Published in final edited form as:

J Biomech. 2013 May 31; 46(8): 1471–1475. doi:10.1016/j.jbiomech.2013.03.004.

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

William J. Anderst*, William F. Donaldson, Joon Y. Lee, and James D. Kang

University of Pittsburgh, Department of Orthopaedic Surgery, Orthopaedic Research Laboratories, 3820 South Water Street, Pittsburgh, PA 15203, USA

Abstract

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.

Keywords

In vivo; Dynamic kinematics; Disc degeneration; Movement direction

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

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.

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) ($0.29 \times 0.29 \times 1.25$ 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 (Biswas et al., 2009; Fazel et al., 2009). 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 collected for each participant. The effective radiation dose for each dynamic trial was estimated to be 0.16 mSv (determined using PCXMC simulation software, STUK, Helsinki, Finland).

A previously validated model-based volumetric tracking process determined 3D vertebral position with sub-millimeter accuracy (Anderst et al., 2011) for all static and dynamic trials. Details describing the model-based tracking process, including hardware and software specifications, calibration and distortion correction procedures, and computational algorithms have been described previously (Anderst et al., 2009, 2011; Bey et al., 2006; Martin et al., 2011). Tracked vertebral motion data was filtered at 1.0 Hz using a fourth-order, low-pass Butterworth filter, with the optimal cutoff frequency determined using residual analysis (Winter, 2009). Six degree-of-freedom kinematics between adjacent vertebrae were calculated for every frame in each trial in accordance with established standards for reporting spine kinematics (Kane et al., 1983; Wu et al., 2002).

Head motion was recorded at 60 Hz using reflective markers placed on the head (Vicon MX). Reflective marker data and biplane radiographic data were collected, synchronized, and placed in a common coordinate system with the origin located in the C7 vertebra of each subject. Co-registration of the two data collection systems was accomplished by using a calibration object that included radiopaque beads and reflective markers. It was previously demonstrated that this type of co-registration can be performed with high accuracy (bead-based RSA accuracy .032 mm and 0.12°; optical tracking accuracy .109 mm and 0.61°) (Kedgley et al., 2009).

Overall head range of motion in the sagittal plane (ROM) relative to C7 was determined for each trial. The head motion relative to C7 (head/C7) was interpolated to obtain head/C7 motion at 1% increments of the total head ROM. In this way, the total head ROM of each participant was standardized to 100%, allowing for comparisons among subjects. Angles between adjacent vertebrae in the sagittal plane were then interpolated similarly to obtain the relative angle at each intervertebral motion segment for every 1% increment of head motion.

The intervertebral angle at each 1% increment of head flexion was subtracted from the intervertebral angle at the corresponding increment of head extension (e.g. the intervertebral angle at 30% of the flexion motion was subtracted from the intervertebral angle at 70% of the extension motion). This subtraction was 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 plane. 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 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.

Acknowledgments

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.

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.

References

- Abebe ES, Utturkar GM, Taylor DC, Spritzer CE, et al. The effects of femoral graft placement on in vivo knee kinematics after anterior cruciate ligament reconstruction. *Journal of Biomechanics*. 2011; 44(5):924–929. [PubMed: 21227425]
- Anderst W, Donaldson W, Lee J, Kang J. Six degree of freedom cervical spine range of motion during dynamic flexion–extension in single level anterior arthrodesis patients and asymptomatic controls. *Journal of Bone and Joint Surgery American*. 2013; 95(6):497–506.
- Anderst W, Donaldson W, Lee J, Kang J. Subject-specific inverse dynamics of the head and cervical spine during in vivo dynamic flexion–extension. *Journal of Biomechanical Engineering*. <http://dx.doi.org/10.1115/1.4023524>, in press.
- Anderst W, Zauel R, Bishop J, Demps E, et al. Validation of three-dimensional model-based tibio-femoral tracking during running. *Medical Engineering & Physics*. 2009; 31(1):10–16. [PubMed: 18434230]
- Anderst WJ, Baillargeon E, Donaldson WF 3rd, Lee JY, et al. Validation of a noninvasive technique to precisely measure in vivo three-dimensional cervical spine movement. *Spine (Phila Pa 1976)*. 2011; 36(6):E393–E400. [PubMed: 21372650]
- Arana E, Marti-Bonmati L, Montijano R, Bautista D, et al. Relationship between Northwick Park neck pain questionnaire and cervical spine MR imaging findings. *European Spine Journal*. 2006; 15(8): 1183–1188. [PubMed: 16311755]
- Bey MJ, Zauel R, Brock SK, Tashman S. Validation of a new model-based tracking technique for measuring three-dimensional, in vivo glenohumeral joint kinematics. *Journal of Biomechanical Engineering*. 2006; 128(4):604–609. [PubMed: 16813452]
- Bible JE, Biswas D, Miller CP, Whang PG, et al. Normal functional range of motion of the cervical spine during 15 activities of daily living. *Journal of Spinal Disorders & Techniques*. 2010; 23(1): 15–21. [PubMed: 20051924]
- Biswas D, Bible JE, Bohan M, Simpson AK, et al. Radiation exposure from musculoskeletal computerized tomographic scans. *Journal of Bone and Joint Surgery American*. 2009; 91(8):1882–1889.
- Boden SD, McCowin PR, Davis DO, Dina TS, et al. Abnormal magnetic-resonance scans of the cervical spine in asymptomatic subjects. A prospective investigation. *Journal of Bone and Joint Surgery American*. 1990; 72(8):1178–1184.
- Cobian DG, Sterling AC, Anderson PA, Heiderscheit BC. Task-specific frequencies of neck motion measured in healthy young adults over a five-day period. *Spine (Phila Pa 1976)*. 2009; 34(6):E202–E207. [PubMed: 19282725]
- Dunsker SB, Colley DP, Mayfield FH. Kinematics of the cervical spine. *Clinical Neurosurgery*. 1978; 25:174–183. [PubMed: 709993]
- Dvorak J, Froehlich D, Penning L, Baumgartner H, et al. Functional radiographic diagnosis of the cervical spine: flexion/extension. *Spine*. 1988; 13(7):748–755. [PubMed: 3194782]
- Dyrby CO, Andriacchi TP. Secondary motions of the knee during weight bearing and non-weight bearing activities. *Journal of Orthopaedic Research*. 2004; 22(4):794–800. [PubMed: 15183436]
- Faizan A, Goel VK, Biyani A, Garfin SR, et al. Adjacent level effects of bi level disc replacement, bi level fusion and disc replacement plus fusion in cervical spine—a finite element based study. *Clinical Biomechanics (Bristol, Avon)*. 2012; 27(3):226–233.
- Fazel R, Krumholz HM, Wang Y, Ross JS, et al. Exposure to low-dose ionizing radiation from medical imaging procedures. *New England Journal of Medicine*. 2009; 361(9):849–857. [PubMed: 19710483]
- Foumani M, Strackee SD, van de Giessen M, Jonges R, et al. In-vivo dynamic and static three-dimensional joint space distance maps for assessment of cartilage thickness in the radiocarpal joint. *Clinical Biomechanics (Bristol, Avon)*. 2012

- Friedenberg ZB, Miller WT. Degenerative disc disease of the cervical spine. *Journal of Bone and Joint Surgery American*. 1963; 45:1171–1178.
- Frobin W, Leivseth G, Biggemann M, Brinckmann P. Sagittal plane segmental motion of the cervical spine. A new precision measurement protocol and normal motion data of healthy adults. *Clinical Biomechanics*. 2002; 17(1):21–31. [PubMed: 11779643]
- Hussain M, Natarajan RN, An HS, Andersson GB. Motion changes in adjacent segments due to moderate and severe degeneration in C5–C6 disc: a poroelastic C3–T1 finite element model study. *Spine (Phila Pa 1976)*. 2010; 35(9):939–947. [PubMed: 20375779]
- Kaiser JA, Holland BA. Imaging of the cervical spine. *Spine (Phila Pa 1976)*. 1998; 23(24):2701–2712. [PubMed: 9879096]
- Kallemeyn N, Gandhi A, Kode S, Shivanna K, et al. Validation of a C2–C7 cervical spine finite element model using specimen-specific flexibility data. *Medical Engineering & Physics*. 2010; 32(5):482–489. [PubMed: 20392660]
- Kane, T.; Likins, P.; Leivseth, G. *Spacecraft Dynamics*. New York: McGraw-Hill; 1983.
- Kedgley AE, Birmingham T, Jenkyn TR. Comparative accuracy of radio-stereometric and optical tracking systems. *Journal of Biomechanics*. 2009; 42(9):1350–1354. [PubMed: 19403137]
- Li G, DeFrate LE, Park SE, Gill TJ, et al. In vivo articular cartilage contact kinematics of the knee: an investigation using dual-orthogonal fluoroscopy and magnetic resonance image-based computer models. *American Journal of Sports Medicine*. 2005; 33(1):102–107. [PubMed: 15611005]
- Liu F, Cheng J, Komistek RD, Mahfouz MR, et al. In vivo evaluation of dynamic characteristics of the normal, fused, and disc replacement cervical spines. *Spine (Phila Pa 1976)*. 2007; 32(23):2578–2584. [PubMed: 17978657]
- Martin DE, Greco NJ, Klatt BA, Wright VJ, et al. Model-based tracking of the hip: implications for novel analyses of hip pathology. *Journal of Arthroplasty*. 2011; 26(1):88–97. [PubMed: 20347253]
- Mathys R, Ferguson SJ. Simulation of the effects of different pilot helmets on neck loading during air combat. *Journal of Biomechanics*. 2012; 45(14):2362–2367. [PubMed: 22840756]
- McDonald CP, Bachison CC, Chang V, Bartol SW, et al. Three-dimensional dynamic in vivo motion of the cervical spine: assessment of measurement accuracy and preliminary findings. *Spine Journal*. 2010; 10(6):497–504. [PubMed: 20359957]
- Moroney SP, Schultz AB, Miller JA. Analysis and measurement of neck loads. *Journal of Orthopaedic Research*. 1988; 6(5):713–720. [PubMed: 3404328]
- Nordin M, Carragee EJ, Hogg-Johnson S, Weiner SS, et al. Assessment of neck pain and its associated disorders: results of the bone and joint decade 2000–2010 task force on neck pain and its associated disorders. *Spine*. 2008; 33(4 Suppl):S101–S122. [PubMed: 18204385]
- Panzer MB, Cronin DS. C4–C5 segment finite element model development, validation, and load-sharing investigation. *Journal of Biomechanics*. 2009; 42(4):480–490. [PubMed: 19200548]
- Penning, L. *Functioneel röntgenonderzoek bij degeneratieve en traumatische afwijkingen der laag-cervicale bewegingssegmenten*. Groningen, The Netherlands: University of Groningen; 1960.
- Reitman CA, Mauro KM, Nguyen L, Ziegler JM, et al. Intervertebral motion between flexion and extension in asymptomatic individuals. *Spine*. 2004; 29(24):2832–2843. [PubMed: 15599287]
- Scarvell JM, Smith PN, Refshauge KM, Galloway H, et al. Comparison of kinematics in the healthy and ACL injured knee using MRI. *Journal of Biomechanics*. 2005; 38(2):255–262. [PubMed: 15598451]
- Sheehan FT. The finite helical axis of the knee joint (a non-invasive in vivo study using fast-PC MRI). *Journal of Biomechanics*. 2007; 40(5):1038–1047. [PubMed: 17141789]
- Siivola SM, Levoska S, Tervonen O, Ilkko E, et al. MRI changes of cervical spine in asymptomatic and symptomatic young adults. *European Spine Journal*. 2002; 11(4):358–363. [PubMed: 12193998]
- Tashman S, Kolowich P, Collon D, Anderson K, et al. Dynamic function of the ACL-reconstructed knee during running. *Clinical Orthopaedics and Related Research*. 2007; 454:66–73. [PubMed: 17091011]
- Thorhauer, E.; Miyawaki, M.; Illingworth, K.; Holmes, A., et al. *American Society of Biomechanics*. Providence, RI: 2010. Accuracy of bone and cartilage models obtained from ct and mri.

- van Mameren H, Sanches H, Beurgens J, Drukker J. Cervical spine motion in the sagittal plane. II. Position of segmental averaged instantaneous centers of rotation—a cineradiographic study. *Spine (Phila Pa 1976)*. 1992; 17(5):467–474. [PubMed: 1621143]
- White AA 3rd, Panjabi MM. The basic kinematics of the human spine. A review of past and current knowledge. *Spine*. 1978; 3(1):12–20. [PubMed: 347598]
- Winter, DA. *Biomechanics and Motor Control of Human Movements*. fourth ed. Hoboken, New Jersey: Wiley; 2009.
- Wu G, Siegler S, Allard P, Kirtley C, et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: Ankle, hip, and spine. International society of biomechanics. *Journal of Biomechanics*. 2002; 35(4):543–548. [PubMed: 11934426]
- Wu SK, Kuo LC, Lan HC, Tsai SW, et al. Segmental percentage contributions of cervical spine during different motion ranges of flexion and extension. *Journal of Spinal Disorders & Techniques*. 2010; 23(4):278–284. [PubMed: 20068468]

Fig. 1.

The average C4/C5 intervertebral angle in the sagittal plane during flexion (blue) and extension (green) for 19 asymptomatic subjects. Intervertebral angle is plotted on the vertical axis, while head orientation in the sagittal plane (as a percentage of total head ROM) is plotted on the horizontal axis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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.

Table 1

Differences between flexion and extension intervertebral orientation at identical angles of head flexion–extension. Significant differences between extension and flexion movement directions were present when the lower bound of the 95% CI of the difference was greater than zero. All values pertain to the group mean data.

	Maximum difference	Average difference in midrange of movement (20% to 80% of total head ROM)	Average difference over total head ROM	Head ROM where extension and flexion were significantly different (%)
C2/C3	0.8°	0.6°	0.4°	21–84
C3/C4	2.8°	2.3°	1.7°	4–96
C4/C5	4.1°	3.5°	2.7°	2–99
C5/C6	3.3°	3.0°	2.4°	2–99
C6/C7	2.0°	1.9°	1.6°	4–98