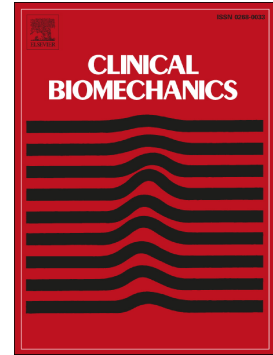


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Digital Tracking Algorithm Reveals the Influence of Structural Irregularities on Joint Movements in the Human Cervical Spine

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Abstract

Background: Disc height loss and osteophytes change the local mechanical environment in the spine; while previous research has examined kinematic dysfunction under degenerative change, none has looked at the influence of disc height loss and osteophytes throughout movement.

Methods: Twenty patients with pain related to the head, neck or shoulders were imaged via videofluoroscopy as they underwent sagittal-plane flexion and extension. A clinician graded disc height loss and osteophytes as “severe/moderate”, “mild”, or “none”. A novel tracking algorithm quantified motions of each vertebra. This information was used to calculate intervertebral angular and shear displacements. The digital algorithm made it practical to track individual vertebrae in multiple patients through hundreds of images without bias.

Findings: Cases without height loss/osteophytes had a consistent increase in intervertebral angular displacement from C2/C3 to C5/C6, like that of healthy individuals, and mild height losses did not produce aberrations that were systematic or necessarily discernable. However, joints with moderate to severe disc height loss and osteophytes exhibited reduced range of motion compared to adjacent unaffected joints in that patient and corresponding joints in patients without structural irregularities.

Interpretation: Digitally-obtained motion histories of individual joints allowed anatomical joint changes to be linked with changes in joint movement patterns. Specifically, disc height loss and osteophytes were found to influence cervical spine movement in the sagittal plane, reducing angular motions at affected joints by approximately 10% between those with and without height loss and osteophytes. Further, these joint changes were associated with perturbed intervertebral angular and shear movements.

Key Words: intervertebral disc; disc height loss; osteophytes; flexion/extension; cervical spine; quantitative fluoroscopy

1. Introduction

Spine health is determined through a complex interplay of a wide range of factors (Figure 1). For example, structural failure and resultant pathological disc height loss (Brinckmann and Horst, 1985; Michalek and Iatridis, 2012; Sharma et al., 2014) not associated with normal aging is an important biomarker for ongoing degenerative changes (Jarman et al., 2015) and at least in the lumbar spine, it increases facet stresses (Dunlop et al., 1984), potentially changes the disc stress profile (Adams et al., 1996b), and can shift load-bearing regions (Pollintine et al., 2004b). Disc height loss, injury or instability at a segment (Kirkaldy-Willis and Farfan, 1982; Neogi et al., 2008; Vernon-Roberts and Pirie, 1977; Videman et al., 1995) through this altered loading (Adams et al., 2000; Adams et al., 1996a; Adams et al., 1996b; Adams et al., 2006; Brinckmann and Grootenboer, 1991; Pollintine et al., 2004a; Pollintine et al., 2004b) can ultimately give rise to osteophytes (Kumaresan et al., 2001), another key anatomical marker. Ultimately, physical disruptions could manifest as pain, which can in turn affect movement of the cervical spine (de Vries et al., 2015). Despite much effort to understand spinal pathophysiological mechanisms, a number of important gaps remain in current knowledge. The goal of this study is to describe how disc height loss and osteophytes affect the motion of specific joints in the cervical spine in patients with pain to address some of these gaps.

Motion of the cervical spine has been investigated from a number of perspectives (Artz et al., 2015; Brown et al., 2005; van Mameren, 1988; White et al., 1975), and aberrant movement patterns have been correlated with degenerative grade (Cheng et al., 2007; Miyazaki et al., 2008), where indicated degeneration can include features associated with normal aging (Adams and Roughley, 2006). Perturbed motion has also been studied in the contexts of fusion (Dekutoski et al., 1994), herniation (Lao et al., 2015), and degeneration (Lee et al., 2015).

Although factors such as disc height loss and osteophyte growth might reasonably be expected to influence spine motion, especially in patients experiencing pain, quantitative analyses of individual joint motions in such patients have been lacking.

Fortunately, videofluoroscopic imaging allows the motions at individual intervertebral joints to be observed. Midrange movements can be visualized, a feature that static x-ray images of end positions cannot offer, and the kinematics of individual vertebrae can be obtained with accuracy, giving it an advantage over skin-mounted instrumentation. While tracking of individual vertebrae in fluoroscopic videos could allow the time course of individual joint motions to be quantified, manual tracking is expensive, time consuming, and impractical when the number of image frames or patients is large. Digital tracking algorithms have been previously developed (Bifulco et al., 2001; Muggleton and Allen, 1997; Wong et al., 2009; Wong et al., 2006; Zheng et al., 2004), but can rely heavily on operator skill, be difficult to implement, or use rigid template shapes that do not account for the effects of image distortion. A new digital algorithm developed by the authors (Balkovec et al., 2017) makes it practical to track the motions of vertebrae in a fluoroscopic video with relative ease and high accuracy, thereby overcoming these challenges.

The detailed tracking information the algorithm provides could lead to improved understanding of how specific anatomical features are associated with aberrant movements, and how such movements might produce downstream mechanical and physiological consequences (Figure 1). Here, we use this new kinematic data to assess the impact that disc height loss and osteophytes have on the sagittal plane kinematics of individual joints in the human cervical spine. We assess whether disc height loss and osteophytes are associated with diminished mobility in the affected segments.

2. Materials and Methods

2.1 Data Collection

Subjects selected for the study had experienced trauma and, at the time of the study, reported a chief complaint of pain related to their neck, head, or shoulders (Table 1). Patients gave informed consent for their image sequences to be used for research purposes, and all protocols were approved by the appropriate authorities. Radiation exposure for a typical image sequence was between 0.75mSv and 1.5mSv. Under care of a specialist, each patient was asked to start from a neutral position, flex his or her cervical spine fully, and then extend it before returning to the neutral position. Sagittal-plane image sequences of these cervical spine motions were collected using a Digital Motion X-Ray (DMX) that provided continuous x-ray at 70-90 kVp and 2-3.5 mA with a 40-inch flange focal distance. A 9-inch image intensifier (Precise Optics, Bay Shore, NY, USA) transferred the signal to a digital CCD camera outputting a 150dpi stream to a DICOM recorder (NAI Tech Products, Auburn, CA, USA). Data from 20 patients were analyzed.

Pre-trauma images were not available for the patients, and so disc height loss was classified manually based on clinical impression by a clinician certified to perform radiological assessments who had no prior interaction with the patients. Disc height loss and osteophyte severity were both classified separately as either none, mild, moderate, or severe. Of the 20 cases, 9 had no height loss at any of the levels visible in the radiographs (NH group), 8 had mild disc height loss at one level or more (MH group), and 3 had moderate or severe height loss at one level or more (DH group). Disc height loss and osteophyte severity appeared to be linked.

2.2 Motion Tracking

The fluoroscopy image sequences of interest typically consisted of 300 frames. Four points on the body of each vertebra were selected manually in the initial neutral-position image, and a

digital template matching algorithm (Velduis and Brodland, 1999) developed specifically to track cervical vertebrae was used to quantify the kinematics of each vertebra (Balkovec et al., 2017). The raw coordinate values were filtered using a dual pass 2nd order Butterworth filter with a cut-off frequency of 1Hz, as determined by residual analysis (Wells, 1980). Relative joint angles were obtained for each set of image sequences using the technique described by Veldhuis and colleagues (Veldhuis et al., 2005), while shear displacement was calculated from the method of Frobin and colleagues (Frobin et al., 1996). Validation tests on this sequence of operations (Balkovec et al., 2017) showed that it produces RMS errors in intervertebral joint angle and shear no greater than 0.4° and 0.055mm, respectively.

2.3 Analysis

All intervertebral motions were normalized to the maximum total angular excursion of the quantified levels of each patients' cervical spine. Intervertebral joint angles were plotted as time-histories and examined for features of clinical interest.

3. Results

Maximum angular excursions and normalized segmental motions for each patient are shown in Table 2. Like previous work on healthy individuals, they show a general consistent increase in intervertebral angular displacement from C2/C3 to C5/C6 (van Mameren, 1988) where the angular displacement of a lower segment is greater than any single segment above it. Group summaries in Table 3 show that the average angular displacement at C5/C6 (20.2% (SD=2.3%)) in the moderate to severe height loss group had notable differences compared to the group with no height loss (30.6% (SD=4.0%)). This group-wise comparison supports the notion that disc height loss and presence of osteophytes reduces motions in the affected joint. To assess whether

further information can be garnered from individual patient records, we turn our attention to specific selected patients.

3.1 Severe Height Loss Case 1 (DH1)

Patient DH1 presented with moderate disc height loss at the level of C5/C6 and severe height loss at C6/C7 along with moderate anterior osteophytes at C5/C6 and severe at C6/C7 (Figure 2). As the time history shows, flexion occurred primarily about the C2/C3 and C4/C5 joints initially, followed by C3/C4 and C5/C6 motions. In extension, motion about the C5/C6 joint stopped, while motion about the adjacent (C4/C5) joint continued (Figure 2, see video, Supplemental Video 1). Total angular displacement for the C2/C3, C3/C4, C4/C5 and C5/C6 joints were 11.8°, 10.6°, 13.1°, and 8.1° respectively (angular displacement at C6/C7 could not be quantified because C7 moved out of the field of view). This case illustrates height loss being associated with osteophytes and reduced motion.

3.2 Severe Height Loss Case 2 (DH2)

DH2 presented with moderate disc height loss at C4/C5 and C6/C7 and severe height loss at C5/C6 (Figure 3). Osteophyte growth was evident anteriorly and classified as mild at C4/C5, moderate at C6/C7 and severe at C5/C6. Due to C7 moving out of the field of view during sagittal plane motions, the angular displacement of the C6/C7 joint could not be quantified. The smallest angular displacement occurred about C5/C6 where there was severe height loss (see video, Supplemental Video 2). Total angular displacement for the C2/C3, C3/C4, C4/C5, and C5/C6 joints were 15.1°, 12.5°, 12.9°, and 9.6° respectively. This case illustrates a correlation between the degree of disc height loss and the extent of motion loss, and is consistent with other cases, such as DH3.

3.3 Severe Height Loss Case 3 (DH3)

DH3 presented with moderate height loss at C4/C5 and severe height loss at C5/C6. There was also severe height loss at C6/C7 but due to the positioning of C7, it could not be tracked, as it did not stay within the field of view. Moderate levels of osteophytic lipping were evident at C4/C5, with severe levels at C5/C6 and C6/C7. There was also a kyphotic deformity of the neck in the patient's neutral posture (Figure 4). The overall range of motion of the neck was severely limited, with most of the motion being qualitatively observed at the craniocervical junction. During flexion, a small amount of motion occurred at C5/C6, the osteophytes at the anterior margins of both vertebral bodies however, appeared to make contact and prevent further motion. As the spine went into extension, the facets of the C5/C6 joint appeared to come close to making contact (see video, Supplemental Video 3) and the range of motion of the segment was severely limited. In total, 7.6° of angular displacement occurred at the joint. Nearly all the angular displacement in extension occurred at the adjacent joint (C4/C5) that had less severe height loss and at the C3/C4 joint which had no height loss (Figure 4). Interestingly, most of the angular displacement (13.6°) occurred at the joint without height loss (C3/C4).

The relative shear measurements are also of note in Case DH3. The C2/C3 joint, where almost no angular displacement occurred, had the highest shear displacement (0.44mm in flexion and 0.27mm in extension). Joints C3/C4 and C4/C5 exhibited a small amount of anterior shear displacement (0.21mm) as the neck flexed, followed by posterior shear displacement (0.35mm) as it extended. Almost no shear displacement occurred at the C5/C6 joint, which had the most severe height loss (Figure 5).

This patient exhibited several noteworthy kinematic characteristics which may have gone unnoticed if only x-rays of end ranges of motion had been available rather than detailed plots of the time course of the individual joint movements.

3.4 Mild Height Loss Cases

In contrast to joints that had moderate/severe height loss, joints with mild height loss did not necessarily exhibit reduced mobility. In some instances (MH4, MH8), motions at joints with mild height loss were noticeably larger than at adjacent levels. There were also instances, such as MH3 (Figure 5, see video, Supplemental Video 4) and, MH4 (Figure 6, see video, Supplemental Video 5) where the pattern of consistent angular increase with descending segment level found in patients with no height loss was contravened, and there was less displacement at the C5/C6 joint than at the C4/C5 joint. The limited mobility of the C5/C6 joint in MH3 under extension may have been due to a posterior lip on C6. The lack of mobility in MH4 was in extension, which could indicate facet joint stiffness. These two cases appeared to be unusual in that most cases where there was a non-consistent angular displacement increase with descending segmental level, the discrepancy was less than 6% of total range of motion.

3.5 Cases Without Height Loss

In all non-height loss cases, there was a general trend for a consistent increase in intervertebral angular displacement from C2/C3 to C5/C6, and even though these patients presented with pain, their average angular displacement for each level were within 1% of those reported by van Mameren (van Mameren, 1988) (Table 3).

4. Discussion

This study demonstrates the value of detailed time histories of individual joint motions for identifying connections between anatomy, pathology, and aberrant movement patterns in the human spine (Figure 1). For example, it shows that patients with mild height loss ($n=8$) did not necessarily follow the consistent angular displacement increase pattern of those with no height loss, nor did they necessarily exhibit diminished segmental mobility at reduced-height joints. In fact, some patients (MH3 and MH4) had unusually high mobility in segments exhibiting mild height loss, and in these cases ligament disruption may be a contributing factor. There were fewer osteophyte growths along the anterior and posterior margins of their vertebral bodies, suggesting that these growths represent relatively early degenerative changes (Kirkaldy-Willis and Farfan, 1982). A threshold at which disc height loss produces aberrant movement has not been established, although overall mobility appears to decline as degenerative features advance. Patients with moderate and severe height loss along with osteophytes ($n=3$; and always at the C5/C6 level) had notably reduced mobility compared to those without height loss. Thus, the study supports the association between the presence of moderate to severe disc height loss together with osteophytes and a reduction in segmental mobility.

This study confirms that when motion is reduced at one joint, either the overall motion of the cervical spine is reduced (Malakoutian et al., 2015), or adjacent segments compensate by providing increased motion. Neither outcome is ideal, as both have potential negative physiological and structural effects (Figure 1). For example, increased motion at adjacent joints can alter joint loading and initiate damage in facets or other components (Dunlop et al., 1984) – especially under repetitive action.

Structural failure is known to initiate progressive height loss (Brinckmann and Horst, 1985; Michalek and Iatridis, 2012; Sharma et al., 2014). Height loss, in turn, is associated with

the presence of osteophytes (Neogi et al., 2008; Vernon-Roberts and Pirie, 1977; Videman et al., 1995), and in this study, osteophytes were observed in all individuals with severe height loss. The height loss-osteophyte connection evidently involves two steps: height loss alters segment loading (Adams et al., 2000; Adams et al., 1996a; Adams et al., 1996b; Adams et al., 2006; Brinckmann and Grootenboer, 1991; Pollintine et al., 2004a; Pollintine et al., 2004b), and as posited (Adams and Roughley, 2006) and supported by finite element investigations, these loading changes facilitate osteophyte growth (Kumaresan et al., 2001). In the lumbar spine, disc height loss is associated with radial bulging of the annulus (Brinckmann and Grootenboer, 1991) and increased loading at the neural arch and vertebral margins (Pollintine et al., 2004b). It would be no surprise, then, to find that disc height loss in the cervical spine is associated with osteophytes and arthritic facets (Videman et al., 1995). While the present study does not establish a causal relationship between osteophytes and mobility, *per se*, it is consistent with the causal network shown in Figure 1 and with the concept that degenerative features associated with altered loading result in modified movements and mechanical properties (Tanaka et al., 2001). Further, the dysfunction that often accompanies early degeneration can induce physiological stabilization (Kirkaldy-Willis and Farfan, 1982) which can in turn alter mechanics of the spine (Al-Rawahi et al., 2011).

Interestingly, nearly half of the patients selected for this study because of reported head, neck or shoulder pain showed no sign of disc height loss. Those with no height loss or severe osteophyte growth (n=9) exhibit a consistent increase in intervertebral angular displacement from C2/C3 to C5/C6 (Table 2, Table 3), consistent with individuals without pain (van Mameren, 1988). Furthermore, the average intersegmental motions of patients in this study were within 1% of those without pain.

In future studies, the number of cases with moderate and severe disc height loss, might be increased so that our conclusions can be strengthened, and possible additional relationships identified. Disc height loss scoring might be enhanced, although in the absence of pre-trauma imaging, clinical classification is a viable option. While the disc height index (Frobin et al., 2002) offers an alternative approach to scoring, if patients had fractured vertebrae (and associated vertebral height loss) the index would not precisely reflect disc height loss itself. Normalizing disc height to the cumulative height of all the measured discs (Balkovec, 2016) is another possibility, but normal differences in disc height between levels would make interpretation of any inter-segmental differences challenging.

In summary, this study has shown that machine tracking of individual vertebrae motions in fluoroscopic image sequences can reveal intervertebral angular and shear displacements of clinical interest. Analyses of these intervertebral motions can, in turn, bolster our understanding of the factors (Figure 1) that govern the function and health of the human spine.

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Figure Captions

Figure 1. Connections between Spinal Injury, Pathology and Function. The figure shows how factors such as structural failure, disc height loss, altered loading, aberrant movement, and physiological stabilization can affect each other. Established relationships are shown with solid lines and numerical citations (citations in brackets provide indirect support), while tentative ones are shown with dashed lines; references are listed relative to their sequential appearance in the references section. The link containing a circled negative sign indicates a downgrading effect. Asterisks denote relationships identified or strengthened by the present study.

Figure 2. DH1 Illustrates Correlation of Height Loss with Osteophytes and Reduced Motion. Fluoroscopic images shown in this study were processed to remove pincushion distortion and improve contrast. As described in the text, four points were manually selected on each vertebra (one representative set is shown on the C2 vertebra) and they were tracked through the full set of images using a computational algorithm. In this patient, the height loss at C5/C6 was moderate (white arrow) and at C6/C7 was severe (yellow arrow), and osteophytes are visible anteriorly at both levels. The time history shows flexion from the neutral position followed by full extension (see video, Supplemental Digital Content 1). While the joint space for C6/C7 was visible, the full body of C7 was not, and so its motion could not be tracked and the angular displacement at C6/C7 quantified. The time history shows irregularities in the C5/C6 motions during flexion, and these irregularities become even more pronounced during extension. Specifically, the C5/C6 angular displacement is considerably lower than would be expected, it does not follow the normal consistent angular increase with decreasing level, and retrograde motion occurs at C5/C6 at the end of extension. All three of these anomalies were observed in multiple patients and are not unique to DH1.

Figure 3. DH2 Shows Correlation between Height Loss Severity and Degree of Motion Loss. Moderate height loss can be seen at the C4/C5 level and severe height loss at the C5/C6 and C6/C7 levels, and anterior osteophyte growth is evident at all of these levels. Under normal circumstances one would expect more motion with descending level but in this case, there is generally less motion at C5/C6 (severe height loss) compared to the joint above it, and C4/C5 (moderate) has nearly the same motion as C3/C4, but less than C2/C3. This example illustrates how height loss and osteophytes are correlated with reduced angular motion at the affected joint, and is consistent with the comparison of the motions in severe height loss patients versus those with no height loss.

Figure 4. DH3 Shows Severe Height Loss, Osteophyte Growth and Facet Joint Interference. Moderate height loss can be seen at C4/C5, and severe height loss is seen at the C5/C6 and C6/C7 levels. There is a kyphotic deformity of the neck in its neutral position, and osteophytic lipping is evident at the indicated joints. This patient exhibits a number of unusual kinematic features. While C3/C4 contributes to both flexion and extension, C5/C6 is restricted from extension motions because of involvement of its facets (see video, Supplemental Digital

Content 3). In contrast, C4/C5 moves almost exclusively in extension because of its pre-existing kyphotic position. C5/C6 also exhibits much less shear than the adjacent joints.

Figure 5. MH3 Shows Joint Motion Restricted by an Anatomical Feature. Because the approach we have taken provides detailed movement information for each joint, we can identify how anatomical details such as the posterior lip on C5 (white arrow) affects the motion at C5/C6. As the time course shows, the lip primarily affects extension. Specifically, one would expect more displacement at C5/C6 than at C4/C5, but that is clearly not the case in this patient.

Figure 6. MH4 Illustrates that Facet Joint Interference can Inhibit Joint Extension. While it is difficult to identify from a static image, the corresponding Supplementary Video (see video, Supplemental Digital Content 5) makes it clear that the C5/C6 joint is prevented from undergoing extension because of facet joint interference (white arrow). Again, having the time course of individual joint motions provides additional information, and one could study the motions in further detail.

Table 1. Summary of patient cases.

Case	Age (Gender)	Complaint	Medical History
DH1	50 (F)	Neck pain, headaches, seizure	Motor-vehicle accident (head on) causing loss of consciousness. History of low back pain
DH2	57 (F)	Left shoulder pain, headaches	Slip and fall
DH3	68 (F)	Neck pain, headaches	Motor-vehicle accident (rear-ended)
MH1	51 (F)	Neck pain	Hit by 10lb object, left sided head injury causing concussion
MH2	58 (M)	Neck pain, headaches	Motor-vehicle accident (rear-ended)
MH3	58 (F)	Neck pain, headaches	Motor-vehicle accident (left-front impact) causing loss of consciousness
MH4	54 (F)	Neck pain, headaches	Motor-vehicle accident (rear-ended) causing loss of consciousness. Previous history of plane crash with facial surgery
MH5	29 (F)	Neck pain, rib fracture, headaches	Motor-vehicle accident (head-on)
MH6	39 (M)	Fracture of C0, C1, C4, Loss of consciousness	Motor-vehicle accident (rollover) causing loss of consciousness
MH7	45 (M)	Neck pain, headaches, shoulder pain	Motor-vehicle accident (rear-ended)
MH8	35 (F)	Neck pain, headaches	Motor-vehicle accident (rear-ended)
NH1	53 (M)	Neck pain, headaches	Train crash causing loss of consciousness
NH2	41 (F)	Neck pain, headaches	Motor-vehicle accident (rear-ended)
NH3	42 (M)	Neck pain, headaches	Motor-vehicle accident (rollover) causing loss of consciousness
NH4	39 (M)	Neck pain, headaches	Motor-vehicle accident (rear-ended)
NH5	40 (F)	Neck pain, headaches	Motor-vehicle accident (right-front impact)
NH6	42 (M)	Neck pain, low-back pain, headaches	Motor-vehicle accident (rear-ended)
NH7	25 (M)	Neck pain, headaches	Assault with head strikes

NH8	57 (F)	Neck pain, headaches	Motor-vehicle accident (head-on) causing loss of consciousness
NH9	45 (F)	Headaches	Motor-vehicle accident (head-on) causing loss of consciousness

Table 2. Normalized range of motion (%) of each segmental level for each case. Cases are listed as severe disc height (DH) cases, mild height loss (MH) cases, and no height loss (NH) cases. Levels exhibiting disc height loss are colored, with yellow indicating mild height loss, orange indicating moderate height loss, and red indicating severe height loss. Disc angles for healthy individuals (van Mameren, 1988) have been normalized as needed and included for comparison.

Case	Total Range (°)	Relative Displacement (%)			
		C2/C3	C3/C4	C4/C5	C5/C6
DH 1	43.6	27.1	24.4	30.0	18.6
DH 2	50.1	30.1	25.0	25.7	19.2
DH 3	33.3	5.9	40.8	30.5	22.8
MH 1	59.4	20.2	28.4	27.3	24.1
MH 2	54.2	27.4	20.1	25.7	26.8
MH 3	44.7	16.7	30.7	36.3	16.3
MH 4	59.6	16.8	23.4	38.9	20.9
MH 5	39.2	33.4	30.4	36.4	
MH 6	61.6	27.8	27.4	19.6	25.2
MH 7	39.9	19.5	31.6	26.1	22.7
MH 8	66.3	15.2	22.8	33.8	28.2
NH 1	46.4	29.9	33.0	37.1	
NH 2	60.0	16.7	21.9	29.1	32.3
NH 3	52.8	18.1	28.2	26.5	27.2
NH 4	58.8	16.1	28.6	27.7	27.6
NH 5	80.5	20.4	22.5	28.4	28.6
NH 6	23.9	34.5	26.3	39.2	
NH 7	68.4	15.0	20.3	27.0	37.7
NH 8	14.0	37.9	62.1		
NH 9	59.3	16.8	21.9	30.9	30.4
van Mameren, 1988 (Averages)	74.0	18.1	23.8	27.6	30.5

Table 3. Normalized range of motion (%) averages and standard deviations for each group. Cases where angular displacement values were available for all four levels are included in the averages.

Group	Normalized Displacement Average (%)			
	C2/C3	C4/C4	C4/C5	C5/C6
Moderate/Severe Height Loss	21.0 (SD=13.2)	30.1 (SD=9.3)	28.7 (SD=2.6)	20.2 (SD=2.3)
Mild Height Loss	20.5 (SD=5.1)	26.4 (SD=4.3)	29.7 (SD=6.9)	23.4 (SD=4.0)
No Height Loss	17.2 (SD=1.9)	23.9 (SD=3.6)	28.3 (SD=1.6)	30.6 (SD=4.0)
Van Mameren, 1988 (Averages)	18.1	23.8	27.6	30.5

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Highlights

Structural irregularities could influence cervical spine kinematics.

Patients were imaged by videofluoroscopy during flexion and extension movements.

A novel digital tracking algorithm quantified the full range of vertebrae movement.

Moderate and severe disc height loss and osteophytes reduced joint motion.

Disc height loss and osteophytes appear to produce aberrant cervical spine movements.

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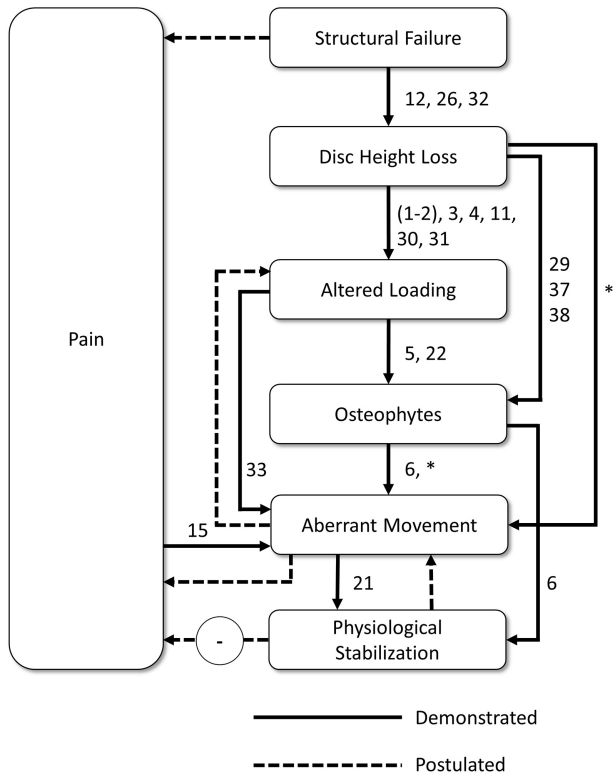


Figure 1

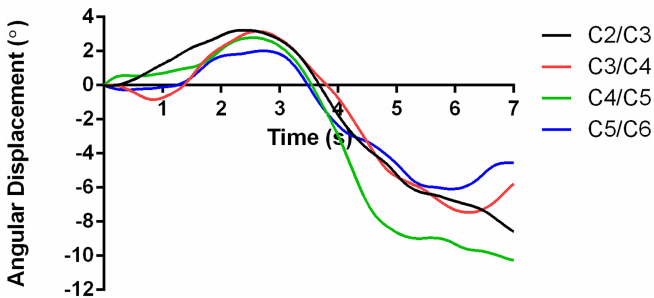
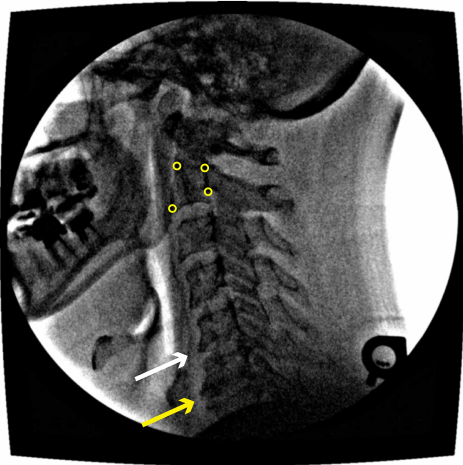


Figure 2

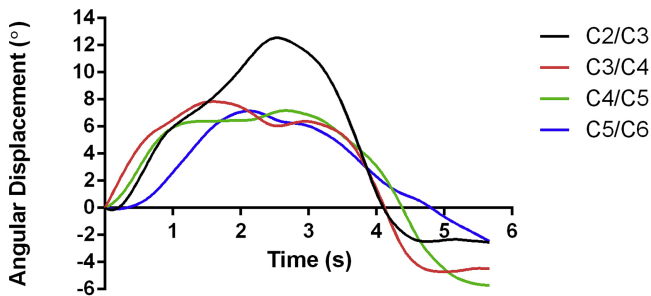
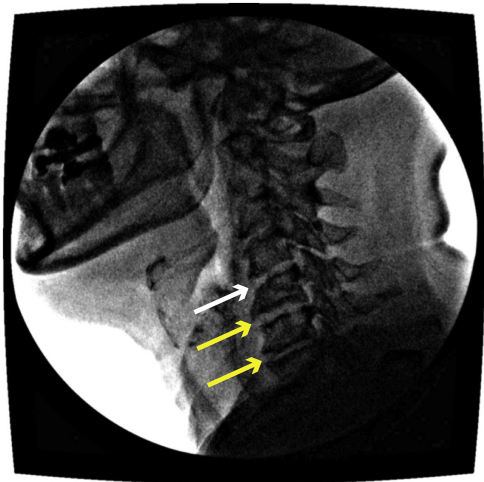


Figure 3

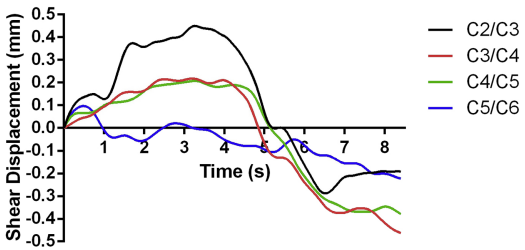
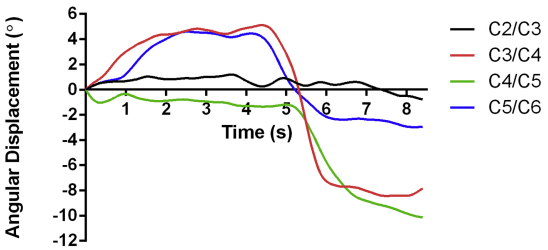
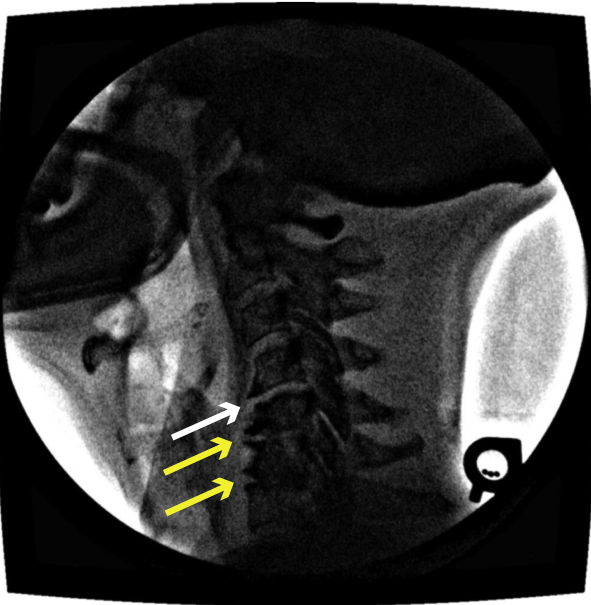


Figure 4

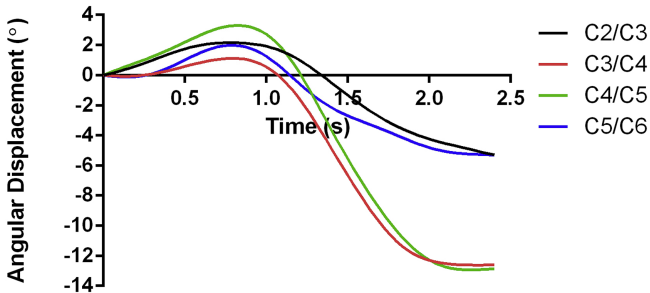
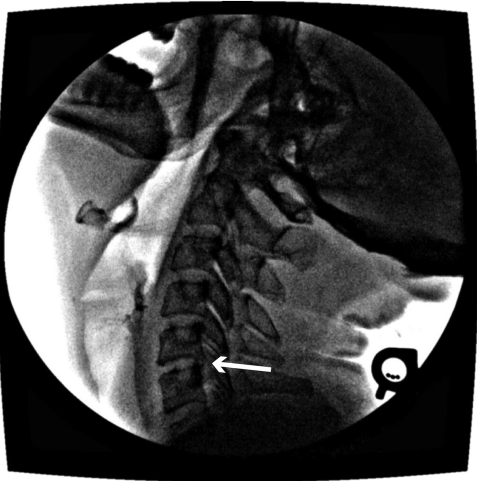


Figure 5

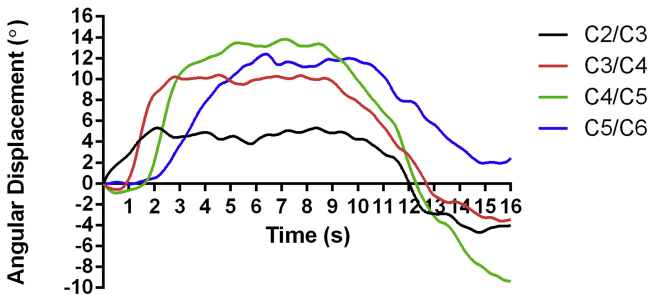


Figure 6