Intervertebral Cervical Spine Kinematics During In Vivo Dynamic Loading: Continuous Motion Paths Defined Using Bootstrap Prediction Bands

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Introduction: Cervical spine kinematics are commonly measured clinically using static full-flexion and full-extension radiographs[1-4]. The most critical limitation of this type of assessment is that neither the dynamic functioning of the neuromuscular system, nor the mid-range kinematics that comprise the majority of spine motion during activities of daily living[5, 6], can be assessed at static endpoint positions. These limitations may be addressed by collecting continuous, full range of motion (ROM) intervertebral kinematics during dynamic functional loading[7] and by calculating continuous intervertebral motion curves over the full ROM.

Unfortunately, statistical analysis of continuous motion curves can be problematic. The statistical methods appropriate for the analysis of single-point numerical data (e.g. angles at full-flexion or full-extension) are inadequate when applied to continuous curves of data[8]. Continuous kinematics data is commonly assessed by calculating point-by-point prediction intervals for the data available at each percent of the movement cycle. The major drawbacks to generating prediction bands using the point-by-point method are that it pre-supposes a Gaussian model for the distribution of data, it does not take into account the correlation between the measurements, and it ignores the fact that many points are being considered simultaneously when an entire curve is considered[8,9]. Thus, prediction bands generated point-by-point may result in a large distortion between the pre-specified probability and the true coverage probability[9].

The bootstrap method is a non-parametric technique for constructing prediction bands that provide the desired coverage based on continuous curves. The bootstrap technique involves generating “pseudo-samples” from the original data curves by sampling the original data curves with replacement. The variability and mean of these pseudo-samples bears the same relationship to the population of the original curves as do the original curves to the underlying population[8]. The true coverage probability when using the bootstrap method has been demonstrated to be far superior to Gaussian methods. Using cross-validation analysis, the estimated true coverage of bootstrap prediction bands (86%, 93%, and 85%) was similar to the target prediction bands (90%, 95%, and 90%, respectively). In contrast, the estimated true coverage using Gaussian point-by-point intervals was only 54%, 73%, and 67%, respectively[8-10].

The objective of this study was to use the bootstrap method to calculate 90% prediction bands for the continuous intervertebral flexion/extension curves of the cervical spine (C1-C7) in young, healthy individuals during dynamic functional loading. These bands may be used to classify new subjects (e.g. fusion or whiplash patients) as belonging to the same population (or not) as the healthy individuals.

Methods: Twenty-eight healthy young adults (27.3±4.6 yrs.; 14 M, 14 F) provided informed consent to participate in this IRB-approved study. Participants performed full ROM flexion\extension (F/E) of their head and neck while seated within a biplane X-Ray system. Three-dimensional vertebral motion was
tracked using a volumetric model-based tracking technique that matched subject-specific bone models (obtained from CT) to the biplane radiographs that were collected at 30 frames/second. This model-based tracking technique has been validated in vivo to have an accuracy of 0.2 mm or better[11]. Reflective markers were placed on the head and torso to determine global head motion relative to the torso. Continuous curves of the intervertebral F/E angle versus head F/E angle were calculated for each motion segment of the cervical spine using ordered rotations (flexion/extension, then rotation, then bending). These intervertebral F/E curves were then normalized to the percent of the head flexion and the percent of head extension range of motion.

The group mean and standard deviation at each percent of the movement cycle were used to generate 90th percent point-by-point Gaussian prediction bands. Bootstrap prediction bands for each intervertebral motion segment were determined as described by Lenhoff [8]. Specific to the current study, the bootstrap technique was performed by generating a finite Fourier sum consisting of 17 Fourier coefficients to characterize the normalized intervertebral F/E curve at each motion segment. Also, 1000 pseudo-sample mean curves were generated for each motion segment in order to perform the bootstrap technique.

**Results:** The Fourier series fit the original curve data well (mean $R^2$: 0.998; mean RMS error = 0.15°). Point-by-point 90% prediction bands were narrower than bootstrap 90% prediction bands. This resulted in several original data curves falling outside of the 90% Gaussian bands at various time points of the movement cycle for each motion segment (Figures 1, 2 and 3). Variability in the kinematic curves was smallest near full flexion ($15.6°±3.6°$), and largest near full extension ($19.9°±5.0°$) (Figures 1, 2 and 3). The mean curves progressively became less symmetric about the middle of the movement cycle from C1-C2 to C6-C7 (Figures 1, 2 and 3), indicating that intervertebral rotation patterns were not the same in flexion and extension, especially for the middle and lower cervical spine.

![Figure 1: C1-C2 full range of motion flexion/extension curves for 28 young healthy subjects (thin blue lines), the group mean curve (thick blue line), 90% point-by-point prediction intervals (thick grey lines), and 90% bootstrap prediction bands (thick black lines).](image)
Discussion: This study calculated mean curves and 90% bootstrap prediction bands for continuous in vivo cervical kinematics in young, healthy individuals performing dynamic, full range of motion F/E. As has been shown previously for gait and shoulder kinematic data [8-10], the 90% prediction bands generated using the bootstrap technique encompass a greater range of variability than the 90% Gaussian prediction bands. The mean curves and prediction bands calculated in this study can be used as a standard for comparison when evaluating clinical patient kinematics. Assessing continuous motion curves in this way can identify the specific points in the motion cycle where differences exist. This information can then be used to focus treatment strategies on the portion of the movement that is abnormal.
The asymmetry evident in the intervertebral kinematic curves suggests that spinal loading at any given head orientation is related to the direction of head movement. This is in agreement with a previous analysis of older asymptomatic participants (19 subjects, average age of 45.6 years)[12]. Thus, in order to fully characterize intervertebral kinematics, continuous kinematic data should be collected during flexion and during extension movements. Furthermore, this direction-dependency in kinematics should be accounted for in computational models of the cervical spine. Finally, the data presented here can be used to assess the biofidelity of in vitro test protocols that mechanically load spine specimens and computational models that use in vitro kinematics for validation purposes. In vitro test protocols that result in symmetric motion curves in flexion and in extension for all motion segments are not accurate representations of in vivo kinematics.

**Significance:** These mean curves, and associated prediction bands, can be used to assess the effects of age, surgical and therapeutic procedures, and degeneration on dynamic functional kinematics of the cervical spine through the entire range of F/E motion, not simply at the end ranges of motion.

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