgery) was included in the present analysis. Surgical indications were spondylotic radiculopathy due to disc herniation or stenosis. The surgeon's preferred approach to this problem was anterior fusion. Exclusion criteria included pregnant females, previous diagnosis of osteoporosis, and any other injury or disease that interferes with spine

function. Patients were identified during clinic visits. Control subjects were recruited through an advertisement in an employee newsletter and word of mouth.

Data Collection

High-resolution CT scans ($0.29 \times 0.29 \times 1.25$ mm voxels) of the cervical spine (C2 through C7) were acquired on each participant (GE Lightspeed 16, GE Medical Systems, Waukesha, WI). Three-dimensional (3D) bone models were generated from the CT volume using a combination of commercial software (Mimics software, Materialise, Leuven, Belgium) and manual segmentation¹². Markers were interactively placed on the 3D bone models to define bone-specific anatomic coordinate systems.

Participants were seated within a biplane X-ray system and directed to continuously move their head and neck through their full range of flexion-extension. A metronome set at 40 to 44 beats per minute was used to assist the participants in moving at a continuous, steady pace to complete each full movement cycle in 3 seconds or less. Biplane radiographs were collected 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 59 movement trials analyzed for this study. Multiple trials from the same subject were averaged to yield a single average dataset for each subject used for statistical analysis. 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 3-second dynamic flexion-extension motion trial was estimated to be 0.16 mSv (determined using PCXMC simulation software, STUK, Helsinki, Finland). For comparison, the effective dose of a cervical spine CT scan has been reported to be between 3.0 mSv and 4.36 mSv^{13,14}.

Data Processing

A previously validated tracking process determined 3D vertebral position with sub-millimeter accuracy¹⁵ by matching bone models from the CT scan to the biplane radiographs for all static and dynamic trials. The volumetric model-based tracking process¹⁵⁻¹⁸ and data processing techniques^{15,19-21} have been detailed previously. Intervertebral position and orientation in each frame of the continuous dynamic trial were normalized to the static neutral trial for each subject. Only the flexion-extension component of vertebral rotation is presented in the current analysis.

Four markers defining a facet-specific plane parallel to the facet surface were placed on each superior facet of the 3D bone model (Figure 1). An automated computer algorithm identified attachment sites for fibers forming each FJC (Figure 2) using average FJC dimensions from the literature²². FJC fibers, lying on the surface of each bone model and oriented perpendicular to the plane of the facet joint in the neutral position²², were represented by points connecting corresponding upper and lower FJC attachment sites (Figure 2). In order to facilitate the analysis, the FJC fibers were grouped into fibers representing the anterior, lateral, posterior-lateral, posterior, and posterior-medial FJC (Figure 2). While the fiber attachment sites remained fixed to the respective bone models, the points that represented the rest of the fiber were allowed to slide across the surface of the bone during the flexion-

extension movement (Figure 3). The total length of each FJC fiber (determined by adding the lengths between consecutive points representing the fibers), and the length of each fiber parallel and perpendicular to the facet joint surface were determined in the static neutral position. Intervertebral flexion-extension angles and FJC fiber deformations (total, shear and compression-distraction) relative to the static position were determined for each cervical motion segment (C2-C3 through C6-C7) over the entire flexion-extension motion. This resulted in a continuous curve relating fiber deformation to intervertebral angle at each motion segment. For analysis purposes, data at each motion segment was divided according to the intervertebral orientation relative to the neutral position (flexion or extension). The rate of fiber deformation per degree of flexion-extension was then determined for each fiber group within each cervical motion segment.

Statistical Analysis

FJC deformation values for the corresponding left and right facets of each subject were averaged to yield a single FJC length value at each motion segment for each instant of the flexion-extension movement. Repeated measures analysis of variance was used to identify differences in the rate of facet joint capsule fiber deformation among motion segments and among fiber regions for the control group (IBM SPSS Statistics, version 21). Analysis of variance was used to identify differences between the control group and the C5-C6 arthrodesis group at the C4-C5 and C6-C7 motion segments. The Bonferroni correction for multiple comparisons was used when significant main effects were identified, with significance set at $p < .05$ for all tests.

Results

The primary mechanism driving facet joint capsule fiber deformation varied depending on fiber location and vertebral orientation. In some cases increased deformation due to shear was countered by decreased deformation due to compression (e.g. Figure 4A and 4B, flexion ROM). In other cases, shear and compression/distraction deformation combined to increase (e.g. Figure 4C-E Flexion ROM) or decrease (Figure 4D and 4E-extension ROM) fiber lengths.

Fibers within all regions of the FJC increased in length as the motion segments moved from the neutral position into increased flexion (Figure 5). The rate of fiber deformation in flexion was not different among motion segments (main effect of motion segment: $p = .159$). However, the rate of fiber deformation was different among fiber regions (main effect of fiber region: $p < .001$). Post-hoc tests indicated fiber deformation rates in the anterior and lateral fiber regions were not different ($p = .198$), however, every other region was different from all others (all $p < .001$).

As the cervical motion segments increased their flexed orientation, the anterior and lateral fibers increased length due to the shear deformation rate (0.17 mm/deg.) being greater than the compressive deformation rate (0.04 mm/deg.). Simultaneously, the posterior-lateral, posterior and posterior-medial fibers increased length due to the combined effects of shear (0.26 mm/deg.) and distraction (0.07 mm/deg.) deformation.

As the motion segments moved from neutral orientation into more extension, only the anterior and lateral fiber regions consistently increased in length (Figure 6). Therefore, only anterior and lateral fiber regions were included in the statistical analysis of the extension range of the movement. The rate of fiber deformation during extension was different among motion segments (main effect of motion segment: $p < .001$). Post-hoc tests indicated the rate of fiber deformation in the C3-C4 motion segment was greater than in C5-C6 and C6-C7 ($p = .003$ and $p = .042$, respectively). The rate of deformation in the anterior region was also greater than in the lateral region ($p = .001$).

When the cervical motion segments were in an extended orientation relative to the neutral position, the mechanism for increasing length was different for the anterior and lateral FJC fibers. The anterior fibers were distracted more than the lateral fibers ($p < .001$), while the lateral fibers experienced more shear than the anterior fibers ($p = .008$).

In an extended orientation, the rate of FJC deformation adjacent to the arthrodesis (0.434%/deg) was less than in corresponding FJCs in asymptomatic subjects (0.969%/deg) ($p = .001$) (Figure 7). In the flexed orientation, the groups were not different ($p = .284$).

Although differences in the rate of FJC deformation were observed adjacent to the arthrodesis, control and arthrodesis groups were not different with respect to static neutral orientation (Table 1), total range of motion (Table 2) and flexion and extension components of total range of motion (Table 3). Additionally, FJC fiber lengths in the static neutral position (Figure 8) were not different between control and arthrodesis groups at any fiber region or vertebral level (all $p > .093$).

Discussion

The first goal of this study was to determine if facet joint capsule deformation in control subjects varies significantly among motion segments and anatomic regions of the facet joint. The second goal was to assess the effect of single-level anterior arthrodesis on FJC deformation during the flexion-extension motion.

The experimental results indicate that FJC deformation is different among motion segments and among FJC regions during flexion-extension in asymptomatic control subjects. These motion segment-specific and FJC region-specific deformations in controls suggest to the basic scientist that strain data acquired from a single motion segment or from a single region of the FJC is not representative of all motion segments and all regions of the facet joint capsule. The experimental design of *in vitro* research should take these differences into consideration.

Additionally, in this study, control subjects and arthrodesis patients demonstrated different rates of FJC deformation in the extended orientation. This finding suggests that arthrodesis may affect adjacent segment facet joint mechanics.

The current results contradict several previous *in vitro* reports of FCJ strain. Some of these differences may have been associated with the high variability associated with spine mechanical testing (7.1% to 17.9% variability in strain⁹ versus 3% to 5% inter-subject

variability in the current study). Also, capsular strain distributions have been reported to be “highly non-uniform” across the surface of the facet capsule³. In contrast, the current results indicate a highly organized and repeatable pattern of strain distribution among the five capsular regions when in flexion and when in extension. One explanation for these differences may lie in the initial positioning of cadaver specimens prior to loading (the “neutral position”). As the current study demonstrates, the neutral orientation is highly variable *in vivo* (Table 1). It may not be advantageous to position all specimens in the same “neutral” orientation for *in vitro* testing³. Additional explanations for discrepancies between *in vivo* and *in vitro* results include differences in range of motion (e.g. only $2.6^{\circ} \pm 1.5^{\circ}$ ROM in extension at C4-C5 under “physiologic loading”¹¹), differences in loading, the age of the participants/specimens, and the techniques used to estimate capsular strain. Overall, the current data indicate that FJC deformations calculated from *in vitro* “physiological loading” experiments differ substantially from *in vivo* results. This also calls into question how well *in vitro* experiments designed to replicate “whiplash loading”⁹⁻¹¹ reflect true *in vivo* facet kinematics during actual whiplash loading.

Considering the well-known changes that occur in the spine with age²³⁻²⁶, the FJC deformation results presented for the control group are likely representative only of subjects within their age-range. Also, arthrodesis patient data was collected approximately 7 months post-surgery, and significant changes in adjacent segment FCJ deformation may occur at a later date. An additional limitation is that FJC dimensions were determined from mean values provided in the literature and not on a subject-specific basis. Furthermore, changes in FJC lengths were presented as “deformation”, rather than “strain”, as the true zero strain length of the fibers is unknown. Finally, the etiology of chronic neck pain following whiplash may be multifactorial²⁷ and not solely related to FJC kinematics.

Previous reports of *in vivo* spine kinematics have neglected to assess kinematics of the facet joints, instead focusing on the motion between adjacent vertebral bodies. The current study is believed to be the first to characterize the facet joint capsule *in vivo* during dynamic, functional loading. These novel results indicate that in asymptomatic controls, FJC deformation is dependent upon motion segment and upon FJC region. Additionally, single-level arthrodesis affects adjacent segment FJC deformation, suggesting a potential mechanical etiology for adjacent segment degeneration.

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Figure 1.

Defining the plane of the facet. Four markers were placed on each facet of the 3D bone model to determine the plane of each facet. The direction perpendicular to the facet was defined by the cross product of the two vectors.

Figure 2.

Posterior and lateral views of the facet joint capsule attachment sites (larger spheres) and fibers (smaller spheres) for one subject. Fibers were grouped for analysis purposes (red = anterior, orange = lateral, teal = posterior-lateral, green = posterior, blue = posterior-medial).

Figure 3.

A close-up view of the facet joint capsule demonstrating that the attachment sites remained fixed but the fibers were allowed to slide across the bone surfaces. A) Near full extension. B) Near full flexion.

Figure 4.

Control group mean FJC deformation (total, shear and compression-distraction) during flexion-extension at the C5-C6 motion segment. Error bars indicate 95% confidence interval of the mean at each 1° increment of flexion-extension. For each FJC region (anterior (A), lateral (B), posterior-lateral (C), posterior (D) and posterior medial (E)), the left vertical axis indicates compression-distraction and shear deformation (in mm), while the right vertical axis indicates total deformation (expressed as a percentage of the total fiber length in the static neutral position).

Figure 5.

Control group mean rate of FJC deformation when in a flexed orientation relative to the neutral position. Error bars indicate 95% confidence interval of the mean for each FJC region.

Figure 6.

Control group mean rate of FJC deformation when in an extended orientation relative to the neutral position. Error bars indicate 95% confidence interval of the mean for each FJC region.

Figure 7.

Mean rate of FJC deformation in adjacent segments when in an extended orientation relative to the neutral position for the control and arthrodesis groups. Overall, the rate of FJC deformation in adjacent segments was less in the arthrodesis group ($p = .001$). Error bars indicate 95% confidence interval of the mean.

Figure 8.

Average facet joint capsule (FJC) fiber length in the static neutral position for all asymptomatic control subjects. Error bars indicate 95% confidence interval of the mean.

Table 1

Mean sagittal plane intervertebral orientation in the static neutral position ($\pm$ standard deviation). Negative and positive values indicate extension and flexion, respectively. All measurements are in degrees. No significant differences were identified between control and arthrodesis groups at any motion segment (all $p > .114$)

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
Control	-6.8 $\pm$ 4.8	-5.1 $\pm$ 7.0	-2.8 $\pm$ 5.3	-0.3 $\pm$ 7.6	-3.7 $\pm$ 6.9
Arthrodesis	N/A	-2.7 $\pm$ 6.2	1.7 $\pm$ 7.8	-2.8 $\pm$ 6.7	-4.1 $\pm$ 7.5

Table 2

Intervertebral total flexion-extension range of motion ($\pm$ standard deviation). All measurements are in degrees. No significant differences were identified between control and arthrodesis groups at any motion segment (all $p > .268$)

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
Control	9.7 $\pm$ 2.5	14.9 $\pm$ 2.8	16.3 $\pm$ 2.2	15.3 $\pm$ 5.2	12.8 $\pm$ 5.2
Arthrodesis	N/A	13.4 $\pm$ 3.4	16.4 $\pm$ 3.5	2.8 $\pm$ 0.7	12.8 $\pm$ 4.3

Table 3

Intervertebral flexion and extension components of total range of motion ($\pm$ standard deviation). All measurements are in degrees. No significant differences were identified between control and arthrodesis groups at any non-operated motion segment in the flexion (all $p > .094$) and extension (all $p > .134$) components of the range of motion

	C2-C3		C3-C4		C4-C5		C5-C6		C6-C7	
	Flexion	Extension	Flexion	Extension	Flexion	Extension	Flexion	Extension	Flexion	Extension
Control	5.1 $\pm$ 1.9	-4.6 $\pm$ 2.3	7.9 $\pm$ 4.2	-7.0 $\pm$ 3.5	7.8 $\pm$ 2.5	-8.5 $\pm$ 3.1	7.1 $\pm$ 3.2	-8.2 $\pm$ 3.9	7.0 $\pm$ 4.6	-5.8 $\pm$ 2.5
Arthrodesis	N/A	N/A	6.6 $\pm$ 3.2	-6.8 $\pm$ 2.3	5.6 $\pm$ 3.6	-10.8 $\pm$ 3.9	1.8 $\pm$ 1.0	-1.0 $\pm$ 1.1	5.8 $\pm$ 3.4	-7.0 $\pm$ 2.5