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Annual Frequency and Magnitude of Neck Motion in Healthy Individuals

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Study Design. Descriptive, cross-sectional design of healthy young adults. Continuous motion monitoring of the cervical spine performed outside of a laboratory setting.

Objective. The objective of this study was to quantify the daily frequency and magnitude of neck motion in healthy human subjects using continuous motion monitoring.

Summary and Background Data. Daily frequency and magnitudes of neck motion in healthy young adults may be useful for clinicians in appropriate treatment programs for individuals with cervical injury and pathology. In addition, the design of cervical disc prostheses requires such information to estimate annual wear. These data are not currently available and as a result current American Society for Testing and Materials (ASTM) testing standard F2423-05 may not be accurate.

Methods. Ten healthy young adults were fitted with a portable device that measured neck kinematics about all 3 primary axes. Participants wore the unit continuously over a 5-day period. Data from each axis were processed to identify motion magnitude and the frequency of motion within 5 degrees increments. Results were extrapolated to yield daily and yearly values of total neck motion, and that attributed to the C5–C6 level for comparison to ASTM standard F2423–05.

Results. Flexion-extension movements were twice as frequent as movements along the other 2 axes. The median motion magnitude was 13° for both flexion-extension and axial rotation and 10 degrees for lateral bending. Estimates of yearly excursion indicate that the average healthy young adult will undergo 335.6 million degrees of flexion-extension, 109.3 million degrees of lateral bending, and 166.9 million degrees of axial rotation. Our findings indicate that while ASTM testing standard F2423–05 appears appropriate for lateral bending and axial rotation, it underestimates the motion experienced in flexion-extension.

Conclusion. Flexion-extension was the primary neck motion during normal daily living, with the majority of motions about all axes being less than 15°. ASTM standard F2423-05 may need to be reviewed regarding flexion-extension.

Key words: cervical spine, kinematics, mechanics, artificial disc, continuous motion monitoring. **Spine 2008; 33:1882–1888**

The daily frequency and magnitude of neck motion in healthy young adults is currently unknown. This information would functionally quantify normal movement behavior and serve as a comparison for those with cervical injury and pathology. This in turn could be used by clinicians to quantitatively asses the severity of a patient's movement disability, develop appropriate treatment plans, and provide a benchmark for those patients rehabilitating from a surgical procedure.

Additionally, quantifying the frequency and magnitude of neck motion could be beneficial to the design of cervical disc prostheses. Cervical disc arthroplasty is a recently evaluated treatment being used as an alternative to fusion after decompression. As with other prosthetic devices, analysis of the wear on the bearing surface is of critical importance. American Society for Testing and Materials (ASTM) Standard F2423–05, outlines the durability test protocol for cervical disc prostheses.[1] It requires that a cervical intervertebral disc prosthetic undergo 30 million degrees of flexion-extension at amplitudes of ± 7.5 degrees (30 degrees excursions, Figure 1) and 24 million degrees of both lateral bending and axial rotation each at amplitudes of 6 degrees (24 degrees excursions). The standards were constructed from estimates based on the observed wear in hip and knee prostheses as data on annual cervical motion are not currently available.

Motions of the head relative to the thorax and intersegmental motions of the cervical spine have been characterized using goniometers,[2] magnetic resonance imaging,[3] roentgenograms,[4] and fluoroscopy.[5,6] Likewise, the maximum degree of motion required to perform routine activities of daily living have been measured and documented.[7] These studies are limited in that they have been performed in a laboratory environment and may not reflect the true living situation. Further, the typical frequency of motion that occurs during normal daily activity has not been determined. Newer sensors using accelerometers and gyroscopes combined with a microcomputer allow measurements of joint motions over long time periods and during normal living conditions.[8–10]

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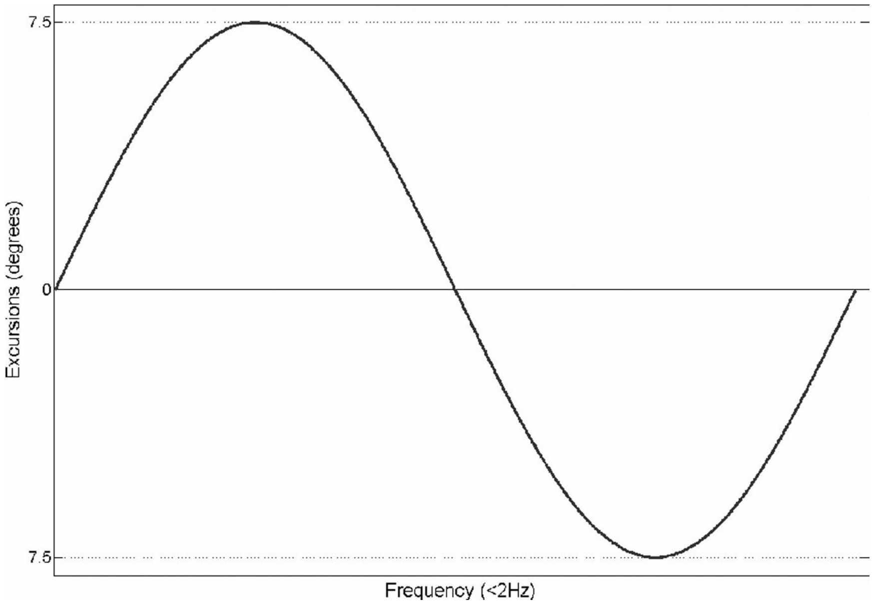

Figure 1. One cycle as defined by ASTM Standard F2423-05 for wear testing in flexion-extension. Amplitude ± 7.5°, frequency <2 Hz.

We recently validated a portable motion monitoring system which allows continuous measurement of cervical motion under routine living environments.[11] The ability to record data outside of the laboratory setting should provide realistic estimates of neck motion magnitude performed during daily living. Further, the daily frequency of neck motion can be defined due to the continuous recording.

The purpose of this study was to quantify the daily frequency and magnitudes of neck motion in healthy human subjects through continuous motion monitoring in normal living environments. Neck motion about 3 axes of motion (flexion-extension, lateral bending, and axial rotation) were characterized during a 5-day period of continuous monitoring. In addition to quantifying the daily frequency and magnitudes of the cervical spine we assessed the accuracy of the wear protocol used by ASTM standard F2423–05 by approximating the excursions experienced at the C5–C6 level of the spine. Current literature indicates that this level of the spine undergoes the most displacement during neck motion.[5,12,13]

Materials and Methods

Subjects

Ten healthy young adults (6 males; 4 females) participated in this study; none of which had any prior cardiovascular, pulmonary, neurologic or musculoskeletal impairment. The average age of the participants was 22.1 ± 1.1 year and the average height and mass were 177.7 ± 10.2 cm and 73.4 ± 13.9 kg, respectively. The study was approved by the University of Wisconsin-Madison Health Sciences Institutional Review Board. Subjects gave their voluntary informed consent and received a monetary payment on completion of their testing.

Procedures

Cervical motion was measured during a 5-day period using the Wisconsin Analysis of Spine motion Performance (WASP) system.[11] This system consists of a data logger and 2 inclinometer arrays that measure angular displacements during flexion-extension and lateral bending, and a gyroscope to measure angular velocities during axial rotation. Data were recorded at 8 Hz and stored to the data logger for subsequent download to a microcomputer. The accuracy of the WASP system was previously validated using a material testing machine and was found to be capable of detecting angular displacements that exceed 3 degrees for both flexion-extension and lateral bending (Figure 2). Although the initial estimate for the unit's accuracy during axial rotation was reported at 10 degrees we have since modified our interpolation algorithms such that axial rotation accuracy is consistent with the other axes of motion (*e.g.*, ±3 degrees).[11]

Using a medical adhesive (Medical Spirit Gum 2100, Kryolan, Berlin, Germany), the WASP sensors were fixed to the lateral aspect of the subject's head (mastoid process) and upper trunk (seventh rib), whereas the data logger was attached to the subject's belt or pocket (Figure 3). Each subject was told to wear the unit continuously over a 5-day period (including one weekend day), removing it only during activities that could have damaged the unit (*e.g.*, showering and contact sports). Subjects were instructed on how to properly orient and place the sensors should the sensors need to be removed and reapplied. A researcher met with the subjects daily to download the previous day's data collection and exchange batteries. This daily meeting allowed researchers to observe whether subjects were orienting the inclinometer arrays correctly on their own and provide additional instruction as necessary.

Before the 5-day measurement period, the WASP system was calibrated against an optical motion capture system (Motion Analysis Corp., Santa Rosa, CA), as previously described.[11] Briefly subjects were fitted with the WASP unit, and 16 reflective markers placed on anatomic landmarks. Subjects were asked to flex-extend, laterally bend, and axially rotate their neck at a comfortable speed through full ranges of motion while the optical motion capture and the WASP system simultaneously recorded the movements. This calibration test allowed us to confirm the functionality and accuracy of the unit before each subject's collection period.

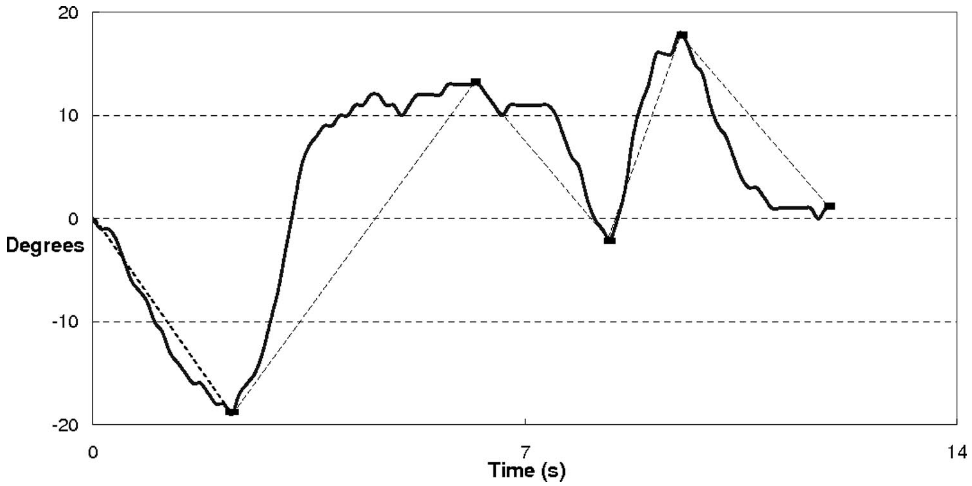

Figure 2. Flexion-extension motion over 14 seconds. The solid line represents the WASP output, the dashed line represents the approximation by the peak detection algorithm, and the square points are the detected peaks.

Data Processing

Data obtained from the WASP unit were processed using custom algorithms (Matlab v.7.2, Mathworks, Natick, MA) to identify motion peaks, defined as the point when the signal slope changes sign and the magnitude of the motion exceeds 3 degrees (Figure 2). Motion magnitude between 2 consecutive peaks was calculated, with the frequency of motions within 5 degrees increments determined.

Optical motion data were processed using a software suite (Visual three-dimensional v.3, C-Motion Inc., Rockville, MD) in which a 2 segment, rigid body model was created and scaled using subject anthropometric data obtained in the motion capture. Motion peaks could then be identified and compared to those detected by the WASP unit. Mean regression slopes and correlation coefficients between the WASP and optical motion results were determined across all subjects.

Data Analysis

The average distribution of motion frequency about each axis that occurred during the 5-day period was calculated with the corresponding motion excursion determined by multiplying the motion frequency by the median value of the motion interval. Results were extrapolated to yield daily and yearly values of total neck motion. The portion of the neck motion that

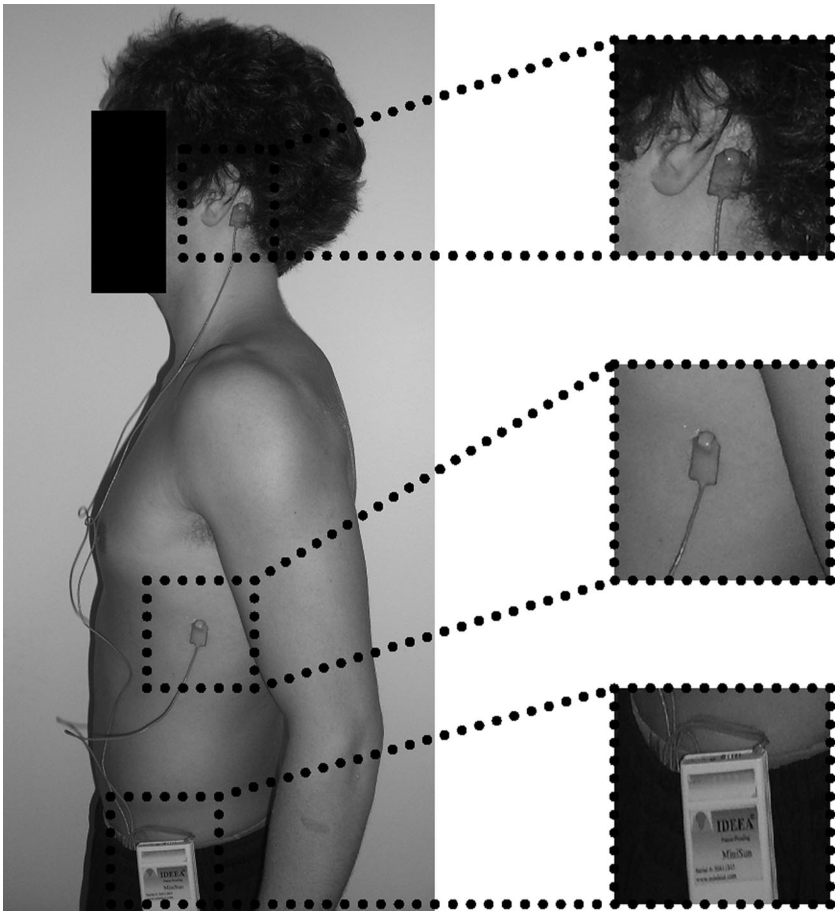
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Figure 3. A subject wearing the portable motion monitoring unit. The sensors are positioned over the mastoid process and the 7th rib while the data logger is clipped to the subject's waist band.

Table 1. Number of Motion Peaks ($\times 10^3$) for Each Subject and Day

Subject	H Collected		Day1	Day 2	Day 3	Day 4	Day 5	Average	SD	Median Range
1	118.1	FE	51.0	71.4	51.5	52.5	56.6	57.0	8.6	13–14
		LB	21.8	30.5	23.1	22.4	26.5	25.1	3.6	10–11
		AR	24.0	32.7	26.5	24.9	29.9	27.8	3.6	13–16
2	95.3	FE	47.8	63.5	98.0	31.0	48.4	53.0	25.3	13–15
		LB	25.2	33.6	54.9	16.3	22.4	27.7	15.0	10–12
		AR	29.0	39.3	52.4	18.1	25.2	30.1	13.4	13–17
3	80.5	FE	49.0	82.2	56.6	58.4	81.8	62.6	15.4	10–13
		LB	17.3	28.4	22.2	25.1	35.1	23.5	6.7	8–12
		AR	18.7	29.4	22.7	26.8	39.9	24.7	8.0	11–17
4	89.8	FE	70.9	27.6	42.1	27.2	61.2	44.4	19.7	13–19
		LB	33.7	11.9	18.8	14.0	24.0	19.6	8.7	9–11
		AR	37.7	13.6	18.7	17.5	28.6	22.1	9.8	10–15
5	58.7	FE	16.4	13.7	78.7	40.8	*	45.5	30.1	8–20
		LB	5.1	7.2	33.0	21.0	*	20.4	13.0	10–11
		AR	5.8	6.6	27.1	18.2	*	17.5	10.2	11–13
6†	58.3	FE	89.8	111.8	80.9	70.6	174.7	92.4	41.5	9–16
		LB	38.2	45.8	39.1	28.6	63.4	39.1	12.9	9–10
		AR	35.6	47.9	30.2	34.7	65.2	38.1	14.2	9–16
7	109.2	FE	44.6	40.3	46.1	41.9	25.6	40.4	8.2	12–16
		LB	18.5	20.0	23.2	17.3	12.8	18.6	3.8	9–12
		AR	18.3	23.5	22.0	17.7	15.0	19.4	3.4	12–14
8	104.4	FE	52.9	60.2	63.0	61.5	52.9	57.9	4.8	11–14
		LB	17.8	23.9	27.5	24.8	22.9	23.2	3.6	9–10
		AR	21.6	27.1	30.6	28.6	28.4	27.0	3.4	10–13
9	84.3	FE	59.7	36.8	35.0	11.6	58.3	42.3	19.8	10–14
		LB	25.7	15.8	16.8	4.8	26.0	18.7	8.7	9–11
		AR	22.9	15.1	19.3	6.5	22.7	18.1	6.8	9–15
10‡	110.5	FE	21.7	28.8	26.0	32.7	32.7	27.8	4.7	10–13
		LB	11.0	13.7	13.2	14.4	16.3	13.6	1.9	9–10
		AR	12.4	14.7	14.3	16.0	17.5	14.8	1.9	11–14

*Data lost in instrumentation error.

†Subject 6 removed the WASP unit while sleeping resulting in greater estimates of daily motion due to the absence of sedentary activity.

‡Subject 10 was recovering from an unrelated surgical procedure resulting in reduced estimates of daily motion due to an increase in sedentary activity.

FE indicates flexion-extension; LB, lateral bending; AR, axial rotation; Median Range, range of daily median motion peak values.

occurred at C5–C6 was estimated based on *in vivo* measurements (18%, flexion-extension; 17%, lateral bending, 10% axial rotation).[4,14]

Results

Motion Frequency

On average flexion-extension movements occurred 2.3 times more often than lateral bending and 2.2 more often than axial rotation. The subjects averaged 52,320 ± 17,370 motion peaks in flexion-extension, 22,952 ± 6910 peaks in lateral bending, and 23,957 ± 7042 peaks in axial rotation per day (Table 1). Extrapolating these numbers to obtain an estimate of annual motion peaks, our subjects averaged 19.1 ± 6.3 million peaks in flexion-extension, 8.3 ± 2.5 million peaks in lateral bending, and 8.7 ± 2.5 million peaks in axial rotation (Table 2).

Motion Magnitude

The median movement across all subjects was 13 degrees in flexion-extension, 10 degrees in lateral bending, and 13 degrees in axial rotation. The majority of peaks during flexion-extension (54.5%), lateral bending (68.9%), and axial rotation (54.9%) occurred through a small range of motion (<15 degrees), whereas only 4.3% of the flexion-extension movements, 1.1% of the lateral bending movements, and 5.5% of axial rotation movements exceeded 50 degrees (Figure 4). Based on this motion distribution, estimates of yearly excursion indicate that the average healthy young adult will undergo 335.6 million degrees of flexion-extension, 109.3 million degrees of lateral bending, and 166.9 million degrees of axial rotation (Table 2). At the C5–C6 spinal level, 60.4 million degrees of flexion-extension, 18.6 million degrees of lateral bending, and 16.6 million degrees of axial rotation occur annually (Table 2).

WASP and Optical Motion Comparison

The average correlation coefficients for flexion-extension (0.93) and lateral bending (0.81) indicate a strong rela-

Table 2. Mean (SD) Daily and Yearly Estimates of Total Neck Excursions (°), and Those Attributed to C5–C6 Spinal Level ($\times 10^6$)

	Daily Excursion	Yearly Excursion	ASTM Standard F2423–05
Flexion-extension			
Total neck	0.919 (0.294)	335.6 (107.4)	—
C5–C6 (18%)	0.165 (0.053)	60.4 (19.3)	30
Lateral bending			
Total neck	0.298 (0.096)	108.8 (35.1)	—
C5–C6 (17%)	0.051 (0.016)	18.5 (5.9)	24
Axial rotation			
Total neck	0.457 (0.151)	167.0 (55.4)	—
C5–C6 (10%)	0.046 (0.015)	17.0 (5.5)	24

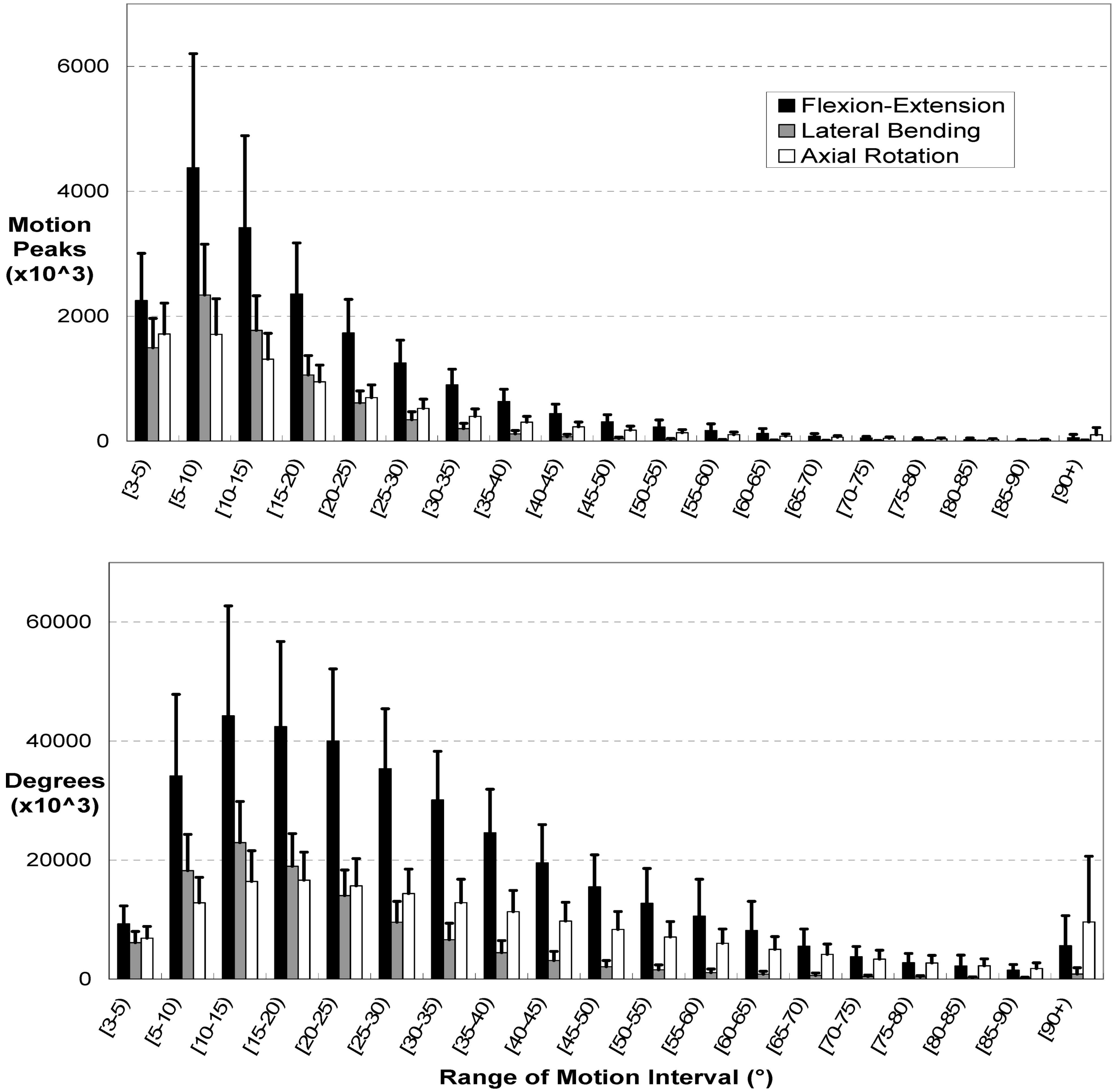

Figure 4. Annual estimates of frequency (top) and excursion of neck motion (bottom) during flexion-extension, lateral bending, and axial rotation averaged across all subjects. Values are distributed within the range of motion interval reflective of the corresponding motion magnitude. Excursions were calculated by multiplying the frequency per bin by the median bin value.

tionship between the WASP unit and the motion capture system. The average linear regression slopes (flexion-extension, 0.78; lateral bending, 0.67) indicate that the motion magnitudes obtained using the WASP unit were consistently less than those measured using the optical motion system.

■ Discussion

Quantifying the annual cumulative movements of the neck is an important step in refining our treatment methods for cervical pathologies. This study is unique because it is the first study that employs the use of a continuous motion monitoring instrument in attempting to quantify cervical motion during normal activities of daily living. Through this study, we found that the greatest excursions occurred in flexion-extension and that the median magnitude of neck flexion-extension was 13 degrees. On average movements in flexion-extension occurred over twice as frequently when compared to movements of lateral bending and axial rotation and the majority of movements along all 3 axes had magnitudes of less than 15 degrees.

Bennett *et al* incorporated the use of a cranial inclinometer instrument to asses the range of motion of the neck during 13 simulated, routine activities of daily living.[7] Although the results provided task-specific measurements of the neck's range of motion, the values may not accurately reflect those experienced in actual living situations and do not indicate the frequency of neck motion during daily life. Our data allows for both, as neck motion was monitored while subjects performed their normal daily activities in a natural environment. Use of a portable motion monitoring device (*e.g.*, WASP) in combination with activity logs could yield range of motion data during specific activities. (*e.g.*, athletics, work, transit, *etc.*)

To determine the appropriateness of ASTM standard F2423–05, the total excursion about each axis incurred during wear testing can be compared to the annual excursion we estimated. The current ASTM standards of 10 million cycles at 24 degrees excursions for both lateral bending and axial rotation seem justified based on our data. However, these data also suggest that the current testing standard of 10 million cycles at 30 degrees excursions for flexion-extension may not accurately replicate the annual motion experienced along that axis. Our data indicate that on average, healthy young adults perform significantly more motion in flexion-extension through the course of a year than those anticipated by the ASTM wear analysis protocol. Further, the distribution of motion magnitudes observed during daily activity suggests that a fixed excursion for wear testing of cervical disc prostheses may not accurately represent neck motion during activity. That is, less than 60% of all motions were equal to or less than the peak-to-peak excursions applied during wear testing (*e.g.*, 15 degrees for flexion-extension; 12 degrees for lateral bending and axial rotation).

Although composite neck motion was quantified using the WASP unit, we were unable to quantify the contributions of the upper thoracic spine to the overall movement. Additionally, while the WASP unit is capable of detecting motion peaks, we were unable to determine where in the anatomic range of motion the peak is occurring. Although subject compliance to testing protocol was generally good, some (*e.g.*, S6) found the device uncomfortable while sleeping and removed it, whereas others simply were not diligent in reapplying the device after its removal. Finally, periods of inactivity when the device was not being worn were removed from the data collection before processing. As a result estimations of daily motion frequency and magnitude may have been different from what was actually experienced as these values were calculated based on the time the subject was wearing the WASP unit.

The linear regression slopes calculated indicate that the peak magnitudes measured by the WASP unit were approximately 20% to 30% less than those recorded by the optical motion system. As the majority of the motion peaks occurred at magnitudes less than 15 degrees, it is reasonable to assume that the inaccuracies of the WASP unit did not have a substantial impact on our results (3–4.5 degrees). Had the WASP unit been more accurate in detecting motion magnitude, we would expect to see slightly larger median motion values and a slight shift to the right in the movement distribution (Figure 4).

Inter- and intrasubject day to day peak variations along all 3 axes (Table 1) were largely due to the fact that our subjects were outside of a laboratory environment performing unprescribed activities of daily living. Our data collection protocol ensured that we captured both weekdays and at least one weekend day in an attempt to account for the variation in physical activity that likely occurs between the two.[14] While natural between day variability was anticipated, inconsistent wearing of the WASP unit by the subjects may have also been a contributing factor. Nonetheless, motion monitoring over multiple days appears to be necessary to capture the inherent variability in activity.

The continuous motion monitoring in this investigation provides initial estimates of normal motion frequency and magnitude distribution. These values and the corresponding measurement techniques could be used to quantify normal movement behavior and the corresponding effects of disease progression. For example, current definitions of disability are largely based on maximum range of motion with reduced consideration of movement frequency. The implementation of a continuous motion monitoring device such as the WASP would allow clinicians to address factors such as movement avoidance in their assessment of patient disability. Likewise, the continuous motion monitoring of patients after a surgical procedure would allow clinicians to assess a patients' recovery and assist in the development of appropriate rehabilitation programs.

In summary, flexion-extension was the primary neck motion during normal daily living, with the majority of motions about all axes being less than 15 degrees. In addition, our results indicate that the ASTM standard F2423–05 protocol is sufficient to reflect annual motion for lateral bending and axial rotation, but less than annual estimates of flexion-extension.

■ Key Points

- The objective of this study was to quantify the daily frequency and magnitude of neck motion in healthy human subjects using continuous motion monitoring.
- Estimates of annual neck excursion indicate that the average healthy young adult will undergo 335.6 million degrees of flexion-extension, 109.3 million degrees of lateral bending, and 166.9 million degrees of axial rotation.
- The majority of peaks during flexion-extension (54.5%), lateral bending (68.9%), and axial rotation (54.9%) occurred through a range of motion less than 15 degrees.
- Our findings indicate that although ASTM testing standard F2423–05 appears appropriate for lateral bending and axial rotation, it underestimates the motion experienced in flexion-extension.

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