In vivo ranges of motion of cervical segments in patients with cervical spondylosis during dynamic neck motions

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Cervical spondylosis refers to degenerative changes in the sub-axial cervical spine. Symptoms caused by spondylosis include axial neck pain, cervical radiculopathy, and cervical myelopathy. One of the most commonly used surgical treatments is anterior cervical discectomy and fusion (ACDF); it is reported that ACDF leads to the development of progressive adjacent segment degeneration (ASD) in over 90% of the patients with up to 25.6% requiring re-operations due to symptomatic ASD.[1] Recent total disc replacement (TDR) prostheses were developed to restore motion capability of the diseased-levels, but clinical outcomes and post-operative re-operation rates were not superior to ACDF.[2] As the etiology of ASD is unclearly defined, a possible explanation for ASD is that the spinal motion restored after ACDF or TDR does not match the *in vivo* physiological motion of the patient-specific cervical spine.[1] Since no *in vivo* data has previously been reported on the cervical motions of symptomatic patients, we evaluated the *in vivo* range of motion (ROM) of each sub-axial cervical segment in spondylotic patients with the symptom at C5–6 using a dynamic imaging technique, and compared the patients' data with those of an asymptomatic control group of matched age and sex distributions. We specifically investigated whether and how spondylosis affects cervical motion before surgical interventions. This research was approved by the Partners Human Research Committee at Massachusetts General Hospital (No. 2012P002508/MGH).

Eight spondylotic patients (four females, four males; age: 26–51 years; Pfirrman grades: III to V at C5–6; ossification of the posterior longitudinal ligament occurred at C5–6 in all patients, producing myelopathy or radiculopathy) and ten asymptomatic subjects (four females, six males; age: 30–59 years; Pfirrman grades: I to III at C5–6) without prior spinal disorders were recruited with institutional review board approval. The cervical spine of each subject was magnetic resonance imaging (MRI)-scanned using a 3 Tesla scanner (MAGNETOM Trio, Siemens, Germany) with a spine surface coil and a proton density weighted sequence. The MRI images (slice thickness: 1.5 mm; image resolution: 282×384 pixels; voxel size: $0.625 \times 0.625 \times 1.500$ mm) were imported into a 3D solid modeling software to construct 3D anatomical vertebral models of the cervical spine.[3] The cervical spine of each subject was then imaged using a dual fluoroscopic system (DFIS)[3] [Figure 1A]. Two fluoroscopes (BV Pulsera, Phillips, Bothell, WA, USA) were positioned with their image intensifiers perpendicular to each other to capture orthogonal images of the cervical spine at 30 frames/s. The subject positioned their cervical spines within the view of the two fluoroscopes. Starting from an upright neutral position and guided by the beat of a metronome, the subject continuously moved the neck in full ranges of flexion-extension and left-right axial twisting neck motions, respectively. Each subject was imaged for less than 3 s for each activity to ensure the collection of a full dynamic cycle and three full cycles were imaged. Each subject received radiation dosage of ~1.0 mSv during the test that is ~2% of the amount one normally receives in 1 year from natural background sources. The fluoroscopic images and 3D vertebrae models were imported in the Rhinoceros solid modeling software (Robert McNeel & Associates, Seattle, WA, USA) to create a virtual DFIS [Figure 1B] which mimics the actual DFIS. Using a previously validated 3D-2D registration technique,[3] the 3D models of the vertebrae were independently translated and rotated in six degrees of freedom until their projections matched to the osseous outlines on the fluoroscopic images. The positions and alignments of the C3-C7 vertebrae captured on the

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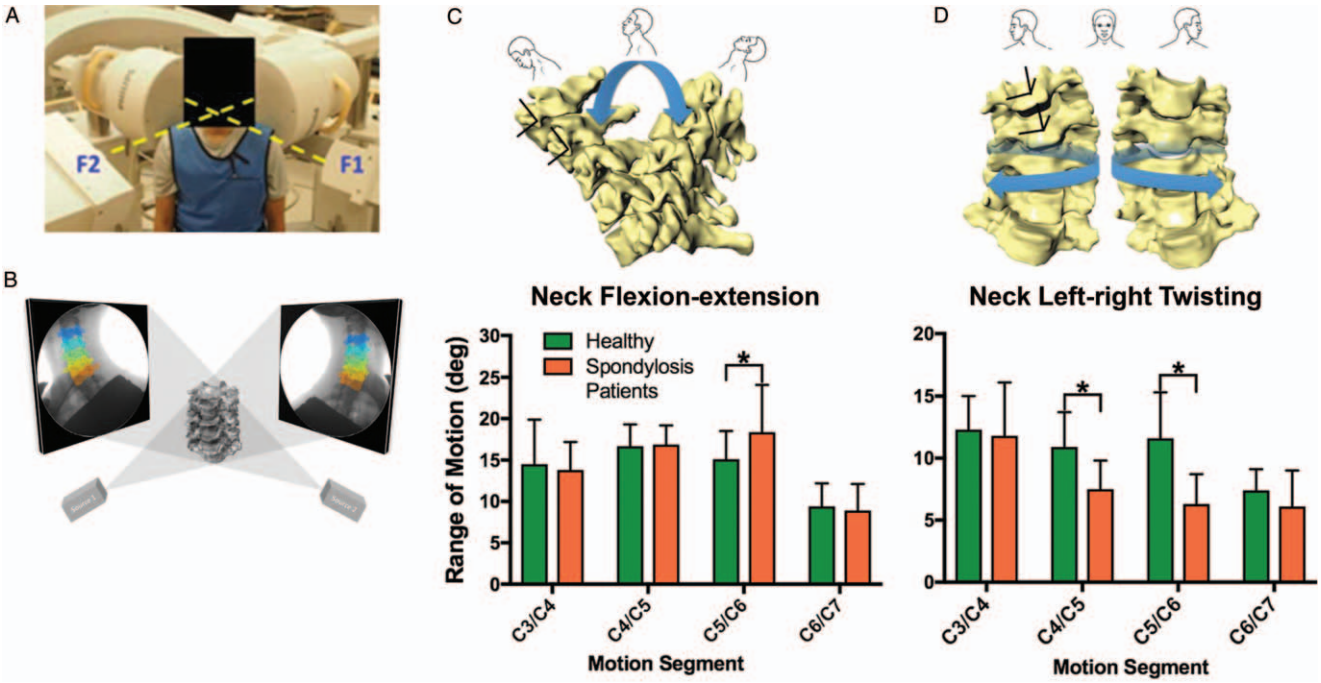

Figure 1: Experimental settings of the dual fluoroscopic imaging system (DFIS) for capturing dynamic images of the cervical spine during neck motion (A). The virtual DFIS combining the paired fluoroscopic images and 3D cervical models to reproduce *in-vivo* cervical motions through a 3D-2D registration procedure (B). Cervical ROMs during flexion-extension of the neck (C). Cervical ROMs during left-right twisting of the neck (D). ROMs: Ranges of motion; Deg: degree.

paired fluoroscopic images were reproduced using the 3D vertebral models. The repeatability of the registration technique was ±0.3 mm and ±0.7° in determining *in vivo* intervertebral kinematics,[3] demonstrating that the DFIS is a feasible and repeatable technique for measurements of *in vivo* spinal motions.

Intervertebral kinematics were calculated as the relative motion of the superior vertebrae with respect to the inferior vertebrae at the C3–4, C4–5, C5–6, and C6–7 levels using Cartesian coordinate systems.[3] We reported the ROMs in principal rotational directions of the neck for the vertebral segments during the two functional activities, that is, flexion-extension and left-right twisting, respectively [Figure 1C and 1D]. The ROM was represented by the difference between the maximal and minimal values of each motion throughout a cycle. The averages of the three trials were used to represent the ROMs of the subject. Student's *t* tests were used to analyze the differences in ROMs between the healthy and spondylotic groups at C3–4, C4–5, C5–6, and C6–7 levels. Statistical significance was set when $P < 0.05$.

During the flexion-extension motion of the neck, the ROM of C3–4 was 14.5° ± 5.7° in healthy group and 13.8° ± 3.6° in the spondylotic patients ($P > 0.05$) [Figure 1C]. At the adjacent level C4–5, the ROM was 16.7° ± 2.7° in healthy and 16.9° ± 2.5° in the spondylotic patients ($P > 0.05$). At the index level C5–6, the mean ROM was 15.1° ± 3.6° in healthy group and 18.4° ± 5.9° in the spondylotic patients. The ROM of the healthy group was significantly lower than the spondylosis group ($P < 0.05$). While at the index level C6–7, the ROM was 9.4° ± 3.0° in healthy group and 8.9° ± 3.3° in the spondylotic patient group ($P > 0.05$).

During the left-right twisting motion of the neck, the ROM of C3–4 was 12.3° ± 2.9° in healthy group and 11.8° ± 4.4° in the spondylotic patients ($P > 0.05$) [Figure 1D]. At the adjacent level C4–5, the ROM was 10.9° ± 2.9° in healthy and 7.5° ± 2.4° in the spondylotic patients. The ROM of the healthy group was significantly higher than the spondylosis group ($P < 0.05$). At the index level C5–6, the mean ROM was 11.6° ± 3.8° in the healthy group and 6.3° ± 2.4° in the spondylotic group. The ROM of the healthy group was significantly higher than the spondylosis group ($P < 0.05$). While at the index level C6–7, the ROM was 7.4° ± 1.8° in healthy group and 6.1° ± 3.0° in the spondylotic patient group ($P > 0.05$).

These results indicate that the two neck motions lead to differences in angular ROMs between the spondylotic and healthy control groups. The spondylotic patients had significantly increased ROM at the diseased (C5–6) level during the flexion-extension motion of the neck, resulting in laxity at the index level. The ROMs were reduced at the diseased (C5–6) level and the proximately adjacent level (C4–5) of the spondylotic patients during the left-right twisting motion of the neck, resulting in stiffening of both the index and proximal adjacent levels. These data indicate that abnormal motion patterns of necks suffering from spondylosis are associated with physiological conditions in neck motions and specific cervical levels.

We found that spondylosis was associated with a reduced ROM of the adjacent segment during the left-right twisting, which is a common daily functional activity of the neck. It highlights that data measured in a single neck motion such as flexion-extension may not comprehensively represent the effect of spondylosis on cervical

behavior in other neck motions. Correspondingly, motion-preserving implants that were developed by considering only a single loading condition may not restore cervical motions under other loading conditions. Therefore, the effects of cervical spondylosis on cervical motion presented in this study could have important clinical implications. Contemporary motion-preserving surgical treatments mostly aim to restore segment motion to "normal" levels, but post-operative complications such as ASD are still often reported.[2] Spinal degenerative changes may result in significantly different motion patterns at the index level before surgery, indicating the long-term adaption of surrounding spinal structures to the disease status. Therefore, decompression surgery[4] which causes minimal iatrogenic changes may be an alternative to ACDF. In addition, re-definition of design objectives for the motion-preserving implants (by further considering spinal tissue load sharing instead of uniquely restoring motion to "normal" levels) is necessary to improve clinical outcomes. Current TDRs commonly using artificial disks with metal-on-polyethylene articulations provide minimal resistance to intervertebral axial rotations. To match the normal intervertebral ROMs ($15.1° \pm 3.6°$ in neck flexion-extension *vs.* $11.6° \pm 3.8°$ in neck left-right twisting) at the index (C5–6) level, TDR could be more suitable for neck flexion-extension motion than for neck left-right twisting. Recently, hybrid application of fusion and TDR has been reported in clinical studies to treat cervical spondylosis.[5] It is shown that the hybrid surgery may have the biomechanical advantages to synergize the over-constraint of fusion and minimal resistance of TDRs. An *in vivo* study is warranted to compare the biomechanical functions of various surgical techniques including segmental fusion, TDR, and hybrid surgeries.

There are several limitations that should be noted when interpreting our data. A *post hoc* power analysis showed that the powers were 72% and 90% for the left-right twisting ROMs at the adjacent (C4–5) and index (C5–6) segments, respectively, but there was only a power of 25% for the flexion-extension ROM at the index segment. Due to the small sample size, whether spondylosis alters segment motion at the diseased level during neck flexion-extension rotation should be further validated. Furthermore, the lack of evaluation of soft tissue status also presents a limitation. Because soft tissue maladies may be associated with abnormal cervical ROMs, it is necessary to further quantify soft tissue changes using MRI in future studies (*eg*, T2 values of the discs). In addition, we only included patients with spondylosis at C5–6. Future studies should also include other cervical degenerative pathologies such as single-level and multi-level cervical degenerations. Investigations of these patients pre- and post-operatively in a prospective, longitudinal fashion should be conducted in order to investigate the kinematic changes of the adjacent segments after surgery and to explore the biomechanical factors related to ASD development.

In conclusion, we investigated the ROMs of a patient cohort with spondylosis at C5–6 during dynamic flexion-extension and left-right twisting neck motions using a dynamic imaging technique. Compared to those of asymptomatic subjects, it was revealed that spondylosis caused higher ROMs at the diseased level during neck flexion-extension, but lower ROMs at both the diseased and proximally adjacent levels during the left-right neck twisting. It indicates that spondylosis affects the ROMs of both the diseased and adjacent levels, depending on the neck motion scenarios. These data could provide valuable insights into the improvement of cervical surgery. We suggest that motion-preserving treatments should further consider pre-operative spinal disease status to restore physiological segmental ROM.

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Conflicts of interest

None.

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