Short communication

Cervical spine intervertebral kinematics with respect to the head are different during flexion and extension motions


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A R T I C L E   I N F O

Article history:
Accepted 3 March 2013

Keywords:
In vivo
Dynamic kinematics
Disc degeneration
Movement direction

A B S T R A C T

Previous dynamic imaging studies of the cervical spine have focused entirely on intervertebral kinematics while neglecting to investigate the relationship between head motion and intervertebral motion. Specifically, it is unknown if the relationship between head and intervertebral kinematics is affected by movement direction. We tested the hypothesis that there would be no difference in sagittal plane intervertebral angles at identical head orientations during the flexion and extension movements. Nineteen asymptomatic subjects performed continuous head flexion-extension movements while biplane radiographs were collected at 30 images per second. A previously validated model-based volumetric tracking process determined three-dimensional vertebral position with sub-millimeter accuracy throughout the flexion–extension motion. Head movement was recorded at 60 Hz using conventional motion analysis and reflective markers. Intervertebral angles were determined at identical head orientations during the flexion and extension movements. Cervical motion segments were in a more extended orientation during flexion and in a more flexed orientation during extension for any given head orientation. The results suggest that static radiographs cannot accurately represent vertebral orientation during dynamic motion. Further, data should be collected during both flexion and extension movements when investigating intervertebral kinematics with respect to global head orientation. Also, in vitro protocols that use intervertebral total range of motion as validation criteria may be improved by assessing model fidelity using continuous intervertebral kinematics in flexion and in extension. Finally, musculoskeletal models of the head and cervical spine should account for the direction of head motion when determining muscle moment arms because vertebral orientations (and therefore muscle attachment sites) are dependent on the direction of head motion.

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1. Introduction

Cervical spine kinematics in the sagittal plane have traditionally been determined using static full-flexion and full-extension radiographs (Dunsker et al., 1978; Dvorak et al., 1988; Frobin et al., 2002; Penning, 1960; White and Panjabi, 1978). However, measurements made using static, end range positions may not accurately represent dynamic behavior, and these images provide no information regarding mid-range motion that is most often encountered during activities of daily living (Bible et al., 2010; Cobian et al., 2009). These shortcomings may explain, in part, the poor correlation between static imaging results and patient pain (Arana et al., 2006; Boden et al., 1990; Friedenberg and Miller, 1963; Nordin et al., 2008; Siivola et al., 2002).

In order to address these limitations associated with static imaging of the spine, imaging during dynamic, functional motion has become more common (Anderst et al., 2013, in press; McDonald et al., 2010; Reitman et al., 2004; van Mameren et al., 1992; Wu et al., 2010). Previous dynamic imaging studies of the cervical spine have focused entirely on intervertebral kinematics while neglecting to investigate the relationship between head motion and intervertebral motion. Detailed knowledge of the relationship between head and vertebral kinematics is necessary to optimize musculoskeletal models that require accurate head and vertebral kinematics to determine moment arms for inverse dynamics calculations (Liu et al., 2007; Mathys and Ferguson, 2012; Moroney et al., 1988). A common assumption of these musculoskeletal models is that the active muscles are determined by the head angle, not the direction of movement (Anderst et al., 2013, in press; Liu et al., 2007; Moroney et al., 1988). Therefore, it is critical to determine if the relationship between head angle and intervertebral orientation (and therefore muscle moment arms) is affected by movement direction. Second, it is not clear how well static images (e.g. radiographs, CT, MRI) represent cervical spine kinematics during in vivo dynamic, functional motion. Knowledge of this relationship is beneficial to the clinician who uses static
images to determine clinical diagnosis. Finally, all techniques currently in use to record intervertebral kinematics during dynamic, functional loading require X-ray exposure to the subject. If it can be demonstrated that the relationship between head movement and intervertebral movement is unrelated to movement direction, exposure can be reduced by limiting data collection to half of the movement (e.g. just flexion or just extension).

The objective of this study was to assess the relationship between head movement and intervertebral kinematics in the sagittal plane. Specifically, it was hypothesized that there would be no differences in intervertebral flexion–extension angles at identical head orientations during the flexion and extension movements.

2. Methods

Following Institutional Review Board approval, data was collected from 19 subjects (average age: 45.6±5.8 years; 6 males, 13 females) who provided informed consent to participate in this research study. These subjects were asymptomatic and had no history of pain or disability involving their cervical spine. High-resolution CT scans (GE Lightspeed 16) (0.29×0.29×1.25 mm voxels) of the cervical spine (C2–C7) were acquired on each participant. The effective dose of a cervical spine CT scan has been reported to be between 3.0 mSv and 4.36 mSv (Anderst et al., 2011). Bone tissue was segmented from the CT volume using a combination of commercial software (Mimics software, Materialise, Leuven, Belgium) and manual segmentation (Thorhauer et al., 2010). A three-dimensional (3D) model of each vertebra was generated from the segmented bone tissue. Markers were interactively placed on the 3D bone models to define bone-specific anatomic coordinate systems.

Subjects were seated within a biplane X-ray system and directed to continuously move their head and neck through their entire range of motion in the sagittal plane. A metronome set at 40 beat/min to 44 beat/min was used to ensure the participants moved at a steady pace to complete each trial (a full and continuous flexion–extension movement) in approximately 3 s. Radiographs were collected at 30 Hz (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 46 movement trials analyzed for this study. A 0.1 s static trial, with the subject looking forward with the head in the neutral position, was also performed at each motion segment for each trial. Results from multiple trials from a single subject were averaged to determine a single value at each 1% of the movement cycle for each subject. Results from all subjects were then used to determine the 95% confidence interval (CI) of the difference between the flexion and extension movement directions at each 1% increment of the movement cycle. When the 95% CI of the difference between flexion and extension movement directions did not include zero, the intervertebral flexion kinematics were significantly different from intervertebral extension kinematics.

3. Results

During in vivo functional loading, for any given orientation of the head, cervical motion segments were in a more extended orientation during flexion and in a more flexed orientation during extension (Fig. 1). These differences in intervertebral angle at identical head orientations during flexion and extension varied by motion segment, with minimum differences at the C2/C3 motion segment and maximum differences at the C4/C5 motion segment (Fig. 2, Table 1). The mean difference in intervertebral angle between flexion and extension movements were significant for C2/C3 from 21% to 84% of the head ROM, and from 4% or less to 96% or more for all remaining motion segments (Fig. 2, Table 1).

4. Discussion

The aim of this study was to assess the relationship between head movement and intervertebral kinematics in the sagittal
The primary finding was that intervertebral angles are significantly different at identical head orientations during the flexion and extension movements. The lower motion segments (C3/C4 and below), in particular, were in significantly different positions for a given head orientation for nearly the entire motion, not exclusively the mid-range of motion.

The study results confirm that a radiograph of the cervical spine collected with the subject in a stationary, mid-range position is not an accurate representation of the orientation of the vertebrae during dynamic motion. This may explain, in part, the low correlation between static imaging results and clinical symptoms (Boden et al., 1990; Kaiser and Holland, 1998). Although differences have been reported between static and dynamic wrist arthrokinematics (Foumani et al., 2012), it is not clear how large the kinematic differences are between static and dynamic kinematics of other joints, such as the knee, that are commonly analyzed in static positions (Abebe et al., 2011; Li et al., 2005; Scarvell et al., 2005) and during dynamic motion (Sheehan, 2007; Tashman et al., 2007). Second, the results indicate that when investigating intervertebral kinematics with respect to global head orientation, kinematics should be determined during flexion movements and during extension movements. In contrast to this finding, knee kinematics appear identical in unloaded flexion and extension (Dyrby and Andriacchi, 2004), although kinematic differences during loaded knee flexion and extension have yet to be investigated. Future studies are necessary to assess the kinematic results (bone kinematics and tissue-level kinematics) when imaging static and dynamic activities, and to assess the effect of

### Table 1

<table>
<thead>
<tr>
<th>Joint</th>
<th>Maximum Difference</th>
<th>Average Difference in Midrange of Movement (20% to 80% of Total Head ROM)</th>
<th>Average Difference over Total Head ROM</th>
<th>Head ROM Where Extension and Flexion were Significantly Different (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2/C3</td>
<td>0.8°</td>
<td>0.6°</td>
<td>0.4°</td>
<td>21–84</td>
</tr>
<tr>
<td>C3/C4</td>
<td>2.8°</td>
<td>2.3°</td>
<td>1.7°</td>
<td>4–96</td>
</tr>
<tr>
<td>C4/C5</td>
<td>4.1°</td>
<td>3.5°</td>
<td>2.7°</td>
<td>2–99</td>
</tr>
<tr>
<td>C5/C6</td>
<td>3.3°</td>
<td>3.0°</td>
<td>2.4°</td>
<td>2–99</td>
</tr>
<tr>
<td>C6/C7</td>
<td>2.0°</td>
<td>1.9°</td>
<td>1.6°</td>
<td>4–98</td>
</tr>
</tbody>
</table>

Fig. 2. The average within-subject difference in intervertebral angle in the sagittal plane between the extension movement and the flexion movement at each motion segment (n = 19 subjects). Differences in intervertebral angles are plotted on the vertical axis for each motion segment versus head orientation in the sagittal plane on the horizontal axis. Solid lines indicate mean differences, dashed lines indicate 95% confidence intervals of the difference.
movement direction on kinematics in other joints. Third, considering the fact that musculoskeletal models of the head and cervical spine assume the active muscles are determined by head angle, not movement direction (Anderst et al., 2013, in press; Liu et al., 2007), the current results suggest that these models should account for the direction of head motion when determining muscle moment arms because vertebral orientations (and therefore muscle attachment sites) are dependent on the direction of head motion. The direction-dependent differences at each motion segment are cumulative, leading to substantially different spine configurations for identical head orientations when moving in flexion or extension. Finally, the results suggest that finite element models that use intervertebral total range of motion as validation criteria (Faizan et al., 2012; Hussain et al., 2010; Kallemeyn et al., 2010; Panzer and Cronin, 2009) may be improved by assessing model fidelity using continuous intervertebral kinematics in flexion and in extension due to the demonstrated effects of movement direction on intervertebral kinematics.

The information reported here is limited to the flexion–extension movement. Further research will be required to determine if intervertebral angles are dependent on head movement direction during other common spine motions such as rotation (i.e. twisting). Finally, the effects of surgery and degeneration on the relationship between head and intervertebral motion remain to be characterized.

Conflict of interest statement

None of the authors have financial or personal relationships with other people or organizations that could inappropriately influence (bias) this work. Authors WFD, JYL and JDK have received a research grant from Stryker, paid to their institution, for research supplies, equipment and personnel unrelated to the current study.

Acknowledgement

This study was supported, in part, by NIH/NIAMS Grant no. 1R03AR056265 and a 21st Century Development Grant from The Cervical Spine Research Society. The study sponsors had no influence on the study design, data collection or interpretation of this work.

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