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A Method to Measure Cervical Spine Motion Over Extended Periods of Time

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Study Design. System validation study.

Objective. To develop and validate a motion sensor system for measuring cervical spine motion over extended time periods.

Summary of Background Data. Many studies using different methodologies have tried to estimate cervical spine motion. These have mostly been carried out in a laboratory setting performing active/passive range of motion or activities of daily living. However, cervical spine performance over extended periods of time in natural environments remains unknown.

Methods. A novel motion sensor system, Wisconsin Analysis of Spine Motion Performance (WASP), was validated using 2 benchmarks: a materials testing machine (MTS) and optical motion tracking laboratory. Parameters tested included drift, frequency response, accuracy, effect of sensor orientation, and coupled motions. Applied motions from the MTS and measured motions in subject volunteers under various conditions were compared with WASP using correlation coefficients. Intersubject and intrasubject variability analyses for WASP were also performed.

Results. The average WASP slopes for accuracy (compared with MTS) in flexion-extension, lateral bending, and axial rotation were 0.89, 0.93, and 0.38, respectively. The correlation coefficient was 0.99 in all cases. Compared with optical motion tracking, the WASP regression slopes were 1.1, 1.02, and 0.4 and the correlation coefficients were 0.98, 0.92, and 0.93 in the 3 axes of motion. Coupled motion was noted during all subject motions. WASP peak detection algorithm had a 0% error discounting boundary conditions.

Conclusion. WASP was accurate in flexion-extension and lateral bending. In axial rotation, WASP was less accurate. However, the system was highly reliable with low intersubject and intrasubject variability. WASP can be used in estimating cervical spine motion with high reliability while keeping in mind the decreased accuracy in measuring axial rotation.

Key words: cervical spine range of motion, motion analysis, validation, peak detection, prosthetic wear. **Spine 2007;32:2092–2098**

The cervical spine is highly mobile, creating a wide visual field while, at the same time, functioning to protect the spinal cord, maintain head alignment, and form a strut that facilitates visceral functions such as glutination and ventilation. Several investigators have characterized ranges of normal cervical spine motion for adults, women, children, and dogs.[1–7] Increasing age results in a 30% to 40% decrease in overall range of cervical motion along all 3 axes.[2] Also, the range of motion required to perform activities of daily living has been investigated. Bennet *et al* measured cervical range of motion in 28 college students while performing 13 activities of daily living.[8] They found that 4 of the 13 tasks required between 30% and 50% of total motion. However, the frequency and magnitudes of motion of the head and neck over long periods of time are unknown.

Characterizing the frequency and magnitude of cervical motion during routine daily activities in the community will functionally quantify normal behavior and disease progression, better define treatment goals, and influence the design of treatment methods. Such information is essential to physicians, surgeons, and therapists who treat patients with cervical spine disorders. Understanding the frequency and range of motion occurring during day-to-day activities would also be helpful to address ergonomic issues in occupational settings and set a benchmark for disability determination with regard to cervical spine motion.

The development of disc arthroplasty has led to a need to assess the effect of motion on the bearing surfaces in order to design for appropriate durability and to aid development of testing protocols. Preclinical studies have used design parameters from total hip arthroplasty/total knee arthroplasty for use in simulators that test cervical disc prostheses. The wear of bearing surfaces is related to many factors, including materials, surface geometry, loads, frequency, lubrication, and magnitudes of motion. Archard analytically related wear rates to be directly proportional to the load and the total overall excursion.[9] However, in order to accurately predict wear, accurate simulation of motion, loads, and operating conditions is essential *in vitro* testing.[10] Thus, to accurately predict *in vivo* prosthetic wear, the total amount of motion must be known.

We developed a method to measure the frequency and magnitude of neck motions over extended periods of time. We adapted a commercially available system that has been validated to measure changes in energy expenditure and daily human activity and modified it for use in the cervical spine.[11–13] Additionally, custom signal processing software

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was developed to reduce data to primary outcome variables. The purpose of this study was to validate the device and the data analysis methods for cervical spine applications.

■ Materials and Methods

Wisconsin Analysis of Spine Motion Performance (WASP) System. The WASP system was designed to measure the frequency and magnitude of neck motion over extended periods of time. WASP consists of 2 sensors, a portable data logger, and custom software suite. Each sensor has 3 different channels representing the 3 axes of motion. The x and y axes channels measure angular displacement (°) corresponding to flexion-extension and lateral bending motions, respectively. The z axis channel measures angular velocity (°/sec) corresponding to axial rotation. Angular displacements are measured *via* inclinometers, while angular velocity is measured using Coriolis principle.[14] For this application, 1 sensor is taped to the mastoid process and 1 to the thorax so that relative neck motion can be determined. After calibration, the WASP system records rotational data from all 3 axes. Output differences between the 2 sensors were stored and processed later.

The data logger consists of a high-speed microprocessor and on board flash memory used to record at 8 Hz and store the data to be downloaded later to a computer for analysis (Figure 1). The data logger has several features to minimize size and power consumption. A nondistortion data compression algorithm significantly reduces the storage size; thus, the space and power consumption are minimized. An interrupt-driven, power-optimized software package minimizes the battery use. As a result, multichannel data can be collected and stored continuously for up to 48 hours. Extremely low power and cross-talk introduce error requiring digital filtering before analysis. Temperature compensation and power-source monitoring further reduce baseline drifting and sensor aging. Once the sensors are attached to the subject or test equipment, the data logger is calibrated to determine the 3 axes of motion with respect to current sensor position.

Custom software was written in C++ for analyzing sensor data stored on the data logger. Before calculating motion frequency and magnitude, the angular velocity data about the z-axis are integrated using trapezoidal numerical integration to determine the angular displacement corresponding to axial rotation.[15] A variant of the split-and-merge algorithm was used for smoothing the angular displacement data from the 3 axes and a slope-based method was used for peak detection.[16] A peak was defined as the point when the signal slope changes sign and the magnitude of the motion is above a threshold of 3°. Thus, changes in slope direction below the threshold of 3° are ignored. Two consecutive peaks defined a motion cycle.

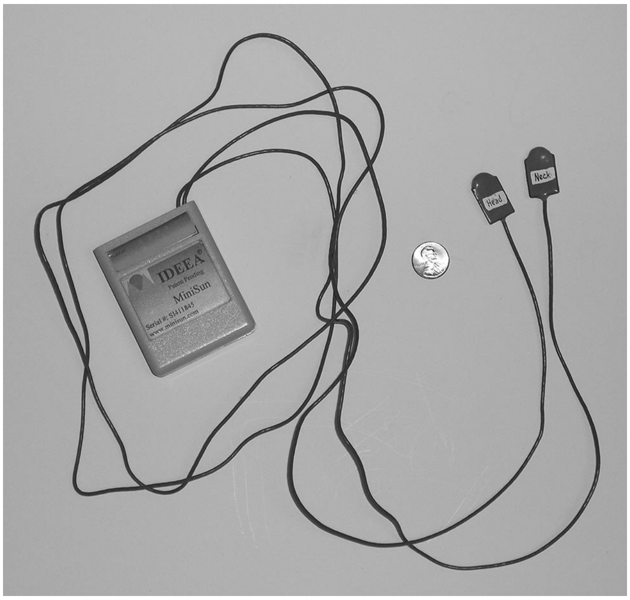

Figure 1. Data logger and 2 sensors for head and trunk. Penny shown for scale.

Most human cervical spine motion is coupled in multiple planes. Even when one is trying to purely flex-extend, nonzero motion in lateral bending and axial rotation axes usually occurs. For this study, motions were defined as primary and secondary. Primary motions are the dominant motion around an axis and a peak in these data are the dominant peak. More rigorously, if amplitude of a peak about an axis is greater than peaks about the other 2 axes within a time window (±1 s), then the peak is a dominant peak. Secondary motions are the peaks in the other 2 axes with lower amplitudes.

Validation Sequence. Validation was performed in a comprehensive manner to determine sensor and software accuracy, instrument drift, the effects of sensor orientation and placement, sensor accuracy, the effect of head velocity and displacement on accuracy, and accuracy during primary and secondary motions. Several approaches were used to compare WASP to output from 2 known calibrated instruments: a materials testing machine (MTS) and *in vivo* using an optical motion capture system (OMC). Output from WASP and the standard (MTS or OMC) was processed to determine peak frequencies and magnitude of motion about all 3 axes.

WASP Software Validation. Peak detection algorithm accuracy was measured by comparing the number of peaks detected by the peak detection algorithm to those detected visually on random cervical spine motion signals. These were obtained from a subject who wore the sensors for 4 hours. Randomly, 25 seconds of the subject's motion at 5 different intervals were visually inspected and the peaks detected. These were compared with results from the peak detection algorithm at a threshold of 3°. The metric used for comparison is average relative error between the software and visually detected peaks.

MTS. An MTS 858 servo hydraulic testing machine (MTS Systems Corp., Eden Prairie, MN) was fitted with a custom fixture that has multiple degrees of freedom. This system allows axial, torsional, and bending testing and has been described elsewhere.[17] The custom fixture has plates that are suspended in bearings and these plates are connected through torque cells to motors so that they can be driven in rotation about the mounting axis. The angular displacement is measured by a rotational potentiometer (accurate to 0.1°) and the bending moment by load cells in the modified MTS system. Motion was applied under displacement control using a sine wave function with variable frequencies. This system allows axial, torsional, and bending testing.

One end of a plastic cervical spine model was potted using epoxy resin and a wooden block was screwed on to the occipital end. One sensor of WASP was attached to the wooden block and the other sensor was attached to the lower grip of the custom fixture of the MTS (Figure 2). For validation purposes, the WASP output was compared with angular displacements from the MTS potentiometers.

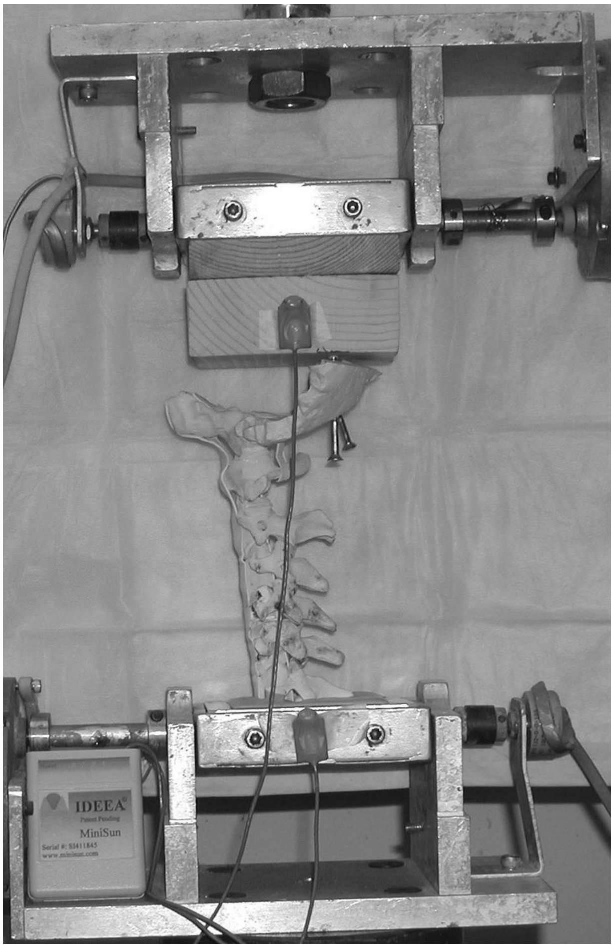

Figure 2. MTS experimental setup.

Table 2. OMC Validation Tests

Test	Parameters	Axes	Metric
Accuracy–speed	Slow, normal, fast	F/E	Slope, correlation coefficient
Accuracy–displacement	Full, half	All	Slope, correlation coefficient
Minimal detectable motion	Minimal movement	All	Degrees
Accuracy		All	Slope, correlation coefficient
Intersubject variability		All	Slope
Intrasubject variability		All	Correlation coefficient
Single plane motion		All	

The validation tests performed using the MTS are given in Table 1. Accuracy was determined by comparing WASP peak amplitudes to MTS applied peak amplitudes. Linear regressions were created and statistically evaluated. We characterized drift in the sensors by applying ±10° motion in flexion-extension 5 times on different days and reported average relative error between the measurements. The system was not continuously powered on throughout the days only during sensor drift testing. We also measured sensor cross-talk, defined as nonzero measurement in the nondominant axes when motion is occurring only in the dominant axis. High cross-talk values can overestimate actual motion measurements. Thus, it is important to keep cross-talk at a minimum. We measured cross-talk by applying motion to 1 axis and then observing the magnitude of motion in the other 2 axes. Reliability tests such as orientation effects and reapplication effects were also assessed.

OMC System. *In vivo* head and trunk kinematics were recorded (64 Hz) using an 8-camera optical passive marker motion capture system (Motion Analysis Corp., Santa Rosa, CA) with accuracy of <1 mm and <0.1°. This system tracked the 3-dimensional coordinates of 9 reflective markers placed on palpable anatomic landmarks. The sampling rate was 64 Hz, which was down sampled to 8 Hz before signal processing.

Six subjects wore the WASP sensors, which were taped to the mastoid and thorax. Nine reflective markers were taped to the subject's body and one adjacent to each WASP sensor. To reduce skin motion artifact secondary to the hair and scalp, 4 additional markers were placed on a helmet that was securely fixed to the subject's head. Before the movement conditions, an initial recording of the reflective marker positions during quiet upright sitting was performed to establish joint centers, body segment coordinate systems, and segment lengths. A 3-dimensional, 2-segment musculoskeletal model (Visual3D, C-Motion, Rockville, MD) was individually scaled to each subject based on this recording and used to calculate cervical spine motions during the movement conditions. All marker coordinates were low-pass filtered (8 Hz) using a fourth-order, zero-lag Butterworth filter.

The OMC was used to validate the following parameters: effect of head velocity and degree of displacement on accuracy, intersubject and intrasubject variability on accuracy, and determination of the minimal voluntary motion that a subject can possibly move (Table 2).

Table 1. MTS Validation Tests

Test	Methods	Axes	Metric
Accuracy	±10°, ±20°, ±30°, ±40° in all axes	All	Slope, correlation coefficient
Coupled motions	a) ±10°, ±20° b) ±20°, ±10°	a) F/E, AR b) AR, F/E c) LB, AR d) AR, LB	Slope, correlation coefficient
Reapplication effect	4 reapplications at ±20°	F/E	Relative error
Orientation	±15°, ±30° in orthogonal plane ±15° in plane	F/E	Relative error
Cross-talk	(±20°, ±40°, ±60°, ±80°)	F/E–LB F/E–rotation LB–rotation	Degrees of cross-talk
Drift	5 random times on 3 days	F/E	Relative error

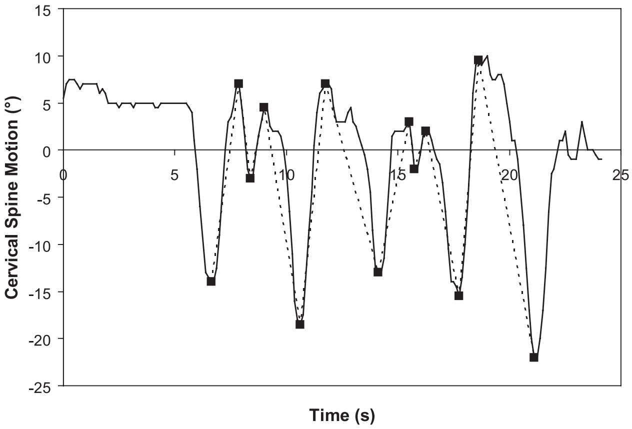

Figure 3. Plot of flexion-extension motion over 25 seconds. The solid line represents sensor output, the dashed line represents the approximation by the algorithm, and the square points (■) are the detected peaks.

To evaluate the effect of head velocity and displacement on accuracy, each subject was asked to perform pure motions (flexion-extension, lateral bending, axial rotation) at varying speeds (slow, normal, fast) and varying amplitudes (half and full range of motion). To detect what constitutes the slightest or most minimal motion that a human can perform, subjects were asked to move so that the motion was barely perceptible to them along each axis. Intersubject variability was determined by comparing accuracy of all motions. The standard deviation of the slope is a measure of the differences in accuracy among different subjects. In a linear regression fit, the correlation coefficient is a quantitative measure of a linear association. We used it as a measure of precision of subject motion. A high correlation coefficient would indicate that the data points representing subject motion were not spatially scattered, thus suggesting that subject motion was not highly variable.

Statistical Analyses. For accuracy comparisons, peaks were detected from the applied angular displacements from the MTS or OMC. Peaks were also detected from the motions recorded by WASP. Peak magnitudes of WASP were then plotted against MTS/OMC peaks. Linear regressions obtained result in slope and Pearson correlation coefficients. For the regression analysis, the independent variables were the applied or observed motions from the MTS or OMC and the dependent variables were the output of the WASP. The slope of the line is an index of accuracy and the correlation coefficient is a measure of precision indicating a linear association. The terms "slope" and "correlation coefficient" in the rest of the document have the above stated meanings.

■ Results

Peak Detection Algorithm Validation

The number of peaks detected visually and by the peak detection algorithm was identical in all 5 trials. Figure 3 shows a random 25-second signal sample in flexion-extension that occurred during a 4-hour period. The peaks detected by the peak detection algorithm are indicated (squares). As previously indicated, the noise threshold for peak detection was set to 3°; thus, peaks below this threshold were not detected.

MTS Validation

Accuracy. Four displacements (±10°, ±20°, ±30°, ±40°) in flexion-extension, lateral bending, and axial rotation were applied by the MTS and values recorded by WASP. The slopes of the regression line between MTS and WASP for peak magnitudes in flexion-extension, lateral bending, and axial rotation, respectively, were 0.89, 0.93 and 0.38 (Figure 4).

There was a strong linear association between WASP and MTS ($R^2 = 0.99$ for all axes). Thus, the precision did not vary with increasing displacement.

Sensor Drift. Drift was quantified by computing the percentage relative error between MTS applied displacement and peaks detected by the WASP over 5 trials on different days over a 1-week period. The average relative error in the detection of peak frequencies between WASP and MTS was 0.25%. The relative error in angular amplitudes ranged from 5.7% to 15.8% but did not degrade over time; indeed, the largest error was seen on the first test, indicating a potential learning curve for attaching the sensors.

Cross-Talk. In pure flexion-extension, the average cross-talk was 1.25% and 1.89% (0.5° and 0.64°) in lateral bending and axial rotation, respectively. When axial rotation was performed, the average cross-talk seen was 2.87% and 9.95% (0.82° and 2.3°) in flexion-extension and lateral bending, respectively. The averages were taken across different amplitudes of motion (±10°, ±20°, ±30°, ±40°). Across this amplitude range, cross-talk remained under 3° and thus below the cutoff for analysis. When pure lateral bending was performed, cross-talk in flexion-extension and axial rotation was 9.5% and 29.6% (2.34° and 7.33°), respectively. We noted that cross-talk in the axial rotation axis when lateral bending motion was performed was on average 7.33° (>3° threshold) and thus would lead to a measurement error.

Orientation Effects. The effect of changing the orientation of the sensor to ±15° and ±30° on the association of MTS to WASP resulted in lower angular displacements from 0.6% to 26.3%

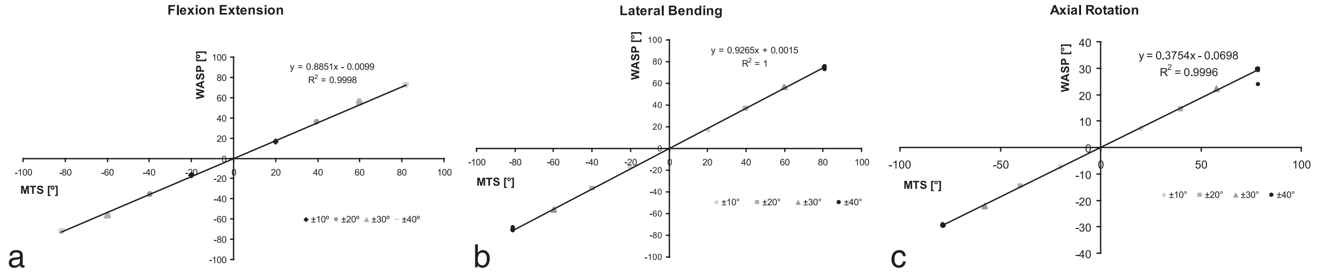

Figure 4. Association in degrees between MTS and WASP in (**a**) flexion-extension, (**b**) lateral bending, and (**c**) axial rotation. Each point denotes about 50 peaks.

Table 3. WASP Accuracy and Precision When Coupled Motion Is Applied by MTS

Coupled Motion		Slope of Linear Regression Between MTS and WASP	
Primary Axis	Secondary Axis	Slope in Primary Axis	Slope in Secondary Axis
AR ± 20°	FE ± 10°	0.39	0.90
FE ± 20°	AR ± 10°	0.88	0.44
AR ± 20°	LB ± 10°	0.45	0.96
LB ± 20°	AR ± 10°	0.94	0.69

(average, 8.55%). The error in measurement of detection of peak frequency still remained small at 0.5% in both cases.

Reapplication. The average percentage error over 4 trials when the sensor was detached and attached back to the same position 4 different times was 17%. This error includes the error introduced by reattaching the sensors without recalibration of the data logger and also the inherent sensor error in motion detection.

Coupled Motion. Flexion-extension (±20°, ±10°) and axial rotation (±10°, ±20°) were applied together by the MTS to determine instrument accuracy in coupled motion. The test was repeated by applying lateral bending (±20°, ±10°) and axial rotation (±10°, ±20°) motions simultaneously. The slopes for the coupled motions of flexion-extension and lateral bending compared well to slopes determined for primary axis motions as shown in Figure 4. We noted that if lateral bending is increased (from ±10° to ±20°), the slope for axial rotation increases. However, this is not the case when we increase flexion-extension. This is a consequence of the cross-talk seen in axial rotation when lateral bending motion is performed as described earlier. The slopes are shown in Table 3. The correlation coefficients ranged from 0.99 to 1.00 indicating high precision.

OMC Validation

Accuracy. Six subjects performed "full" and "half" range of motion in the 3 axes for 5 cycles. WASP accuracy remained excellent in flexion-extension and lateral bending with overall mean regression slopes of 1.02 (SD, 0.23) and 1.10 (SD, 0.32), respectively. The mean regression slope in angular rotation was only 0.40 (SD, 0.25). The average cross correlation coefficients were 0.98 (SD, 0.034), 0.92 (SD, 0.19), and 0.93 (SD, 0.10) for flexion-extension, lateral bending, and axial rotation indicating a high degree of reliability and reproducibility.

Table 4. WASP Regression Line Slopes With Subjects Performing Various Motions at "Medium" Speed

	Flexion-Extension		Lateral Bending		Axial Rotation	
Subject No.	Half	Full	Half	Full	Half	Full
1	1.12	1.30	1.34	1.19	0.59	0.75
2	0.93	0.93	0.96	0.86	0.30	0.13
3	1.10	1.02	1.14	1.21	0.50	0.30
4	1.14	1.17	1.38	1.13	0.60	0.44
5	0.7	0.85	0.75	0.87	0.21	0.29
6		0.78		0.79		0.25
Average	1.00	1.01	1.12	1.01	0.44	0.36
SD	0.19	0.20	0.27	0.19	0.18	0.22

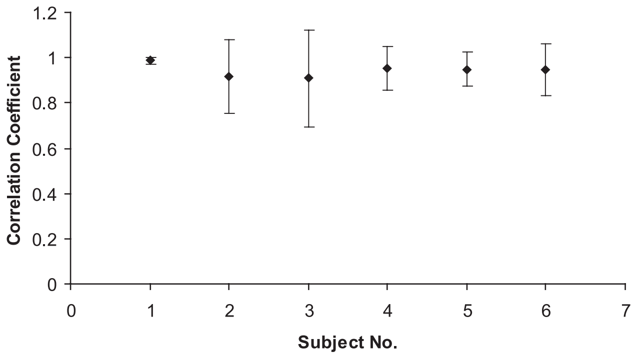

Figure 5. Correlation coefficients (SD) for all 6 subjects.

The individual slopes for "half" and "full" motions for the subjects are shown in Table 4. It is seen that association between WASP and OMC was also independent of the amplitude of subject neck motion.

Speed of Head Motion. The average slopes of WASP to OMC peak amplitudes for all velocities were 1.02, 1.1, and 0.4 for flexion-extension, lateral bending, and axial rotation, respectively. Accuracy in flexion-extension and lateral bending measurements was not affected at physiologic velocities; however, axial rotation was affected to a greater degree (slope range, 0.039–0.8).

Intersubject Variability. For quantification of intersubject variability, we looked at motions of different subjects and used standard deviation of the regression slope (a measure of accuracy) as a metric. SD range for subjects performing motion at medium speeds was 0.18 to 0.27 (Table 4). The intersubject variability was also independent of speed and amplitude of motion.

Intrasubject Variability. Figure 5 shows correlation coefficients and SD for each of the 6 subjects. Each point represents the average correlation coefficient for all the motions (18 motions: "half" and "full" amplitude, and 3 speeds, in all 3 axes of motion) that the subject performed. The overall average correlation coefficient for all subjects was 0.94 and SD was 0.13. Thus, although there is intrasubject variability, WASP results in high precision in subject motion.

Single Plane Motion. Coupled motions were measured when subjects were asked to move in a single plane for a full range of motion (Figure 6). All subjects had detectable coupled motion

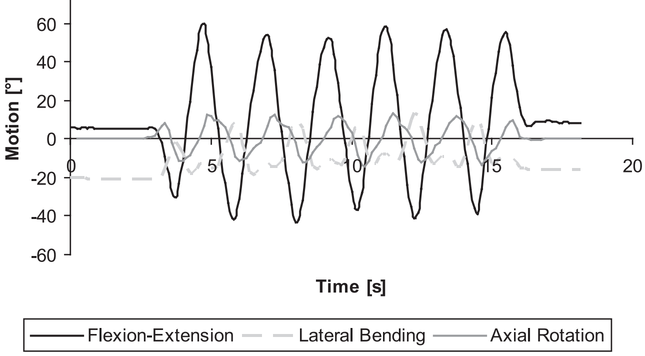

Figure 6. Coupled motions from WASP during primary flexion-extension motion.

during primary motion in 1 axis. This was observed from both OMC and WASP.

Minimum Motion. Subjects were asked to move their head as little as possible. The average minimal motions were 5.3° (range, 2.6°–12.0°) in flexion-extension, 7.9° (range, 4.7°–16.1°) in lateral bending, and 5.7° (range, 4.1°–10.4°) in axial rotation. All of these (with the exception of axial rotation) were above the sensors' 3° threshold. Note the excellent accuracy of the sensor compared with OMC. Axial rotations of less than 10° could not be measured with the WASP system, although they were detected using the OMC.

■ Discussion

The range of motion of the cervical spine has been well characterized from cadaveric, radiologic, goniometric, and video investigations.[2,18–22] However, these studies are only analyzing the range of motion over 1 or a few trials. The quantification of cervical spine motion during continuous activity provides important insight into disease processes involved with overuse syndromes and joint degeneration. This information is important for the design and testing of artificial disc replacements. Further, this information has strong occupational and ergonomic application. A variety of techniques have been developed, including videotape reduction, use of motion sensors, mechanical goniometers, direct visual counting, and gait laboratories. However, the use of microelectronic sensors, such as those included in the WASP system, allow data collection with minimal effect on subject behavior and can be obtained during normal activities of daily living at work and home.[23]

The purpose of this study was to determine the performance of our system by comparing to 2 accurate benchmarks. We examined a variety of factors that could potentially affect the unit's performance. We tested WASP peak detection, sensor drift, effects on accuracy of the amount of displacement and speed (at normal physiologic speeds), cross-talk between sensors, effects of sensor orientation and reapplication on WASP accuracy, and coupled motion accuracy. We also looked at intersubject and intrasubject variability.

Sensor drift ranged from 5.7% to 15.8% when measured over a week. Sensor orientation and reapplication effects were determined as these will be important variables when used in a subject over long periods of time. Orientation off axis of up to 30° resulted in only 8.55% less detected motion. Similarly, the effect of reapplication of the sensors resulted in a 17% difference. However, both of these effects could have been minimized by initial recalibration of the sensor, which determines the initial orientation and is accomplished by the subject standing as straight as possible and pressing a button on the data logger. In flexion-extension, the error of the WASP system as compared with MTS was 12%; thus, with calibration after reapplication, the error could be theoretically reduced by 5%.

The ability to detect the number of peaks or cycles was extremely precise (<1% difference) under all test conditions. We set a threshold of 3° as a minimum motion based on noise in the system. This was further validated by determining what constituted the least amount a subject could move. The average minimal motions were 5.3° (range, 2.6°–12.0°) in flexion-extension, 7.9° (range, 4.7°–16.1°) in lateral bending, and 5.7° (range, 4.1°–10.4°) in axial rotation.

In flexion-extension and lateral bending, WASP was strongly correlated to both the MTS and OMC systems. This was true for both primary and secondary axes movements and was independent of speed at physiologic range and the degree of displacement. While the ability of the WASP to accurately capture high speed movements may be compromised due to the 8 Hz sampling rate, this was not observed during the volitional movements performed. A review of the raw OMC data collected at 64 Hz indicates the average (SD) frequency of volitional movement during the self-selected fast trials was as follows: axial rotation, 0.94 Hz (1.61); flexion-extension, 0.84 Hz (1.64); and lateral bending, 0.88 Hz (1.97). The greatest frequency of volitional motion observed for any one subject was 1.6 Hz. Thus, the sampling rate of the WASP system was 4 times that of the fastest recorded motion, well above the Nyquist limit.

The performance of the WASP was poorest in axial rotation. We think that this was due to the Coriolis effect sensor. The Coriolis effect is the tendency of an object to drift sideways when moving above a rotating object. This is important when considering ballistics, ocean currents, and meteorology. Sensors or gyroscopes use this principle to measure changes in angular velocity for many applications in the automotive, aerospace, defense, and medical industries. The sensors use paired piezoelectric (such as silicon or quartz) elements similar to tuning forks. Under rotation about the symmetric axis, there is differential deflection of the 2 elements that is detected by differential capacitance or beam deflection. After signal processing, this is translated into angular velocity. The performance is affected by temperature and drift and requires careful calibration. To measure angular displacements, our output signal required mathematical integration, which may have introduced inaccuracies. Our inaccuracy of between 35% and 40% was predictable, linear, and may have been a result of poor calibration. The results are easily corrected by a calibration constant, which can be determined for the sensor and subject. However, this limited the measurement in axial rotation to a minimum of 10°.

Cross-talk was only seen in axial rotation when lateral bending was performed. No other motion revealed significant cross-talk. Thus, it might appear that there is motion in the axial rotation and lateral bending axes when there is actually only motion in the lateral bending axis. However, appreciable axial rotation cross-talk that would be detected is only seen at high lateral bending amplitudes.

We always observed coupled motion even when subjects were trying to perform single plane motion. Thus, a subject performing flexion-extension only was found to have lateral bending and axial rotation motions also. Malmstrom *et al* observed a similar phenomenon and concluded that coupled motions are part of normal cervical motion.[24]

Finally, we looked at intersubject and intrasubject variability. We find that, although intrasubject variability is low, intersubject variability would require individual sensor calibration for each subject.

■ Conclusion

The WASP system was designed to continuously measure the frequency and magnitude of neck motion. We compared it with 2 standards: MTS and using 6 subjects with OMC. WASP software resulted in no errors in peak motion frequency and magnitude measurement discounting boundary conditions. WASP had a high accuracy in measuring motion magnitude in flexion-extension and lateral bending as compared with MTS but was somewhat lower in axial rotation. In all 3 axes of motion, WASP had a high accuracy in measuring motion frequency. Precision was high in measuring both motion magnitude and frequency. Also, WASP accuracy in measuring motion magnitude was independent of the amplitude and speed of motion. Cross-talk was only seen in axial rotation when lateral bending was performed and was seen in no other case. Intersubject variability was seen. However, it is not clear whether this would affect subject motion data. It would be recommended to calibrate WASP to each subject before gathering data in order to get the most accurate data. Intrasubject variability was low, indicating high reliability of the WASP system. Although it has some limitations in axial rotation, WASP can accurately and reliably measure frequency and magnitude of continuous motions.

■ Key Points

- Cervical spine performance over extended periods of time in natural environments is unknown.
- We developed and validated the Wisconsin Analysis of Spine Motion Performance (WASP) system for measuring cervical spine motion.
- WASP has high accuracy and reliability in measuring cervical spine motion in flexion-extension and lateral bending with a lower accuracy in axial rotation.
- Coupled motion is observed in individuals even when attempts are made to move only in a single plane.

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