Validity and Reliability of an Inertial Measurement Unit–based 3-Dimensional Angular Measurement of Cervical Range of Motion

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Abstract

Objective: This study aimed to assess the reliability and validity of an inertial measurement unit (IMU)–based 3-dimensional (3D) angular measurement system for evaluating cervical range of motion.

Methods: Thirty-three healthy participants (21.9 ± 2.1 years; 162.0 ± 6.0 cm; 55.8 ± 9.0 kg; 21.2 ± 2.4 kg/m^2) were evaluated. Kinematic data of the cervical joints were simultaneously obtained using the IMU 3D angular, goniometer, and photographic measurements during cervical flexion (0°, 30°, and 50°), extension (30°, 50°), side-bending (0°, 20°, 40°), and rotation (45°). Test–retest reliability was investigated in each measurement method. Concurrent validity was assessed with the direct comparison between the IMU 3D angular measurement and other methods.

Results: The IMU 3D angular measurement showed mostly good to high test–retest reliability with relatively small standard error of measurement and the minimal detectable change values. The concurrent validity of IMU 3D angular measurements in the cervical range of motion was mostly reasonable. However, the measurement bias between the 2 methods tended to be larger at the end range of each plane.

Conclusion: Using the IMU 3D angular measurement in cervical spine is recommended because of its mostly good to high reliability and reasonable validity. However, using the IMU 3D angular measurement at the end range of each plane should be carefully considered owing to the poorer validity. (J Manipulative Physiol Ther 2019;42:75-81)

Key Indexing Terms: *Imaging, Three-Dimensional; Neck; Cervical Vertebrae; Range of Motion, Articular; Reproducibility of Results*

Introduction

The evaluation of range of motion (ROM) is a fundamental examination of musculoskeletal disorders. Several studies have reported a strong association between cervical ROM and cervical impairment.[1-3] Also, cervical ROM can identify physical disorders, and such measurements generally provide useful prognostic data.[4] Consequently, measurements of cervical ROM are routinely executed and emphasized for providing effective medical and rehabilitation interventions.

Health care professionals use various methods such as visual estimation, goniometers, inclinometers, photographs, and complex 3-dimensional (3D) motion analysis to assess cervical ROM.[1,5,6] Although these methods are widely used in the clinical setting, cervical ROM is generally challenging to measure accurately in 3 planes (sagittal, frontal, and transverse) because of the complex anatomical structure and coupled cervical spine movements.[7] Complex 3D measurements such as using the electromagnetic or audiovisual technologies are ideal to ensure optimum accuracy; however, their use is difficult and complicated for clinicians.[6]

With technological advances, inertial measurement unit (IMU)–based 3D measurement systems have shown potential for estimating 3D body kinematics. Several studies have positively assessed the body kinematics in the thorax, shoulder girdle, and lower limbs during motion

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tasks and reported ease of use.[8-10] A previous study investigated the reliability of an IMU 3D measurement system for assessing cervical ROM and reported good to excellent reliability.[11] However, the study included a limited dataset and small sample size. Moreover, the validity of the 3D measurement system for assessing cervical ROM has not been investigated. A measurement method must be both reliable and valid to be clinically useful.[12]

Therefore, this study aimed to assess the reliability and validity of an IMU 3D angular measurement system for evaluating cervical ROM. We hypothesized that the IMU 3D angular measurement in evaluating cervical ROM would show high reliability and reasonable validity.

Methods

Participants

For sample size estimation, a 1-way random-effects model was used in a pilot study with 5 participants.[13] A necessary sample size of 30 was calculated with an effect size of 0.62, power of 0.80, and α-level of 0.05. A total of 33 healthy participants (32 female, 1 male; mean age, 21.9 ± 2.1 years; mean height, 162.0 ± 6.0 cm; mean weight, 55.8 ± 9.0 kg; mean body mass index, 21.2 ± 2.4 kg/m^2) participated in this study through a public announcement at a university in Chungcheongbuk-do. The exclusion criteria were any cervical pathology, psychiatric condition, neurological or musculoskeletal disorder, previous neck surgery, and recent musculoskeletal trauma affecting neck ROM. The population included in this study was a convenience sample recruited by purposive and snowball sampling. This study was approved by the Cheongju University Institutional Review Board for Human Subject Research (1041107-161228-HR-008-04). All participants provided written informed consent for the data collection and agreed to participate in the study.

Experimental Methods

IMU 3D Angular Measurement (MyoMotion 3D Motion Analysis System). A MyoMotion (Noraxon Inc, Scottsdale, Arizona) 3D angular measurement system was used to investigate the ROM of the cervical spine. A small IMU sensor positioned on a body part trails its 3D angular orientation. The IMU sensors of the MyoMotion were attached by elastic straps or double-sided tape to the body segments to be measured. The MyoMotion IMU sensors include a 3D accelerometer, gyroscope, and magnetometer that can estimate 3D angles of each IMU sensor in absolute space and transmit the motion of the human body to the MyoMotion receiver. The MyoMotion3D angular measurement system is completely wireless and does not require calibration of the measurement space.[14] The MyoMotion IMU sensors can be placed on up to 16 joint segments for measuring the full body model, as suggested in the MR3 motion analysis software (Noraxon Inc).

For cervical ROM assessment, 3 IMU sensors were attached to the head (middle of the back of the head), upper thoracic area (below C7 along the spinal cord but high enough to not be affected by upper trapezius muscle movement), and pelvis on the bony area of the sacrum. Before each trial, IMU sensor calibration was completed for accurate measurement. The calibration posture was sitting straight with neutral head positioning and the arms next to body with the elbows bent at 90° to determine the value of the 0° angle in the cervical joint. The cervical ROM changes were recorded at a sampling frequency of 200 Hz. Positive values of the angle depending on the joint and axis corresponded to flexion, left side-bending, and right rotation at each plane.

Photographic Measurements. A webcam was mounted on a tripod at a 3-m distance from each participant and aligned to the cervical level and perpendicular to the ground during image recording. To reduce the potential errors presented by the participants' positioning, participants were seated on a mark placed on the floor. Each was instructed to maintain a straight trunk and a natural head and neck position by looking at a mark positioned 2 m in front of them at eye level. During the data collection of cervical spine movements of flexion and extension, side-bending, and rotation at each specific angle, recorded video images were captured and processed using the ImageJ program, version 1.43 (National Institutes of Health, Bethesda, Maryland) to measure the joint angle, in degrees, between 2 lines as Figure 1.[15] The cervical spine movements of flexion and extension were calculated by the intersection of a line that ran parallel to the base of the nares and another line that ran through the angle of the horizontal line though the middle of the tragus. The cervical spine movements of side-bending were calculated as the intersection of a line that ran through parallel to an imaginary line between the participant's acromion process and another line that aligned with the tip of the participant's nose. The cervical spine movements of rotation were calculated as the intersection of a line that ran parallel to a line between the participant's acromion processes and another line that aligned with the participant's nose.

Procedure. A primary researcher, a physical therapist with 13 years of experience, had a familiarization period with each participant for 5 minutes to achieve acute measurements of the cervical joint motions before the data collection. For cervical flexion and extension, the researcher stood at the participant's side and placed the axis of the goniometer over the external acoustic meatus. The fixed arm was held vertically while the moving arm was aligned with the base of the nares. Their cervical joint was passively positioned into flexion angles (0°, 30°, and 50°) and extension angles (30°, 50°). For cervical side flexion, the researcher stood in front of the participant with the axis

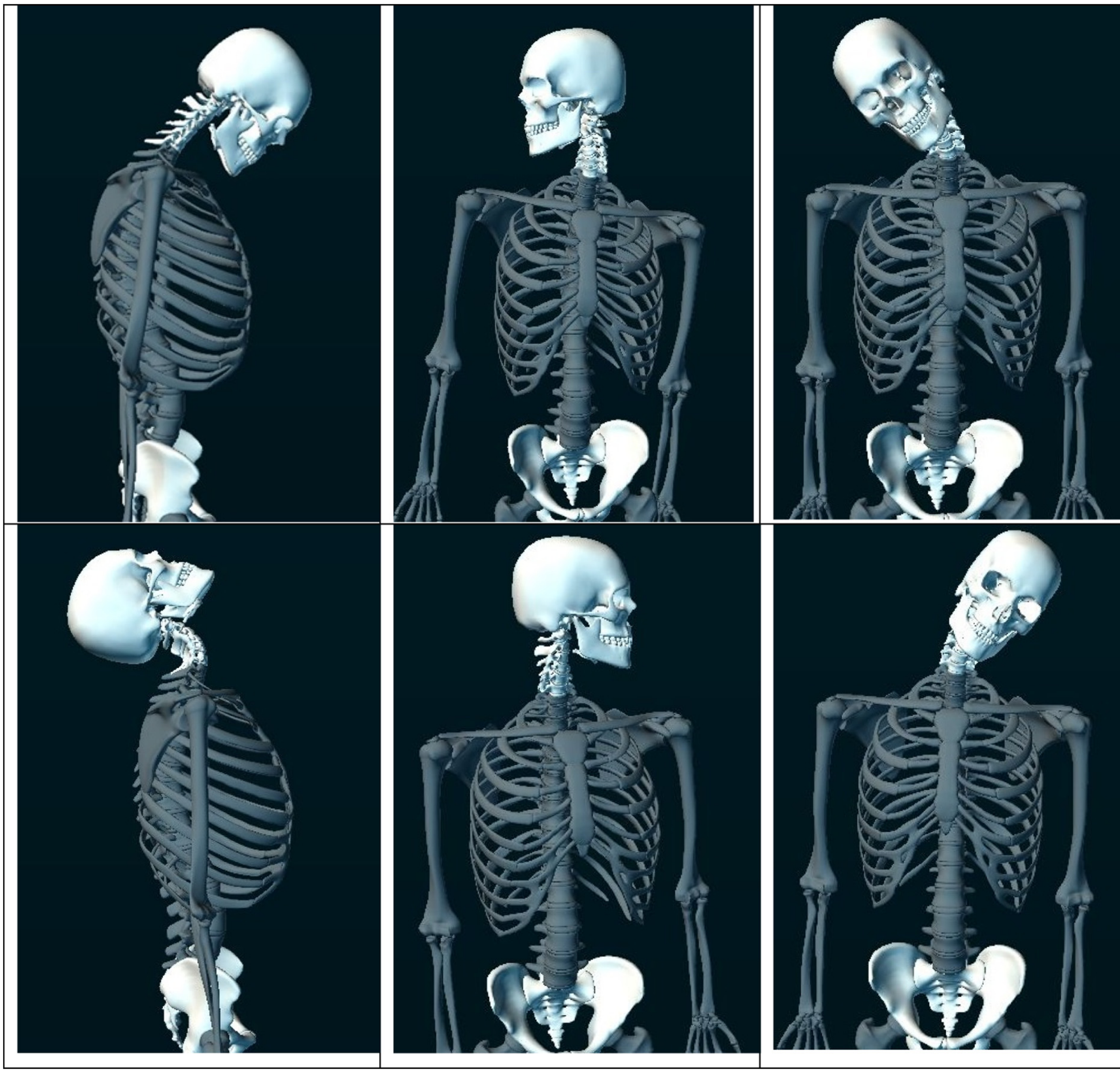

Fig 1. *A MyoMotion 3-dimensional angular measurement system.*

of the goniometer placed over the center of the participant's sternal notch, the fixed arm aligned parallel to an imaginary line between the participant's acromion process, and the movable arm aligned with the tip of the participant's nose. Their cervical joint was then passively positioned into right side-bending (0°, 20°, and 40°) and left side-bending (20°, 40°). For cervical rotation, the researcher stood behind the participant and looked down at the top of the head. The goniometer was centered on the vertex of the participant's head, the fixed arm aligned parallel to a line between the participant's acromion processes, and the moving arm aligned with the participant's nose. Their cervical joint was passively positioned at 0° of rotation, 45° of right rotation, and 45° of left rotation. The maximum angle at each plane was determined in a pilot study to minimize the compensatory movements associated with cervical joint motion.

Kinematic data of the cervical joints were simultaneously obtained using the IMU 3D angular measurement and photographic measurement during cervical flexion and extension, side-bending, and rotation in a random order. This measurement was repeated 3×, and the mean values were used to reduce the measurement errors. After a 10-minute rest, a second measurement session was practiced to calculate test–retest reliability. Therefore, a direct comparison could be completed between the IMU and the goniometer measurement and between the IMU and the photographic measurement in each individual participant.

Table 1. *Test–Retest Reliability Results of the MyoMotion for Measuring Shoulder Angle*

Plane	Position	ICC	Mean	SEM	MDC
Sagittal	Flexion 0°	0.75	2.43	0.51	1.41
	Flexion 30°	0.92	27.25	1.35	3.74
	Flexion 50°	0.99	44.89	1.35	3.74
	Extension 30°	0.63	–27.45	1.18	3.27
	Extension 50°	0.97	-45.59	1.36	3.77
Frontal	Side-bending 0°	0.83	–1.54	0.48	1.33
	Right side-bending 20°	0.81	–21.38	1.25	3.46
	Right side-bending 40°	0.95	–32.38	1.47	4.07
	Left side-bending 20°	0.79	18.83	1.57	4.35
	Left side-bending 40°	0.99	31.05	1.78	4.93
Transverse	ROT 0°	0.92	0.95	0.56	1.55
	Right rotation 45°	0.97	39.23	0.75	2.08
	Left rotation 45°	0.98	–45.07	1.12	3.10

ICC, intraclass correlation coefficient; *MDC*, minimal detectable change; *ROT*, rotation; *SEM*, standard error of the measure.

Statistical Analysis

Test–Retest Reliability. Test–retest reliability was assessed using the corresponding intraclass correlation coefficient (ICC) (3,2) of the IMU 3D angular measurement of cervical ROM. This ICC was selected because it enabled the concurrent evaluation of inter- and intrasession variability. The inter- and intrasession reliability would be analyzed independently only when the ICC value was small.[16] In determination of the level of reliability, the ICC (3,2) values were defined as poor when <0.69, fair for values of 0.70 to 0.79, good for values of 0.80 to 0.89, and high for values of 0.90 to 0.99. The standard error of measurement (SEM) and the minimal detectable change (MDC) were investigated to find absolute reliability. The SEM was well defined as standard deviation multiplied by the square root of the ICC subtracted from 1, whereas the MDC was calculated by multiplying the SEM by the square root of 2.[17,18]

Concurrent Validity. Concurrent validity between the 2 systems was analyzed using their 95% CIs and Bland-Altman plots. The 95% limits of agreement (LOA) between the IMU 3D angular measurement and the other 2 measurement methods were compared for the cervical ROM.[17] This was achieved by investigating the difference between the goniometer and the IMU 3D angular measurements and between the IMU 3D angular measurements and the photographic measurements against their means and calculating the systematic bias ± random error, such as 95% LOA.[19] The 95% LOA were defined as the mean difference ± 1.96 SD of the difference, so that 95% of differences ranged within these limits. If the 95% LOA were greater than ±5°, the differences between measurement methods were considered clinically significant.[19] All statistical analyses were performed using SPSS Statistics software 23 (IBM Corp, Armonk, New York).

Results

Test–Retest Reliability

The test–retest reliabilities of the IMU 3D angular measurement for cervical ROM assessment are described in Table 1 with ICC, SEM, and MDC. In the sagittal plane, the MyoMotion system had fair to high relative reliability for measuring cervical ROM with ICC (3,2) values, except cervical extension at 30°, which showed poor relative reliability. In the frontal plane, the MyoMotion system had fair to high relative reliability for the measurement of cervical side-bending to either side. In the transverse plane, the MyoMotion system had high relative reliability for the measurement of cervical rotation with ICC (3,2) values. Relatively small SEM and MDC values were reported for all cervical positions from the 3 planes.

Concurrent Validity

Table 2 shows the 95% LOA between the MyoMotion system and the goniometer and the 95% LOA between the MyoMotion system and the photo method. The MyoMotion

Table 2. *95% Limits of Agreement Between Measurements of Shoulder Joint Angle Obtained Using the IMU, Goniometer, and Photo Methods*

		MyoMotion vs Goniometer		MyoMotion vs Photo	
Plane	Position	Mean Bias	95% LOA	Mean Bias	95% LOA
Sagittal	Flexion 0°	2.43	1.39 to 3.48	-3.24	-4.58 to -1.89
	Flexion 30°	-2.60	-5.25 to -0.07	-3.94	-7.36 to -0.52
	Flexion 50°	-4.85	-7.40 to -2.30	-7.43	-11.63 to -3.23
	Extension 30°	2.0	-0.43 to 4.51	3.40	1.51 to 5.29
	Extension 50°	4.15	1.46 to 6.85	4.88	2.72 to 7.05
Frontal	Side-bending 0°	-1.70	-2.65 to -0.76	-3.70	-4.76 to -2.65
	Right side-bending 20°	-2.62	-4.47 to -0.78	-2.96	-5.14 to -0.78
	Right side-bending 40°	5.9	4.16 to 7.66	1.83	-1.36 to 5.02
	Left side-bending 20°	1.02	-1.13 to 3.18	-2.46	-4.72 to -0.20
	Left side-bending 40°	-6.63	-8.11 to -5.15	-1.95	-3.93 to 0.04
Transverse	Rotation 0°	0.95	-0.17 to 2.08	-2.46	-3.67 to -1.25
	Right rotation 45°	-5.77	-7.27 to -4.26	-4.70	-7.25 to -2.15
	Left rotation 45°	-0.07	-2.30 to 2.17	2.21	0.09 to 4.33

IMU, inertial measurement unit; *LOA*, limits of agreement.

system measurements in the cervical ROM were accurate (the 95% LOA for the discrepancy between the measurements were within ±5°) and matched those of the goniometer or the photo method.[20] However, cervical right side-bending at 40°, left side-bending at 40°, and right rotation at 45° between the MyoMotion and the goniometer presented significantly different angles (the 95% LOA for the discrepancy between systems exceeded ±10°). Cervical flexion of 50° between the MyoMotion and the photo method presented significantly different angles (the 95% LOA for the discrepancy between systems exceeded ±10°). The mean bias between the MyoMotion and other 2 methods at the end range of each plane tended to be larger.

Discussion

This study reports the reliability and validity of an IMU 3D angular measurement system for evaluating cervical ROM. The MyoMotion system had fair to high test–retest reliability for measuring cervical ROM in most positions with relatively small SEM and MDC values. The MyoMotion system measurements were relatively accurate compared with the goniometer and photo method measurements.

The IMU 3D angular measurement had fair to high relative reliability in the sagittal plane and side-bending to either side except cervical extension at 30°, which showed poor relative reliability. Only 1 previous study reported the reliability for measuring cervical ROM with IMU sensors in 12 participants.[11] The study reported that the ICC values were good in cervical flexion and extension (ICC, 0.89) and cervical side-bending (ICC, 0.88). This reliability level was comparable to other methodologies used to quantify cervical spine flexion and extension and side-bending with using an electromagnetic and optical motion analysis system.[21-23] During the measurement of cervical rotation, the MyoMotion system had high relative reliability and was more reliable than other planes. Theobald et al[11] also reported high reliability (ICC, 0.98) compared with cervical flexion and extension and side-bending. In addition, relatively small SEM and MDC values were reported for all cervical positions from the 3 planes. This result indicates decent absolute reliability.[11] Consequently, we found that the IMU 3D angular measurement in the cervical ROM was mostly good to highly reliable and could be considered an accurate measurement tool.

The IMU 3D angular measurements of cervical ROM were accurately matched with those of the goniometer and photo method. The mean bias between these measurements was mainly <5°. Although no previous study investigated the validity of IMU 3D angular measurements for the cervical joints, a study comparing the cervical ROM device and Vicon measurement reported a –1.0° to 10.9° mean difference.[24] Also, the other study using advanced technology such as electromagnetic motion analysis of the cervical joint presented similar mean differences (2.2° ± 4.2°).[8] When the 95% LOA for the discrepancy between the goniometer or the photo method measurements was within ±5°, it was considered a valid measurement tool in the clinical environment.[20] Therefore, the IMU 3D angular measurement in the cervical spine could be considered a valid measurement tool.

However, the mean bias between the IMU 3D angular measurement and goniometer in cervical right side-bending at 40°, left side-bending at 40°, and right rotation at 45° and between the IMU 3D angular measurement and the photo method in cervical flexion at 50° presented significantly different angles (the 95% LOA for the discrepancy between systems exceeded ±10°). Inokuchi et al[24] claimed that the validity of the measurement would be inaccurate when the 95% LOA for the discrepancy between systems exceeded ± 10°. This finding implies that the mean bias between the IMU 3D angular measurement and the other 2 methods at the end range of each plane tended to be greater. Consequently, evaluators should consider that the validity of the IMU 3D angular measurement may decline at the end range of each plane.

Limitations

The limitation of our study was its predominance of young female participants. A previous study reported sex-based differences in cervical joint angle measurements on radiographs. Therefore, generalization to groups of male patients should be performed with caution. Also, the applicability of these results to patients with neck disorders or children and seniors may be limited because the study population consisted of healthy and cooperative young volunteers. Also, there is a possibility that the power of the research was not enough owing to the small sample size. Finally, in our study, the reliability at the end of the movement of the neck was relatively poorer. Although the investigator instructed the participant not to move the trunk, there is also a possibility that the compensation movement of the trunk joints may not be fully controlled. Therefore, further studies should consider a larger and more diverse population, including patients with other neurological disorders.

Conclusion

The IMU 3D angular measurement in the cervical ROM was mostly good to highly reliable and could be considered a valid measurement tool. However, the validity of using the IMU 3D angular measurement would be reduced at the end range of each plane. Therefore, using the IMU 3D angular measurement of cervical ROM is recommend owing to its high reliability and validity, with careful consideration at the end of ROM in each plane.

Funding Sources and Conflicts of Interest

No funding sources or conflicts of interest were reported for this study.

Contributorship Information

Concept development (provided idea for the research): T.-L.Y., H.-N.K., J.-H.M.
Design (planned the methods to generate the results): T.-L.Y., H.-N.K., J.-H.M.
Supervision (provided oversight, responsible for organization and implementation, writing of the manuscript): T.-L.Y., H.-N.K., J.-H.M.
Data collection/processing (responsible for experiments, patient management, organization, or reporting data): T.-L.Y., H.-N.K., J.-H.M.
Analysis/interpretation (responsible for statistical analysis, evaluation, and presentation of the results): T.-L.Y., H.-N.K., J.-H.M.
Literature search (performed the literature search): T.-L.Y., H.-N.K., J.-H.M.
Writing (responsible for writing a substantive part of the manuscript): T.-L.Y., H.-N.K., J.-H.M.
Critical review (revised manuscript for intellectual content, this does not relate to spelling and grammar checking): T.-L.Y., H.-N.K., J.-H.M.

Practical Applications

- The IMU–based 3D angular measurement of cervical ROM has fair to high reliability and accuracy and ease of use.
- The IMU–based 3D angular measurement system is recommended to evaluate the cervical range of motion of dental hygienists in clinical practice.
- Furthermore, the inertial measurement unit–based 3D angular measurement system may be useful to evaluate and modify the cervical ROM of various occupations.

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