

In Vivo Kinematics of Normal, Degenerative, Fused and Disk-Replaced Cervical Spines

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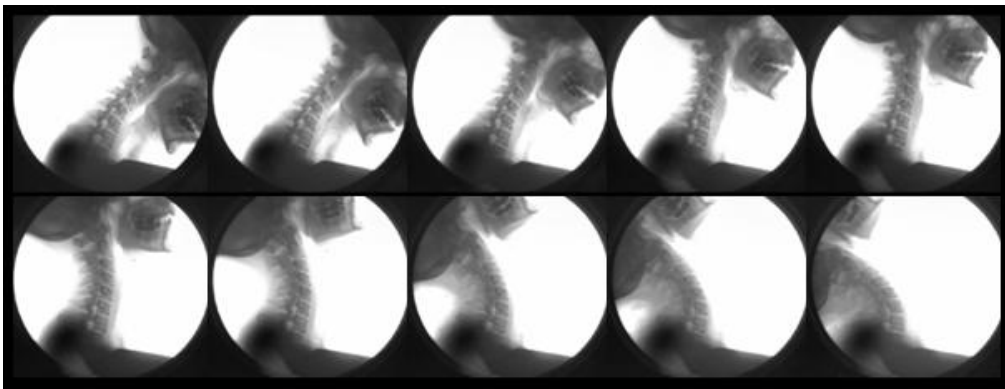
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INTRODUCTION

Cervical spine disorders are often associated with degenerative processes of the intervertebral disc and the facet joints. These structures are critical to maintain normal motion in the neck. Surgical treatment of cervical spine degenerative disorders most commonly involves excision of the degenerated disc and subsequent bony fusion resulting in a total loss of motion at that level. The phenomenon of “transition syndrome” or degeneration of disc spaces adjacent to cervical fusions has been recognized. There is some question whether this is the result of presumed abnormal motion and stresses at the adjacent levels, or a function of natural history or both. Kinematic studies have been conducted under in vitro conditions or with a quasi-static approach. Previously, fluoroscopy has been utilized to study motion patterns in the cervical spine only in a general qualitative mode. Of late, a few authors have begun quantitative motion analysis, but accuracy has been limited by the relatively imprecise methodology heretofore, available. The analysis in the present study utilizes a recently developed technique of computer digitization of fluoroscopic images to allow for a more accurate measurement process to determine the in vivo motion patterns. Furthermore, this methodology allows specific analysis of the relation of the vertebral bodies to each other versus time in actual in vivo dynamic motion studies. Thus, the position and relative angular rotations of one motion segment in relation to the others as well as to the neutral vertical plane can be accurately determined. This capability is crucial to advancing our ability to identify normal patterns of motion in the neck. The methodology also allows for more precise analysis of pathologic situations such as the degenerate cervical spine and the post-fusion state or post-disk replacement state. The aim of the present limited study was to analyze cervical motion under in vivo condition to identify the motion patterns in subjects having either a normal, degenerative, fused or disk replaced cervical spine.

METHODS

In vivo cervical spine kinematics were determined for 40 subjects. Ten subjects had a normal spine, 10 a degenerative spine, 10 a post-operative fused spine and 10 a post-operative disk replaced spine. All subjects having a degenerative, fused or cervical disk replacement were symptomatic at the C5-C6 level. While under fluoroscopic surveillance, each subject was asked to perform a neck extension-to-flexion activity. The minimum follow-up time was six months after implantation of the cervical fusion or disk replacement (Spinal Dynamics, Mercer Island, WA).



All fluoroscopic exams on subjects having a normal, degenerative or fused spine were conducted at the Rocky Mountain Musculoskeletal Research Laboratory (RMMRL). Each subject was examined using a high frequency pulsed fluoroscopy unit (Radiographic and Data Solutions, RADS, Minneapolis, MN). Subjects having a disk-replacement were examined under fluoroscopic surveillance in Belgium.

Each fluoroscopic exam was captured on videotape for subsequent computational digitization (Figure 1). A total of 10

Fig 1. Example of a subject flexing and extending her neck under fluoroscopic surveillance in the sagittal view.

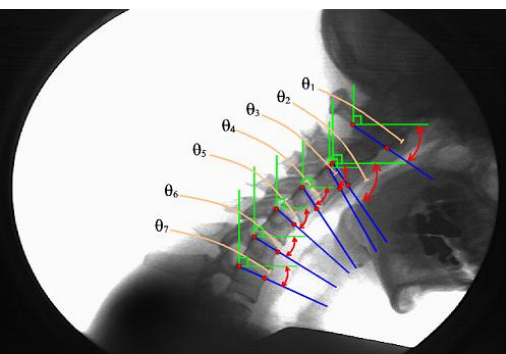


Fig 2. Digitization method used to analyze the cervical spine.

sequential images from each subject's fluoroscopy video were downloaded to a computer. Each vertebra was analyzed with respect to its adjacent vertebrae and with respect to a fixed axis (Figure 2). The time factor in the analysis was generated from the fluoroscopic video frames. Frames were captured at a rate of 30 frames per second, which translates into 0.033 seconds between frames. Relative measurements were taken between successive vertebral bodies. These measured angles were plotted against time allowing for a visual comparison of the individual vertebral motions. Since it has been hypothesized that the forces increase in the cervical spine at the adjacent levels with respect to the fused joint, the comparative kinematic analysis between pre and post-operative conditions concentrated on determination of adjacent vertebral motions.

Calculations of $\gamma_{n,n+1}$ represented the difference in angular values between the two vertebral bodies of question (body n, and body n+1). Each angular measurement was plotted with respect to time to determine the relative angular positions between each vertebral body (Note: the C7-T1 intervertebral disc space was not measured due to limitations in viewing with fluoroscopy). A sign convention was developed for this analysis denoting a negative value if the longitudinal axis of the vertebral body was measured below the horizontal reference, and positive if above the horizontal reference frame.

RESULTS

Initially, each subject was analyzed with respect to an axis in the fixed reference frame. On average, subjects having a normal cervical spine experienced a fan shaped motion (Figure 3). From terminal extension to terminal flexion each subject experienced a motion pattern similar to the average, where each cervical joint experienced progressive increasing rotation.

On average, subjects having a spinal disk replacement experienced a similar motion pattern to the subjects having a normal cervical spine (Figure 4). Although, subjects having a normal cervical spine did experience greater terminal extension than the subjects having a cervical disk replacement, the cervical disk replacement subjects did experience a

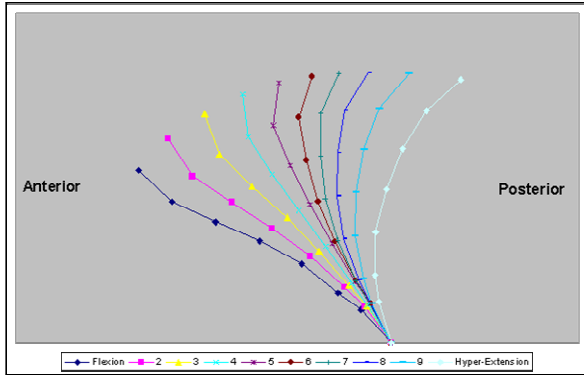


Fig 3. Average motion pattern for the subjects having a normal cervical spine.

progressive increase in joint rotation.

Unlike subjects having a normal or disk-replacement cervical spine, subjects having a degenerative cervical spine experienced less range-of-motion at each cervical joint (Figures 5 and 6). On average, the subjects experienced progressive rotation at each joint, but subject-to-subject analysis revealed variations in this kinematic pattern. Certain subjects experienced significantly less range-of-motion or limited rotation between certain vertebral bodies. Subjects having a fused spine also experienced, on average and subject-to-subject comparisons, less range-of-motion (Figures 7 and 8). Also, at the fusion, the subjects experienced no motion, which was transferred to the adjacent levels. Subject-to-subject comparisons also revealed variable patterns that were not similar to the average plot.

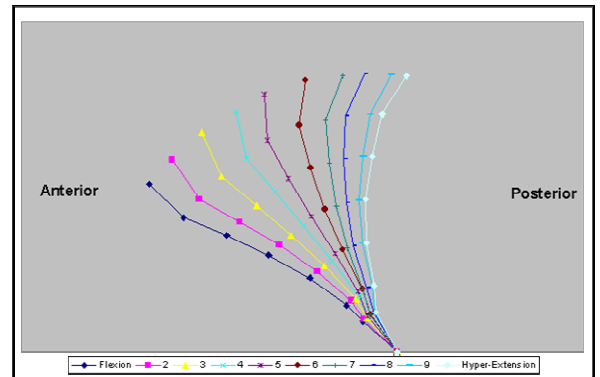


Fig 4. Vertebral digitization showing average motion of all disk replacement subjects.

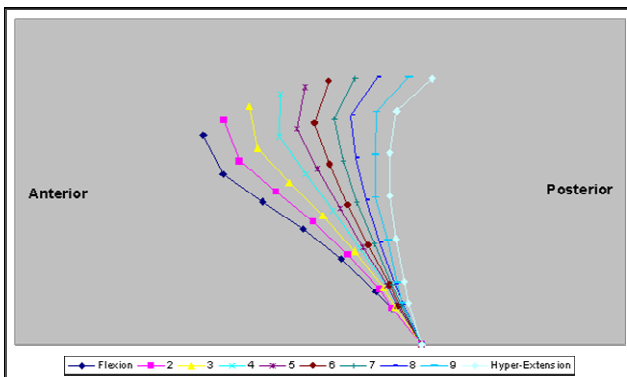


Fig 5. Vertebral digitization showing average motion of all degenerative subjects.

spine, respectively. Subjects having a degenerative or fused cervical spine experienced - 21.0 and -26.7 degrees of rotation, respectively. Therefore, at full (terminal) flexion, the normal and disk-replacement subjects experienced similar rotation angles that were both statistically

A comparison was then conducted at each disk to determine variations in the kinematic patterns between the four groups. The average angular rotation for the four groups at C1 with respect to the fixed reference frame revealed similar kinematic patterns between the normal and the disk-replacement subjects. At the first analyzed frame of the fluoroscopic videos (full flexion) the average rotation angle was -42.9 and -48.1 degrees for subjects having a normal and a disk-replacement cervical

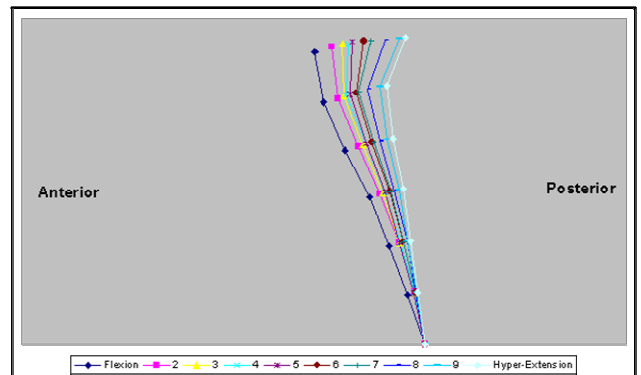


Fig 6. Vertebral digitization showing a subject with a degenerative cervical spine experiencing less range-of-motion.

different than the other two groups ($p < 0.05$). At terminal extension all four groups experienced a similar extension angle, and from mid-flexion to full extension all four groups experienced similar kinematic patterns of C1 relative to the fixed reference frame.

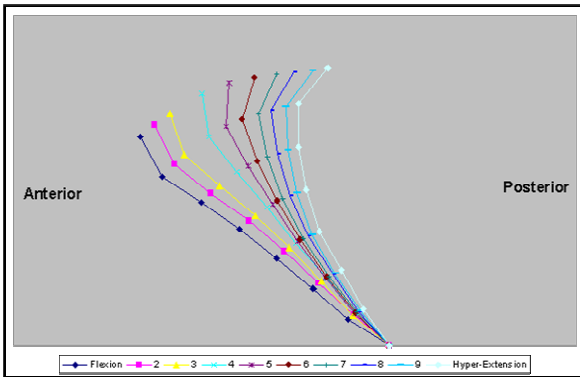


Fig 7. Vertebral digitization showing average motion of all fused subjects.

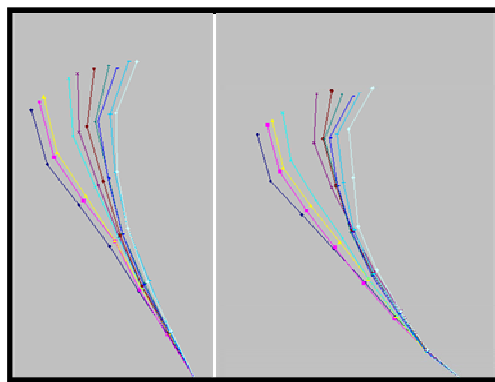


Fig 8. Two subjects having fusion who experienced variable kinematic patterns. The first subject experienced minimal motion at each joint (left), while a second subject experienced minimal motion near the fusion, but attempt to compensate at the upper levels for the loss in motion.

average relative rotation of C4 with respect to the fixed reference frame was -57.9 and -57.4 degrees for the normal and disk-replacement subjects, respectively. On average, the fusion and degenerative subjects, experienced less rotation than the other two groups. On average, the fusion subjects experienced -48.5 degrees of C4 rotation, while the degenerative subjects experienced -46.0 degrees of rotation. At full extension the average amount of rotation was 12.5 , -0.8 , -6.1 and -15.7 degrees for the normal, disk-replaced, degenerative and fused subjects, respectively. Through the range-of-motion, subjects having a disk-replacement experienced the kinematic patterns most similar to the normal cervical spine. At C4, the subjects having a fusion again could not achieve flexion angles similar to the other three groups. Subjects having a normal cervical spine were the only

subjects that could achieve a positive flexion angle at full flexion.

At C5, which is part of fusion, subjects having a fused cervical neck experienced significantly different kinematics than all three groups ($p < 0.05$).

At full flexion, the subjects having a normal, disk-replacement or fused cervical spine experienced a similar rotation angle of C5 with

A comparison of the rotation of C2 with respect to the fixed reference frame revealed that the disk-replacement subjects, again on average, experienced a kinematic pattern more similar to the normal cervical spine subjects. At full flexion the average relative rotation of C2 with respect to the fixed reference frame was -62.5 and -65.2 degrees for the normal and disk-replacement subjects, respectively. On average, the fusion and degenerative subjects, experienced less rotation than the other two groups. On average, the fusion subjects experienced -52.2 degrees of C2 rotation, while the degenerative subjects experienced -49.7 degrees of rotation. At full extension the average amount of rotation was 28.2 , 12.0 , 6.8 and 0.0 degrees for the normal, disk-replaced, degenerative and fused subjects, respectively. Through the range-of-motion, subjects having a disk-replacement experienced the kinematic patterns

most similar to the normal cervical spine.

The kinematic patterns for the C3 rotation was similar to C2. A comparison of the rotation of C3 with respect to the fixed reference frame revealed that the disk-replacement subjects, again on average, experienced a kinematic pattern more similar to the normal cervical spine subjects. At full flexion the average relative rotation of C4 with respect to the fixed reference frame was -63.4 and -61.9 degrees for the normal and disk-replacement subjects, respectively. On average, the fusion and degenerative subjects, experienced less rotation than the other two groups. On average, the fusion subjects experienced -51.9 degrees of C3 rotation, while the degenerative subjects experienced -49.8 degrees of rotation. At full extension the average amount of rotation was 20.6 , 7.6 , 0.3 and -8.9 degrees for the normal, disk-replaced, degenerative and fused subjects, respectively. Through the range-of-motion, subjects having a disk-replacement experienced the kinematic patterns most similar to the normal cervical spine. Subjects having a fusion could not flex their neck enough to achieve positive average amount of neck flexion.

The kinematic patterns for C4 rotation was also similar in pattern to C1, C2 and C3. A comparison of the rotation of C4 with respect to the fixed reference frame revealed that the disk-replacement subjects, again on average, experienced a kinematic pattern more similar to the normal cervical spine subjects (Figure 9). At full flexion the

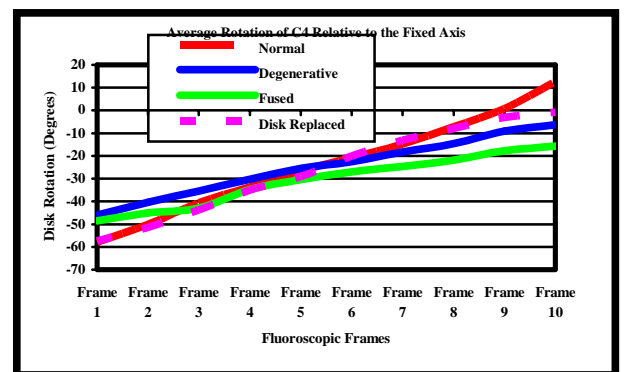


Fig 9. Comparison of the average rotation of C4 with respect to the fixed reference frame.

respect to the fixed reference frame. The average rotation angle was -48.8 , -50.0 , and -46.7 degrees for the normal, disk-replacement and fused subjects, respectively. On average, the subjects having a degenerative cervical spine experienced only -40.2 degrees of C5 rotation. From full flexion to the up-right position of the head, the degenerative subjects experienced less C5 rotation than the other three groups. From mid-flexion through terminal extension, subjects having a fused cervical spine experienced significantly more rotation of C5 than the other three groups ($p < 0.05$). On average, at terminal extension the amount of C5 rotation was 0.8 , -8.9 , -8.9 and -26.7 degrees for subjects having a normal, disk-replacement, degenerative and fused cervical spines, respectively. Again, at terminal flexion, the only group able to extend their neck to a positive rotation angle was the normal cervical spine group.

At C6, the other vertebral body that was fused, the fused subject again experienced a very different kinematic pattern compared to the other three groups. At full flexion, the average rotation angle for C6 was most similar between the normal and fused groups, but throughout extension to terminal extension, the fused group experienced significantly greater flexion ($p < 0.05$). At full flexion the average rotation angle for C6 was -45.3 , -42.4 , -35.5 and -45.3 degrees for the normal, disk-replacement and fused subjects, respectively. Throughout neck extension, the subjects having a degenerative cervical spine experienced, on average, less flexion than the other three groups. Therefore, from terminal flexion to terminal extension the subjects having a disk-replacement experienced the most similar kinematic pattern to the normal cervical spines. At terminal extension, the average C6 rotation angle was -10.8 , -12.2 , -11.8 , and -25.9 degrees for the normal, disk-replacement, degenerative and fused cervical spines, respectively.

At C7, on average, subjects having a fused spine experienced a significantly different kinematic pattern than the other three groups ($p < 0.05$). From terminal flexion to terminal extension the fused subjects experienced significantly greater flexion than the other three groups. At full flexion, the average rotation angle for C7 was -39.5 , -44.7 , -35.6 and -54.2 degrees for the normal, disk-replacement, degenerative and fused subjects, respectively. At full extension, the average rotation angle of C7 was -15.1 , -24.3 , -14.5 and -35.9 degrees for the normal, disk-replacement, degenerative and fused subjects, respectively.

Throughout the neck flexion/extension activity the normal subjects were able to achieve more extension than the other three groups, while the fused subjects experienced the least amount of ability to extend their neck. At all seven vertebral bodies, the subjects having a disk-replacement experienced the most similar kinematic pattern to the normal cervical spine subjects. The subjects had the most continuous vertebral body motion and were able to transition well from full flexion to full extension.

The overall rotation of all seven vertebral bodies demonstrated again that the subjects having a disk-replacement experienced the most similar motion compared to the normal cervical spines. The average overall rotation of C1 was 86.7 , 81.7 , 62.3 and 61.8 degrees for the normal, disk-replacement, degenerative and fused subjects, respectively. At C2, the average amount of rotation was 90.7 , 77.2 , 56.5 and 52.2 degrees for the normal, disk-replacement, degenerative and fused subjects, respectively. At C3, the average amount of rotation was 83.9 , 69.5 , 50.0 and 43.0 degrees for the normal, disk-replacement, degenerative and fused subjects, respectively. At C4, the average amount of rotation was 70.4 , 56.7 , 39.8 and 32.8 degrees for the normal, disk-replacement, degenerative and fused subjects, respectively. At C5, the average amount of rotation was 49.7 , 41.1 , 31.3 and 20.0 degrees for the normal, disk-replacement, degenerative and fused subjects, respectively. At C6, the average amount of rotation was 34.5 , 30.2 , 23.7 and 19.4 degrees for the normal, disk-replacement, degenerative and fused subjects, respectively. At C7, the average amount of rotation was 24.4 , 20.4 , 19.1 and 18.3 degrees for the normal, disk-replacement, degenerative and fused subjects, respectively. Again, the normal cervical spine subjects experienced the greatest amount of overall disk rotation, but the disk-replacement subjects were able to achieve more motion than the degenerative and fused cervical spine subjects. The greatest difference in overall rotation occurred at C1 through C5, which is due to these vertebral bodies experiencing more motion during the flexion/extension activity.

A final comparison was then conducted between the four groups to determine the relative vertebral body rotations. Interestingly, the normal subjects experienced an initial increase in neck flexion between C1 and C2. The other three groups experienced a decrease in neck flexion as the head moved towards extension. At full extension, C1 (-42.9 degrees) is more extended than C2 (-62.5 degrees) (or more upright). Throughout neck extension C1 does extend more than C2 and at terminal extension C1 experiences a significantly greater rotation angle (C1 = 43.8 , C2 = 28.2 degrees), but the difference in the amount of flexion at full flexion is greater than the difference of extension at terminal extension (C2 > C1 @ full flexion = 19.6 degrees, C1 > C2 @ full extension = 15.6 degrees). Therefore, the total amount of rotation for C1 and C2 for the normal subjects was 86.7 and 90.7 degrees, respectively. Therefore, the average change in rotation between C1 and C2 was -4.0 degrees for the normal subjects. At the fused cervical joint and at the adjacent cervical joints the disk-replacement subjects experienced the most similar kinematic patterns. Although it is assumed that the fused subjects will compensate for loss motion at the adjacent vertebra, this finding was not substantiated in this study. The fused subjects did experience greater motion at the C1-C2 and C2-C3 joints, which may be where these subjects attempted to compensate for lost motion at the fused joint. At the C5-C6 level, the fused subjects did not experience a relative change in rotation, which is to

be expected, but at the C4-C5 and C6-C7 levels, subjects having a disk-replacement were able to achieve greater relative rotational motion.

DISCUSSION

In its normal state, the human cervical spine appears to have a pattern of motion comparable to an opening fan. The base of the fan is held fixed in the hand, or in the case of the neck, the C7 vertebrae is anchored to the thorax. Opening the fan, or initiating a flexion/extension motion in the neck, results in a smooth, even alteration in position of the segmental components relative to the fixed base point.

Degenerative changes in the cervical spine cause neck motion to revert to a tight pattern more comparable to a flagpole bending slowly and stiffly in the wind. The overall excursion is less and the degenerate segments contribute little to the total motion. Movement is also relatively slow, with a reduction in angular velocities resulting in more time required to achieve a smaller overall displacement.

A cervical fusion results in an interesting alteration of motion pattern, which attempts to revert spinal motion back to near normal excursion, but with a “hinge” pattern. The fused segment acts as the fixed base of the hinge with the remaining levels exceeding their motion in the normal state. The subjects in this study having a fused cervical spine experienced less extension than the other three groups. These subjects did not appear to have the ability fully extend any of their vertebral bodies.

The subjects having a disk-replacement cervical spine appeared to have the most similar kinematic pattern to the normal subjects. One subject did appear to limited rotational motion at each cervical joint, but this could be due to early post-operative results. Most subjects having a disk-replacement were able to achieve more overall and relative rotation than the fused or degenerative subjects.

This study has identified the “fan”, “flagpole” and “hinge” motion patterns, which appear to correspond with the normal and disk-replacement, degenerate and post fusion states in the cervical spine. The analysis has validated the spine modification of the digitization software originally developed for evaluation of total hips and knees. As a research tool, the analysis of digitized in vivo fluoroscopic images has potential application in answering questions regarding the consequences of surgery on motion patterns, the effectiveness of various cervical orthoses and in rooting out a biomechanical cause for “transition syndrome”

Cervical spine disc degeneration is a problem that affects millions of people. The surgical treatment of this problem traditionally has involved vertebral fusion, and, although, patients often regain strength and sensation and experience decreases levels of pain, it has been seen that these fusions show inconsistent long-term clinical results. This study has determined that subjects having a cervical disk-replacement experience better kinematic patterns and more continuous rotational motion at each cervical joint. Also, as a surgeon includes more levels in the fusion, motion abnormalities may become more pronounced at adjacent levels. Therefore, it can be assumed from this pilot study that subjects having a disk-replacement could benefit greatly and experience overall motions that are more normally than those seen with fusions.

Intuitively, one would expect that motion patterns would differ among the four cervical spine groups analyzed in this study, and, in reviewing the kinematic results it was evident that motion patterns were vastly different. On average, subjects having a normal cervical spine experienced the greatest amount of range-of-motion. Subjects having a disk-replacement experienced the next highest amount of range-of-motion. There was a significant difference in the motion patterns for the fused and degenerative subjects, which lead to a decrease in overall range-of-motion. The pain associated with cervical disc degeneration may be one of the factors that adversely affected the range-of-motion for these subjects. The majority of the fused subjects demonstrated the inability to fully extend their vertebral bodies from the upright position to terminal extension.

A concern for the fused cervical spines is that the abnormal motions in levels adjacent to fusions may contribute to disc degeneration. By compensating for lost motion at the fused levels, the other levels (typically C1-C2, C2-C3) may subject increased stresses at the adjacent vertebral bodies to the fusion. It was previously assumed that adjacent levels will experience greater range-of-motion which could lead to premature breakdown at the adjacent level. This study has shown that the fused subjects attempt to recover lost motion at the C1-C2 and C2-C3 levels which could lead to increased torques at the adjacent levels. This study is a preliminary attempt to characterize in vivo motion patterns for subjects in four cervical disk groups. Further analysis should be conducted before definitive conclusions could be made. It could be beneficial to conduct a three-dimensional in vivo analysis to determine the six degrees-of-freedom in the normal, disk-replacement, degenerative and fused cervical spines.

References furnished upon request.