The Feasibility of Using Electromagnetic Motion Capture System to Measure Primary and Coupled Movements of Cervical Spine

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Abstract

In the latest research, the application of three-dimensional electromagnetic tracking system (ETS) for biomechanical and kinesiologic research of cervical spine has been demonstrated. Little information is available regarding coupled movements that accompany the primary movement in vivo. The purpose of the present study was to investigate the feasibility of quantifying the primary movements of the cervical spine and their corresponding coupled motions in healthy subjects by a three-dimensional ETS. Twenty healthy subjects (10 males and 10 females) participated in the study. Cervical extension, flexion, side bending, rotation in neutral position, and rotation in a position of full cervical flexion were analyzed via ETS. All measurements were performed actively except for rotation in a position of full cervical flexion. According to our results, the high intraclass correlation coefficient (ICC (2,1)) values (greater than 0.791) suggested that ETS is appropriate for measuring primary movements in the cervical spine. However, the ETS could not be applied for the coupled movements with ICC (2,1),which varied widely from 0.089 to 0.942. Except for coupled side bending during performance of primary flexion (0.757), coupled extension-flexion during performing primary left-side bending (0.942) and coupled extension-flexion during performing primary rotation to the right (0.863), the ICC (2, 1) values of other coupled movements were below 0.750. The current findings provide the basis for further application of the ETS to evaluate cervical spine kinematics for clients with movement disorders excluding those coupled motions that could not be reliably measured by ETS. Meanwhile, the three-dimensional motion patterns monitored by ETS may provide a diagnostic basis for detecting and characterizing cervical movement dysfunction.

Keywords: Three-dimensional measurements, Range of motion (ROM), Electromagnetic tracking system (ETS), Intraclass correlation coefficient

1. Introduction

The evaluation of joint range of motion (ROM) and motion patterns are common physical examination parameters with which to objectively examine joint disability in clinical settings. Alterations in cervical ROM and motion patterns has been demonstrated in specific populations with cervical and providing clinicians with information that aids in the treatment plans and outcome measures to monitor the efficacy of rehabilitation programs [1-5].

Over the past few decades, many assessment techniques have been applied to estimate the cervical ROM, such as visual estimation, tape measure, universal goniometer, electronic digital inclinometer, and cervical ROM device. Most of these instruments have been described as feasible and reliable methods in measuring the cervical ROM [6]. Although many of these instruments are easy to use and widely applied in the clinical setting, a disadvantage is that most tools can only provide maximum ROM from a single plane and during static joint position. Namely, these instruments do not provide dynamic information on primary movement. The primary movements are defined as the movements that take place in the cardinal plane and the coupled movements are defined as other movements that

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occur simultaneously in the associated planes related to the primary movement plane [5,6]. Several studies have confirmed that the cervical coupled movements are component parts of the normal cervical motion [2,7-9]. The cervical coupled movements usually take place during performance of the cervical primary movements in the cardinal plane and may be affected by spine disorders [10-13]. In terms of clinical diagnoses or demands for research, both the primary movements and the coupled movements provide critical reference bases for clinical diagnoses and kinematic applications. For these reasons, some accurate techniques have been reported for evaluating the three-dimensional spinal ROM, such as radiography and computed tomography scan [14-17]. However, the disadvantages of such methods are radiation exposure, cost of evaluation and availability of equipment.

In contrast, many studies had demonstrated the application of electromagnetic tracking system (ETS) for biomechanical and kinesiologic research on/into human joint movements [4,10,16,18-25]. The results from previous investigations also confirmed that ETS is a suitable, accurate and easy-to-use instrument for measurement of spinal kinematics and measuring the three-dimensional spinal ROM [4,10,16,21,22,25]. The ETS is a non-invasive measurement tool consisting of a standard range transmitter that generates low-frequency electromagnetic fields which are detected by one or multiple sensors. The orientation of the receiver frame with respect to the transmitter frame is defined by the receiver’s x, y,and z axes with respect to the transmitter frame’s X, Y and Z axes, respectively. This orientation between axes systems can be defined by Euler angles of azimuth, elevation, and roll. The angle align command allows you to mathematically transform the receiver’s x, y and z axes to the orientation witch differs from that of the actual receiver. The ETS can track consecutive positions (X, Y and Z Cartesian coordinates) and orientations (azimuth, elevation, and roll) of the sensors relative to a transmitter. Consequently, the ETS can not only provide dynamic and continuous information, but also concurrently measure the three-dimensional joint ROM in three planes over the time period of the movement.

Although several studies have stated that the ETS is a reliable and accurate instrument for exploring the cervical ROM, most of these investigations focused only on the cervical primary movement in the cardinal plane [10,21,22,25]. Understanding the kinematics of the cervical spine could be a paramount issue in clinic. Both the primary movements and the coupled movements should be considered. However, little information was available about the coupled movements that accompany primary movement in past investigations. On the side, the motion patterns were also less discussed while executing the cervical movements. Therefore, the present study aimed to investigate the feasibility of quantifying the primary movements of the cervical spine and their corresponding coupled motions in healthy subjects by a three-dimensional ETS.

2. Materials and methods

2.1 Subjects

Twenty collegiate students (10 males and 10 females) with a mean age of 21.8±1.8 years old (range, 20-24 years) volunteered for the study. None of the subjects had any history of cervical surgery, cervical trauma or cervical pain. Informed consent, approved by the Institutional Review Board (IRB), was obtained from all volunteers prior to taking part in the study.

2.2 Instrumentation

A six-degrees-of-freedom ETS (LIBERTY^{TM}, Polhemus Inc, USA) was used to record the kinematic data. Real-time three-dimensional positions and orientations of the sensors were tracked at a measurement frequency of 120 Hz. In this experiment, three receivers where hardwired to system electronics unit were used to sense the positions and orientations of these sensors relative to the transmitter. Two of these receivers were firmly affixed to the forehead and the midpoint between the incisura jugularis and processus xiphoideus, respectively (Fig. 1). The third receiver was mounted on a palpation stylus, pen-shaped device for locating bone landmarks. The transmitter was positioned near the subject.

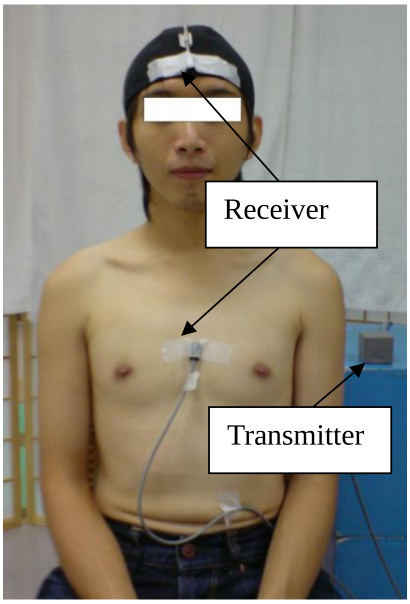

Figure 1. Experimental set-up of the electromagnetic tracking system (ETS). One receiver was affixed to the forehead and the other one was affixed to the midpoint between incisura jugularis and processus xiphoideus. The transmitter was positioned near the subject.

According to manufacturer specifications, the static root mean square (RMS) accuracy is 0.0762 cm for X, Y or Z position and 0.15° for sensor orientation. The useful operation range is in excess of 180 cm (LIBERTY^{TM} USER MANUEL, Revision F. Colchester, Vermont; Polhemus Inc.; 2008).

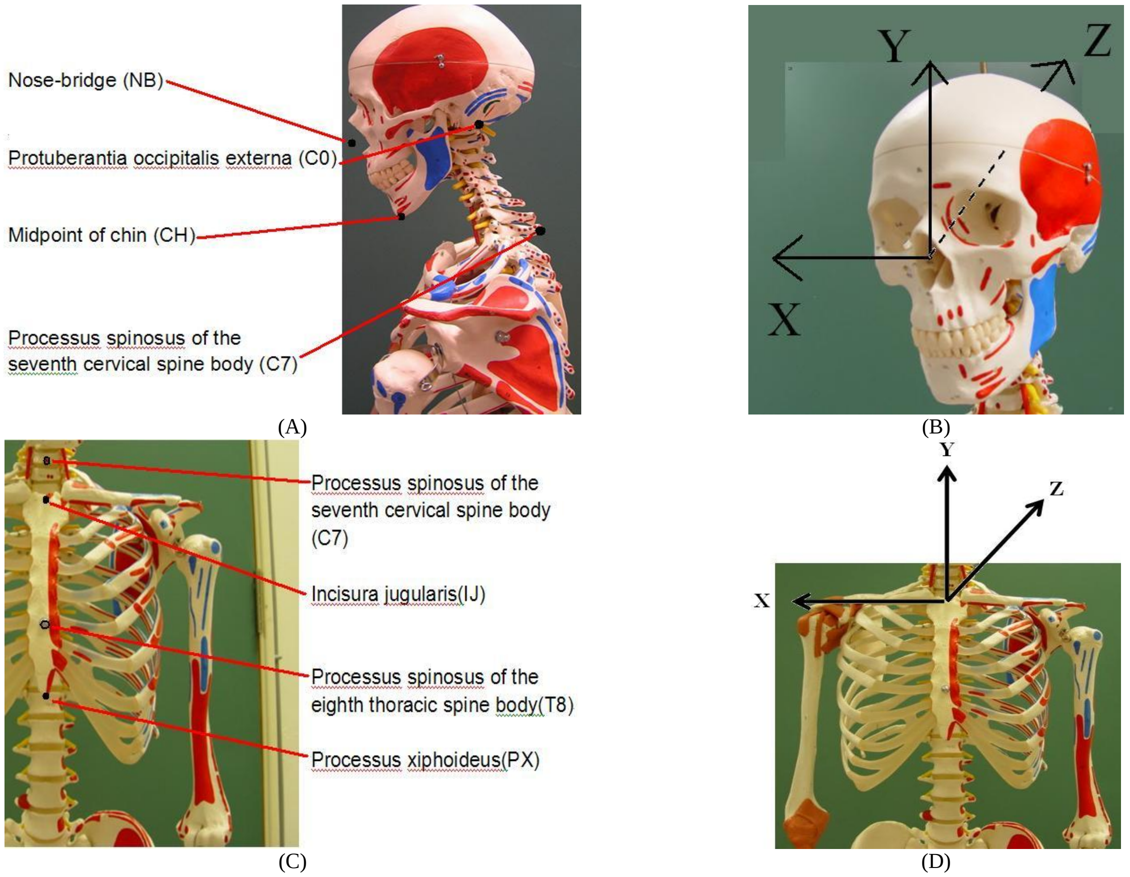

Figure. 2 Anatomical bony landmarks and the coordinate systems of head (A, B) and thorax (C, D): (B) The reference coordinate system of head originated from the nose-bridge and made up by the nose-bridge, the mid-point of the chin, and the protuberantia occipitalis externa. (C) The reference coordinate system of the thorax originated from incisura jugularis and made up by the processus xiphoideus, incisura jugularis, the processus spinosus of the seventh cervical spine body, and the processus spinosus of the eighth thoracic spine body.

2.3 Experimental protocol

All measurements were performed by the same tester. In order to eliminate measurement errors, the subjects' position was standardized. All subjects were seated on a wooden chair so that their thoracic spine maintained contact with the backrest. The subject's feet were flat on the floor, and their arms rested freely on their thigh. All subjects were asked to relax their neck and keep to look straight ahead. In order to precisely facilitate the description of the cervical ROM in three-dimensional space, two sets of reference coordinate systems of the head and thorax were constructed before the actual measurement [22]. Seven anatomical bony landmarks (Fig. 2) were palpated and recorded together with the stylus receiver. These bony landmarks were as follows: nose bridge, chin mid point, processus xiphoideus, incisura jugularis, protuberantia occipitalis externa, processus spinosus of the seventh cervical spine body, processus spinosus of the eighth thoracic spine body. Accordingly, the reference coordinate systems of head and thorax were set up (Fig. 2) and their relationship with the receivers on head and thorax in neutral position was determined. The reference coordinate systems of head and thorax were defined with the X-axes pointed to the right, the Y-axies pointed upward vertically and the Z-axis being the cross product formed by the X- and Y-axies and directed backward.

After initial measurement, all subjects were instructed only to perform cervical movements and to avoid compensatory movements in the thoracic region. All subjects were asked to execute cervical movement at a normal velocity until the maximum ROM was reached. Afterwards, they returned to the neutral position after each movement. No feedback was provided to correct the subjects' patterns of movements. Based on the suggestions of Prushansky et al. [26] and Guides to the Evaluation of Permanent Impairment [27], the cervical movements are commonly subdivided into six primary movements. So, the trial of movements in the present study included extension, flexion, rotation to the left and the right in the neutral position and side bending to the left and the right. Moreover, the upper cervical spine represents a unique anatomic structure. A large amount of rotation occurs in the upper cervical spine [28]. Dvorák proposed a particular experimental test, the full flexion combined rotation test, to examine upper cervical (C0-C2) spine dysfunction [1]. The author stated that the lower cervical segments below the second vertebra may be blocked during maximum flexion of the cervical spine. As a result, rotation of the upper cervical spine (C0-C2) could be determined. Therefore, all subjects were also asked to perform left and right rotation in a position of full cervical flexion. In order to keep the cervical spine in maximum flexion, a tester manually maintained the cervical spine in this position (Fig. 3). All measurements were performed actively except for full flexion combined rotation test, and the sequence was randomized. After completion of the first trial of measurements, subjects repeated another two additional trials of measurements according to the same procedure as the above protocol. Each trial of measurements was separated by at least five minutes.

To assess reproducibility of the ETS, ten of these subjects (5 males and 5 females) were asked to perform the same test on two separate days. The experimental protocol was the same as above.


(A) (B)

Figure. 3 Range of motion measurements for rotation to left (A) and right (B) in a position of full cervical flexion. In order to ensure the cervical spine was in maximum flexion, an examiner manually maintained the cervical spine in this position.

2.4 Calculation of the cervical range of motion

While subjects were performing movements, the attached receivers recorded the consecutive position and orientation data. The receiver data could be used to reconstruct the coordinate systems of head and thorax at each moving point. Therefore, the relative joint angles of cervical spine could be computed by mathematical Euler angle [29,30] using MATLAB software (Mathworks Inc., MA, USA). The formula for calculating the relative joint angles of cervical spine was as follows:

$$\begin{bmatrix} v_{bx} \\ v_{by} \\ v_{bz} \end{bmatrix} = \left(R_x(\alpha_b) \cdot R_y(\beta_b) \cdot R_z(\gamma_b) \right)^T \cdot \begin{bmatrix} b_x - o_{bx} \\ b_y - o_{by} \\ b_z - o_{bz} \end{bmatrix}$$

where v_{bx}, v_{by} *and* v_{bz} were the coordinates of the vector ${}^{R}V_b$ between the bone receivers and the bony landmarks; b_x, b_y *and* b_z were the coordinates of position vector ${}^{G}B$ of the bony landmarks; o_{bx}, o_{by}, o_{bz} were the coordinates of the position vector ${}^{G}O_b$ of the bone receiver; and α_b, β_b ,γ_b were the Euler angles describing the orientation of the bone receiver. After calculating the cervical ROM for each movement, the quantitative variables of the cervical ROM were normalized to 100% of the motion cycle. Each motion cycle included primary and coupled movements.

2.5 Data analysis

Mean values and standard deviations of three trials were calculated for each primary and coupled movements. Positive values indicated extension, rotation to the left and side bending to the left. Negative values indicated flexion, rotation to the right and side bending to the right. Owing to the small sample size of the present study, the non-parametric Mann-Whitney *U*-test was performed to determine whether there were gender differences. The accepted level of statistical significance for all assessments was $p<0.05$. Moreover, Jordan suggested that the Pearson correlation coefficient, the paired Student *t*-test and repeated measures analysis of variance (ANOVA) are inappropriate statistical methods for reliability studies [31]. They have some limitations as a result of the variation among the subjects being not especially small. The intraclass correlation coefficient [ICC (2, 1)] may be conceptualized as the ratio of between-group variance to total variance and reflects both degree of correspondence and agreement among measurements. Therefore, the ICC (2, 1) is the recommended method for reliability studies. The ICC (2, 1) ranges between 0.00 and 1.00, with values closer to 1.00 representing stronger reliability [31]. Consequently, the cervical primary and coupled movements of ten subjects (5 males and 5 females) were used to assess the test-retest reliability of the ETS by means of the ICC (2, 1) with random effects model and 95% confidence intervals. According to general definition, good reliability was defined for the values of ICC (2, 1) above 0.75, and poor to moderate reliability was defined for the values of ICC (2, 1) below 0.75 [32]. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS 12.0, Chicago, IL).

3. Results

The mean values and standard deviation (SD) of the cervical primary ROM for each movement for males and females are summarized in Table 1. There were no significant differences in the cervical primary ROM between genders for all movements ($P > 0.05$). As gender did not significantly affect the cervical primary ROM, we pooled the cervical primary ROM from both genders for further analyses.

As expected, the cervical coupled movements were found when subjects performed primary movement. The mean values and SD of the cervical coupled movements are given in Table 2. When performing primary extension and flexion, the cervical coupled movements were small. In particular, there was more obvious coupled rotation which reached greater than 10° on average during performance of primary side bending. During rotation in a position of full cervical flexion, there was also larger coupled side bending. In addition, the directions of the coupled motions were specific to the directions of the primary movement. Coupled side-bending was contralateral direction during rotation in a position of full cervical flexion and was ipsilateral direction during rotation in a neutral position. The three-dimensional motion patterns of all movements are depicted graphically according to the consecutive data obtained from the present study (as shown in Fig. 4).

Table 1. The mean (standard deviation) and ICC (2, 1) (95% CI) of the cervical primary ROM (units: degrees).

Movement		ROM			Pa	ICC (2, 1) b
		Total	Male	Female		
Extension-Flexion	Extension	64.4 (13.2)	68.2 (14.9)	60.6 (10.1)	.131	.856 (.569-.962)
	Flexion	57.2 (9.5)	54.8 (10.6)	59.7 (7.7)	.597	.791 (.393-.943)
Side bending	Left	42.4 (6.2)	42.9 (5.5)	41.9 (6.8)	.520	.870 (.570-.966)
	Right	42.7 (7.9)	41.3 (8.1)	44.1 (7.5)	.290	.836 (.460-.957)
Rotation (Neutral position)	Left	68.1 (7.4)	68.2 (7.2)	68.0 (7.7)	.970	.829 (.446-.955)
	Right	65.7 (8.6)	66.7 (8.5)	64.7 (8.6)	.544	.791 (.382-.943)
Rotation (Full flexion)	Left	48.6 (7.7)	47.8 (8.2)	49.4 (7.1)	.940	.930 (.759-.982)
	Right	48.3 (8.0)	45.4 (7.0)	51.1 (7.9)	.198	.897 (.657-.973)

a Mann-Whitney U-test was used to determine the gender difference between male and female.

b Intraclass correlation coefficient with random effects model [ICC (2, 1)] and 95% confidence were used to assess the test-retest reliability

Table 2. The mean (standard deviation) and ICC (2, 1) of the cervical coupled ROM (units: degrees).

Primary movement		Coupled movement		
		Extension-flexion	Side bending	Rotation
Extension-Flexion	Extension		5.3 (3.2) [.449] [b]	5.6 (3.3) [.407] [b]
	Flexion		-5.3 (2.9) [.757] [b]	-4.8 (2.4) [.447] [b]
Side bending	Left	-9.1 (5.5) [.942] [b]		11.3 (6.0) [.735] [b]
	Right	-7.6 (3.9) [.460] [b]		-11.6 (5.3) [.546] [b]
Rotation (Neutral position)	Left	7.4 (3.6) [.174] [b]	7.9 (3.7) [.089] [b]	
	Right	7.0 (3.9) [.863] [b]	-7.2 (3.8) [.491] [b]	
Rotation (Full flexion)	Left		-11.3 (5.6) [.181] [b]	
	Right		11.9 (6.8) [.613] [b]	

[a] Positive values represented extension, rotation to left and side bending to left. Negative values represented flexion, rotation to the right and side bending to the right.

[b] Intraclass correlation coefficient with random effects model [ICC (2, 1)] and 95% confidence intervals were used to assess the test-retest reliability.

For the reproducibility of the ETS, a summary of the ICC (2, 1) values and 95% confidence intervals for each primary movement is presented in Table 1. The ICC (2, 1) values for each primary movement ranged from 0.791 to 0.930. The ICC (2, 1) values for the cervical coupled movements during performance of primary movement are given in Table 2. Except for coupled side bending during performing primary flexion (0.757), coupled extension-flexion during primary left-side bending (0.942) and coupled extension-flexion during primary rotation to the right (0.863), all other ICC (2, 1) values were below 0.75.

4. Discussion

In the present study, the results of the cervical primary ROM for extension, flexion, left- and right-side bending, and left and right rotation in neutral position were generally in good agreement with the previous studies that measured the cervical ROM in healthy young subjects using ETS [10,21,25,33,34]. The comparison of the cervical primary ROM regarding previous studies is presented in Table 3.

The discrepancies were small when compared with previous reports. A previous study utilized three-dimensional ultrasound-based motion system (Zebras, CMS 70P) to examine cervical ROM for a Chinese population [35]. Although a larger difference was presented in extension, the results of the cervical primary ROM for other movements were similar. The cervical primary ROM in extension found in the present study (64.4°) was about 10° smaller than the finding of Wang et al. (75.4°). A possible reason that may have led to reduced cervical primary ROM in extension may be due to differences in the methodology. In the present study, the upper thoracic ROM could be excluded as the coordinate system of head and thorax was used to determine the cervical ROM. In contrast, Wang et al. used a triple marker on the shoulder cap as the reference coordinate. Thus, the upper thoracic ROM may have contributed to greater cervical primary ROM in extension.

For the rotation ROM of the upper cervical spine, the present study revealed results that were also similar to those of past investigations [36-38]. The rotation ROM of the upper cervical spine had been reported as approximately 44° for left and right side. In addition, the ratios of left and right rotation ROM between upper cervical spine and total cervical spine in the present study were 71% (48.6°/68.1°) and 74% (48.3°/65.7°), respectively. The ratios were almost identical to the findings of Panjabi et al. [38]. Who reported that the upper cervical region comprised about 75% of the total cervical rotation.

With regard to the gender effect on the cervical primary movements, Tott et al. demonstrated that there was no gender effect on the primary cervical movements [10]. Likewise, the results of the present study reported that gender did not significantly contribute to difference in the primary cervical ROM.

Review of previous studies which explored the cervical coupled movements revealed that some of the results concurred with those of the present study [4,8-10]. During extension and flexion, the cervical coupled movements were small. During side bending, coupled ipsilateral rotation was observed. During rotation in a neutral position, the coupled extension and ipsilateral side bending were found, simultaneously. There was coupled contralateral side bending during rotation in a position

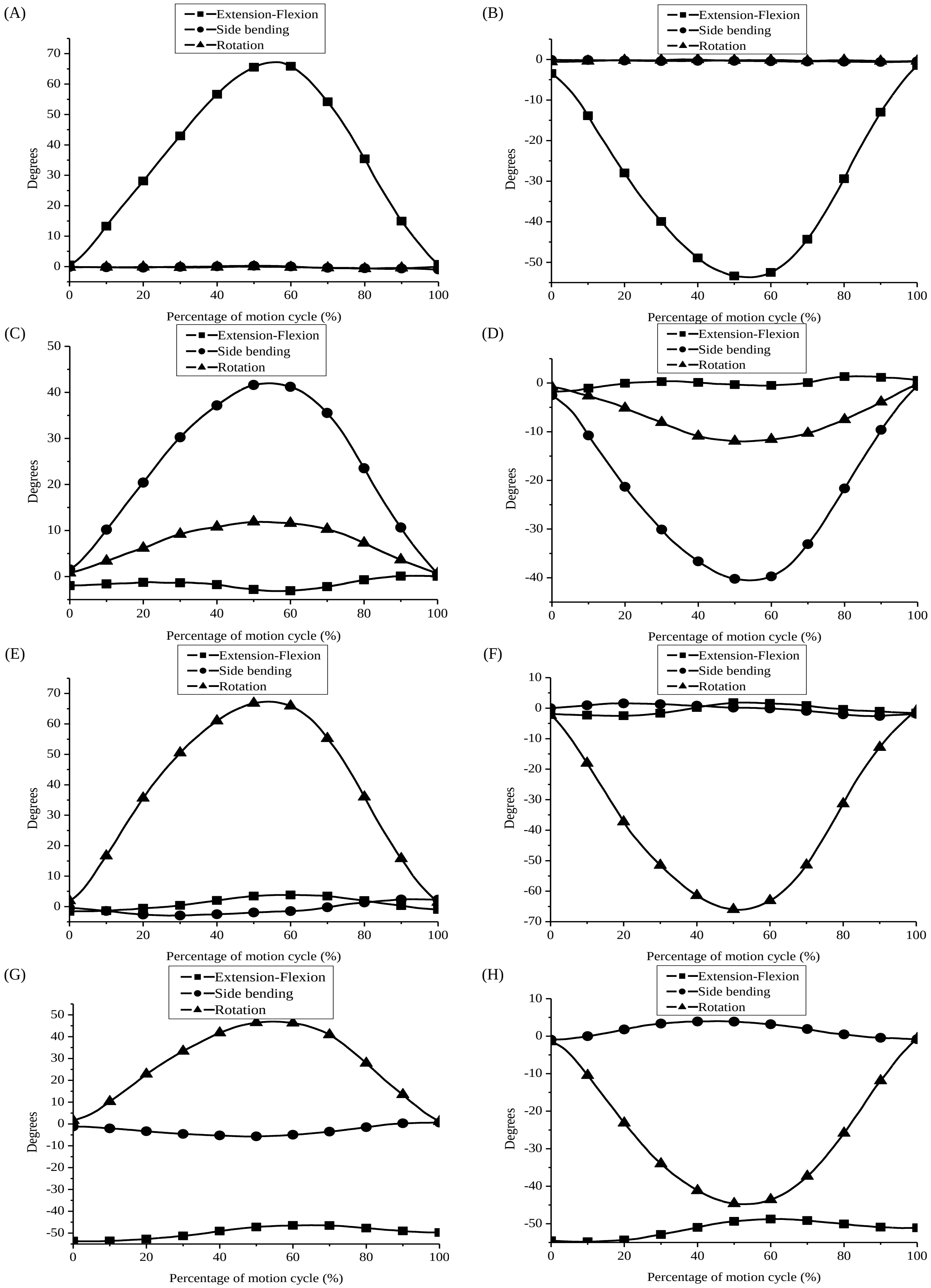

Figure 4. Three-dimensional motion patterns of the primary and coupled movements: (A) extension; (B) flexion; (C) left-side bending; (D) right-side bending; (E) left rotation in neutral position; (F) right rotation in neutral position; (G) left rotation in a position of full cervical flexion; (H) right rotation in a position of full cervical flexion. Positive values represent extension, rotation to the left and side bending to the left. Negative values represented flexion, rotation to the right and side bending to the right.

Table 3. The comparison of the cervical primary ROM (units: degrees).

Authors	Method	Subjects (n); Age (years)	Extension-flexion[c]	Side bending[c]	Rotation (Neutral position)[c]	Rotation (Full flexion)[c]
Trott et al. [11]	Electromagnetic tracking system	30; 20-29[a]	E: 76.1 F: 57.5	L: 45.4 R: 47.6	L: 71.7 R: 78.0	
Jordan et al. [22]	Electromagnetic tracking system	72; 34.2	E: 68.5 F: 66.1	L: 47.1 R: 44.9	L: 82.7 R: 76.5	
Morphett et al. [26]	Electromagnetic tracking system	28; 40.5	107.08[b]	77.97[b]	152.51[b]	
Gelalis et al. [34]	Electromagnetic tracking system	10; 29.3	E: 67.2 F: 62.8	L: 40.1 R: 39.3	L: 71.9 R: 69.0	
Lansade et al. [35]	Infra-red POLARIS measurement system	20; 20-29[a]	128[b]	87[b]	152[b]	
Wang et al. [36]	Ultrasound-based coordinate measuring system	40; 21.9	E: 75.4 F: 53.0	L: 38.4 R: 39.5	L: 65.1 R: 63.4	
Amiri et al. [37]	Electromagnetic tracking system	15; 27.60	F: 66.17		L: 81.14 R: 78.57	L: 39.8 R: 44.3
Hall et al. [38]	Cervical range of motion device	28; 43.3	E: 60 F: 51	L: 35.7 R: 35.2	L: 66.0 R: 64.9	44[d]
Feipel et al. [9]	Ultrasound-based coordinate measuring system	133; 20-29[a]	E: 57 F: 66	L: 44 R: 45	L: 72 R: 71	L: 69 R: 67
Present study	Electromagnetic tracking system	20; 21.8	E: 64.4 F: 57.2	L: 42.4 R: 42.7	L: 68.1 R: 65.7	L: 48.6 R: 48.3

[a] Only age range of subjects was provided.

[b] Values represent the global cervical primary ROM.

[c] E indicates extension; F indicates flexion; L indicates left side and R indicates right side.

[d] Average rotation in a position of full cervical flexion was 44° to each side.

of full cervical flexion. In particular, coupled flexion was found during side bending, in accordance with the findings of Dall'Alba et al. [4]. However, Malmström et al. found that side bending was accompanied by coupled extension [9]. Moreover, the quantitative coupled movements revealed large variations when compared to previous observations [4,8-10]. These variations in findings with respect to the quantitative coupled movements may be in part caused by the different methodologies and anatomical structure, or variations in daily activity of the cervical motion between subjects. The ratio of the coupled rotation to the primary side bending was approximate 30% (11.3°/42.4° for left side and 11.6°/42.7° for right side), which resembled the results of Feipel et al. [8] (13°/44° for left side and 16°/45° for right side). The ratio of the coupled side bending to the primary rotation in the neutral position was approximately 10 % (7.9°/68.1° for left side and 7.2°/65.7° for right side), which was similar to the findings of Trott et al. [10] (8.8°/71.7° for left side and 11.3°/78° for right side) and Feipel et al. [8] (7°/72° for left side and 4°/71° for right side). Surprisingly, the ratio of the coupled side bending to the rotation in a position of full cervical flexion was about 25% (11.3°/48.6° for left side and 11.9°/48.3° for right side), which was different from the results of Feipel et al. [8]. These authors reported that the coupled side bending approximated 60% of the primary rotation (43°/69° for left side and 46°/67° for right side). Furthermore, one potential factor which contributed to the large discrepancy was the occurrence of compensations. In the present study, subjects were asked to maintain maximum cervical flexion as far as possible. In the study of Feipel et al., reduction in maximum cervical flexion was occurred.

Previous studies have documented the reliability of the ETS for measurement of the cervical primary movements in healthy subjects [21,22,25,33,36]. Except for the rotation in a position of full cervical flexion, the results of the present study displayed ICC (2,1) values that were generally higher than those of previous studies. Further, the sequence of performance of all movements in previous studies was consistent, whereas the sequence in the present study was randomized. Hence, the sequence effect on the results in the present study can be excluded. For rotation in a position of full cervical flexion, the ICC (2,1) values for the left and right rotation in a position of full cervical flexion were 0.930 and 0.897, respectively. The results were quite comparable to the observations of Amiri et al. [36]. Accordingly, the high ICC (2,1) values from the present study indicated that the ETS is a good reliable assessment instrument for measurement of the primary cervical movements.

Previous studies have demonstrated that the ETS is a suitable, accurate and easy-to-use instrument for investigation of spinal kinematics and measuring the three-dimensional spinal ROM [4,5,10,15,16,21,22,25,33,36]. However, most of these investigations only focused on the cervical primary movements in the cardinal plane and explored the reliability of ETS for measuring the cervical primary movements [21,22,25,33,36]. Although a few studies reported the applications of ETS to investigate the cervical coupled movements [4,5,10], no study examined the test-retest reliability of the ETS for measurement of the cervical coupled movements. Unexpectedly, the ICC (2,1) values of the ETS for measuring the cervical coupled movements in the present study varied significantly. Except for coupled side bending during performing primary flexion (0.757), coupled extension-flexion during performing primary left side bending (0.942) and coupled extension-flexion during performing primary rotation to right (0.863), the ICC (2, 1) values of other coupled movements were below 0.750. According to past observations [12,39], posture and muscular activity may influence the direction and magnitude of the cervical coupled movements. In the present study, subjects were asked to perform the test twice on two different days to assess the reproducibility of the ETS. Subjects may vary in their postures or may have different levels of underlying muscular activity on two different days. In addition, Edmondston et al. proposed that initial posture would influence the three-dimensional kinematics of the cervical spine [40]. Finally, the sample size for assessing reproducibility of the ETS was small (5 males and 5 females). Hence, these factors may contribute to lower ICC observed in the current study.

Moreover, the three-dimensional motion patterns of all movements obtained from the present study were comprised of the cervical primary and coupled movements. Unlike the quantitative coupled movements, which were only static information, the graphic motion patterns recorded the consecutive information during primary movements. Furthermore, Woodhouse et al. pointed out that altered movement patterns in the cervical spine were found in whiplash and chronic neck pain patients [5]. Thus, these three-dimensional motion patterns could serve as another diagnostic basis for the assessment of cervical disabilities in the clinical settings.

Some limitations of the present study should be noticed.The subjects in the present were all young college students, and the sample size was small. Thus, the results of the present study did not seem to exactly reflect the cervical primary and coupled movements for the general populations. The accuracy of the palpation of the bony landmarks was not recorded. Therefore, this could account for the measurement bias for the palpation of the bony landmarks. Due to the fact of relatively small cervical coupled movements both in the direction of side-bending and rotation during the execution of active flexion and extension, we cannot rule out the possibility of a systemic error somehow introduced in the experiment procedure. The ETS sensor configuration in this current study was not able to detect differences in coupled motions in different part of the cervical spine. The neutral position for each subject was not standardized. Thus, it is possible that some subjects may have moved slightly from the neutral position.

The ETS is not only a non-invasive instrument for measuring the cervical movements but can provide detailed information on dynamic movements. The high ICC (2, 1) values also confirmed that ETS is appropriate and applicable for the measurement of the primary movements of the cervical spine. The current findings provide the basis for further application of the ETS to evaluate cervical spine kinematics for clients with movement disorders exclude those coupled motions that could not be reliably measured by ETS. Further work will focus on large number of individuals with cervical disabilities. Moreover, the accuracy of the palpation of the bony landmarks and the neutral position will be further explored.

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