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ORIGINAL RESEARCH

Validity of Inertial Measurement Unit (IMU Sensor) for Measurement of Cervical Spine Motion, Compared with Eight Optoelectronic 3D Cameras Under Spinal Immobilization Devices

Wijittra Liengswangwong[1], Natcha Lertviboonluk[1], Chaiyaporn Yuksen[1], Parunchaya Jamkrajang[2], Weerawat Limroongreungrat[2], Atipong Mongkolpichayaruk[2], Chetsadakon Jenpanitpong[1], Sorawich Watcharakitpaisan[1], Chantarat Palee[1], Picharee Reechaipichitkool[1], Suchada Thaipasong[1]

[1]Department of Emergency Medicine, Faculty of Medicine, Ramathibodi Hospital, Mahidol University, Bangkok, Thailand; [2]College of Sports Science and Technology, Mahidol University, Nakhon Pathom, Thailand

Correspondence: Chaiyaporn Yuksen, Department of Emergency Medicine, Faculty of medicine, Ramathibodi Hospital, Mahidol University, 270 Rama VI Road, Thung Phaya Thai, Bangkok, Ratchathewi, 10400, Thailand, Email chaipool0634@hotmail.com

Background: The assessment of cervical spine motion is critical for out-of-hospital patients who suffer traumatic spinal cord injuries, given the profound implications such injuries have on individual well-being and broader public health concerns. 3D Optoelectronic systems (BTS SmartDX) are standard devices for motion measurement, but their price, complexity, and size prevent them from being used outside of designated laboratories. This study was designed to evaluate the accuracy and reliability of an inertial measurement unit (IMU) in gauging cervical spine motion among healthy volunteers, using a 3D optoelectronic motion capture system as a reference.

Methods: Twelve healthy volunteers participated in the study. They underwent lifting, transferring, and tilting simulations using a long spinal board, a Sked stretcher, and a vacuum mattress. During these simulations, cervical spine angular movements—including flexion-extension, axial rotation, and lateral flexion—were concurrently measured using the IMU and an optoelectronic device. We employed the Wilcoxon signed-rank test and the Bland-Altman plot to assess reliability and validity.

Results: A single statistically significant difference was observed between the two devices in the flexion-extension plane. The mean differences across all angular planes ranged from −1.129° to 1.053°, with the most pronounced difference noted in the lateral flexion plane. Ninety-five percent of the angular motion disparities ascertained by the SmartDX and IMU were less than 7.873° for the lateral flexion plane, 11.143° for the flexion-extension plane, and 25.382° for the axial rotation plane.

Conclusion: The IMU device exhibited robust validity when assessing the angular motion of the cervical spine in the axial rotation plane and demonstrated commendable validity in both the lateral flexion and flexion-extension planes.

Keywords: reliability, validity, inertial measurement unit, SmartDX, cervical spine angular motion

Introduction

The cervical spine is the most frequently afflicted segment within spinal column injuries, often giving rise to potential spinal cord impairments.[1,2] Notably, a significant proportion, twenty-five percent to be precise, of spinal cord injuries trace their origins to the adverse consequences associated with inadequately conducted out-of-hospital patient transport or medical procedures;[3] moreover, it is related to blunt injuries[4] and traffic accidents. The consequences of traumatic spinal cord injuries extend their repercussions beyond individual realms, engendering impacts on personal and societal health. This impact manifests in diverse dimensions, encompassing physical and psychological well-being, elevated

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susceptibility to mortality, compromised social welfare, and the imposition of significant financial burdens upon healthcare systems.[5,6] Thus, cervical spine motion detection is essential for out-of-hospital patient transport monitoring.[7]

Nowadays, various types of motion capture sensors are available, exemplified by the likes of 3D motion capture sensors (Vicon), optoelectronic systems (BTS SmartDX), and goniometer sensors. All are acknowledged as the quintessential benchmarks in motion measurement.[1–6] Nonetheless, the utilization of these devices faces inherent challenges attributed to their cost, complexity, and dimensions, which collectively constrain their utility beyond the controlled laboratory milieu, particularly within the context of out-of-hospital scenarios.[3,4,6,8–10] Consequently, the demand for portable, cost-effective, and user-friendly alternatives becomes apparent. Devices such as smartphones, smartwatches, or inertial measurement unit (IMU) sensors emerge as more fitting choices for clinical application, surpassing the conventional standards set by established devices.[2,3,11–13]

IMU was a gold-standard methodology, and it has proven that this cutting-edge technology can accurately evaluate human spine posture during gait.[14] Inertial sensors have proven to be a non-invasive and effective tool for assessing spine posture, offering significant benefits for clinical use. A novel procedure has also been introduced to create a subject-specific spine multibody model for computational simulations using different types of 3D orientation sensors.[15]

The study of Hage R et al[9] evaluates the accuracy of a portable IMU known as DYSKIMOT. This evaluation encompassed a comparative analysis of its measurement of head rotational kinematics with that of the esteemed gold standard optoelectronic system (Elite, BTS). The IMU has relatively high accuracy. Furthermore, the study of Mjøsund HL et al,[16] which studies the accuracy of an IMU (ViMove) in measuring lumbar inclination motion compared with a reference standard laboratory 3D analysis system (Vicon), concluded that the IMU's accuracy is acceptable However, based on the abovementioned studies, there is a lack of prior studies on the accuracy of portable measurement units compared to 3D optoelectronic systems for cervical spine motion measurement.

The long spinal board (LSB), Sked stretcher, and vacuum mattress are popular and safe devices used for the transportation of emergency patients outside the hospital.[2,13] They are particularly effective in immobilizing the cervical spine. However, each device has distinct indications for use. The LSB and vacuum mattress are suitable for transporting trauma patients in routine out-of-hospital emergency situations.[17,18] In contrast, the Sked stretcher is ideal for moving emergency patients in specific scenarios, such as confined spaces, narrow areas, or steep slopes.[2]

The primary objective of this study was to investigate the accuracy and reliability of an IMU for measuring cervical spine motion in healthy volunteers compared to a 3D optoelectronic motion capture system (BTS bioengineering Smart DX 5000, Italy).

Methods

Study Design and Setting

This study was conducted as a method-oriented experimental study employing a cross-over design, and was conducted from April 6, 2022, to May 25, 2022.[2]

The principal focus of this study encompassed the evaluation of the accuracy and reliability of an IMU compared to a 3D optoelectronic motion capture system. This evaluation specifically centered upon the quantification of angular motions within the cervical spine, spanning the domains of flexion-extension, axial rotation, and lateral flexion. These measurements were contemporaneously conducted during three distinct activities: lifting, transferring, and tilting patients at a 90-degree angle.

The experimental procedure was executed through the implementation of a randomized crossover design, whereby each participant was randomly allocated to one of three distinct sequences: the LSB, Sked stretcher, and vacuum mattress configurations. Each sequence featured the involvement of a total of four participants.

To recruit volunteers, invitation posters were strategically displayed across the university campus. Interested individuals who expressed willingness were subsequently coordinated for scheduled appointments, allowing them to actively engage in the study.

The Institutional Review Board of the Faculty of Medicine at Ramathibodi Hospital granted ethical approval for this experimental investigation, and the approval code is COA MURA2022/180. Each participant in the study provided written informed consent, aligning with the ethical principles governing research involving human subjects, as outlined in the Declaration of Helsinki.

Participants

The study's criteria for inclusion encompassed adult volunteers aged between 18 and 60 years, falling within a height range spanning from 150 to 190 cm. Individuals presenting with pre-existing spinal deformities, including scoliosis, kyphosis, flatback syndrome, chin-on-chest syndrome, or a history of prior spine injury, as well as those classified as obese (with a BMI equal to or exceeding 30 kg/m²), were systematically excluded from participation. All eligible Participants were secured with a cervical collar to ensure head immobilization. Subsequently, both an IMU and optoelectronics markers were affixed to them. These individuals were then randomly assigned to one of the three instruments above for the study.

Twelve participants were enrolled in the present study, comprising 5 females and 7 males. Their demographic details are as follows: age, 20.50 ± 3.03 years; weight, 59.83 ± 8.90 kg; height, 168.50 ± 7.78 cm; and BMI, 21.01 ± 2.15 kg/m². None of the participants had conditions related to the cervical spine. These details are further elaborated in Table 1.

Data Gathering

Our study recorded various variables from all participants who met the eligibility criteria. These variables included baseline characteristics such as age, gender, Body Mass Index (BMI), height, and weight. We also documented medical comorbidities and prior medical histories, including diabetes mellitus, dyslipidemia, asthma, allergic rhinitis, previous surgical procedures, and past trauma. Furthermore, we assessed angular motions, specifically lateral flexion, flexion extension, and axial rotation, using two sensors simultaneously: the IMU and optoelectronics markers. These motions were recorded during patients' lifting, transferring, and tilting using the LSB, Sked stretcher, and vacuum mattress (Figure 1).

Motion Capturing and Analysis

Before proceeding with the validity and reliability analysis, we obtained angular motions of the cervical spine across all three planes: lateral flexion, flexion extension, and axial rotation, using both sensors. Optoelectronics reflective markers were attached to the middle of the volunteer's forehead, the sternal notch, and between the lowest ribs. For the first two marker positions (specifically, the middle of the forehead and the sternal notch), IMUs were also affixed to capture angular motions simultaneously.

Table 1 Characteristics of the Volunteers. Data are Presented as Mean ± SD or N (%)

Characteristics	Total (N = 12)
Gender (Male)	7 (58.33%)
Age (year)	20.50 ± 3.03
Weight (Kg)	59.83 ± 8.90
Height (cm)	168.50 ± 7.78
BMI (Kg/m^2)	21.01 ± 2.15
Underlying disease	1 (8.33%)
Prior surgery history	2 (16.67%)
Prior trauma history	1 (8.33%)

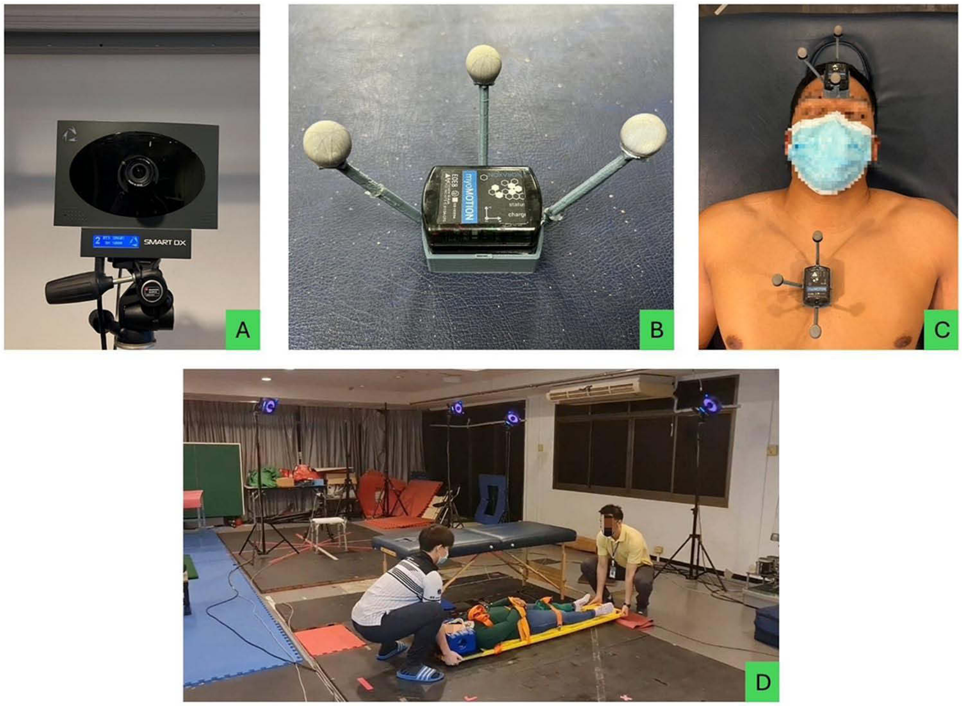

Figure 1 The optoelectronic camera (**A**), optoelectronic markers affixed to the IMU (**B**), sensors attached to the volunteer's body (**C**), and the laboratory's capture field during motion recording (**D**).

Our randomization method employed a block of three randomizations using a crossover design, encompassing the three instruments: LSB, Sked stretcher, and vacuum mattress. We ensured the randomized sequence was concealed using SNOSE (Sequentially numbered, opaque, sealed envelopes). Participant assignments encompassed lifting, transferring, and tilting a volunteer with all three randomized instruments. Angular motions were then meticulously analyzed during these three activities.

During the procedure, four individuals took positions at each corner of the transportation equipment, orienting themselves to face it directly. With feet positioned shoulder-width apart, each individual bent their knees and maintained an erect spinal posture to ensure proper biomechanics for lifting. A power grip was employed by each participant, using both hands to secure the instrument firmly. A designated team leader orchestrated the entire process, using verbal cues to synchronize the team's movements and ensure simultaneous action.

All participants elevated the equipment in unison for the lifting phase, leveraging power predominantly from their legs and ensuring their backs remained straight. Subsequently, during the transfer phase, participants moved cohesively for a distance of 2 meters, maintaining the equipment's level and balance. Upon reaching the designated position, the team leader issued another verbal cue, prompting the team to use a controlled knee-bending technique to lower the equipment to the floor. Lastly, during the tilting phase, two team members worked harmoniously to tilt the equipment to a precise 90-degree angle.

Outcome Measurement and Statistical Analysis

Our primary objective was to ascertain the validity of angular motion measurements of the cervical spine across three planes (lateral flexion, flexion extension, and rotation) when using the IMU compared to the optoelectronic sensor. Categorical data were presented through frequency and percentage, while numerical data were depicted using the mean and standard deviation. We employed STATA version 16.0 to analyze both validity and reliability, utilizing the Bland-Altman plot methodology.

The sample size determination was informed by the study conducted by Bolink SA et al,[8] which examined the validity of an IMU in assessing pelvic orientation angles during gait, sit-to-stand transfers, and step-up transfers using an optoelectronic motion capture system as a comparison. Based on our calculations, a sample size of 8 was deemed necessary to ensure with 95% confidence that the lower limit of a two-sided 80% confidence interval would exceed the non-inferiority margin. The total sample size was twelve.

Table 2 Cervical Angular Motion Across Three Planes, as Measured by the SmartDX and the IMU Device, Was Compared Using the Wilcoxon Signed-Rank Test

Angle Planes	SmartDX	IMU	P-value
Lateral Flexion Median (IQR)	6.5 (4.65–10.65)	8.59 ± 4.27	0.11
Flexion-Extension Median (IQR)	8 (5.75–12.75)	7.67 (6.00–11.41)	0.02
Axial Rotation Median (IQR)	14.45 (8.38–85.39)	12.67 (8.66–82.31)	0.37

Result

We employed the Wilcoxon signed-rank test to compare the cervical angular motion across three planes (lateral flexion, flexion extension, and axial rotation) as measured by the SmartDX optoelectronic camera and the IMU sensors. These results are detailed in Table 2. The data did not exhibit a normal distribution. Notably, there were no statistically significant differences between the measurements from the two devices when assessing lateral flexion and axial rotation (with p-values of 0.11 and 0.37, respectively). However, a statistically significant difference was observed for the flexion-extension angular motion with a p-value of 0.02, indicating a significant difference at an alpha level of 0.05.

The Bland-Altman plots depict the differential measurements of cervical spine angular motion captured by the SmartDX and the IMU device across each plane. These differences were mainly within the 95% limits of agreement (1.96×SD), although some outliers were observed (as shown in Figures 2–4). The mean discrepancies across all angular planes ranged from −1.13 to 1.05 degrees, with the most pronounced difference observed in the lateral flexion plane. The limits of agreement (LOA) indicate that 95% of the angular motion discrepancies between SmartDX and IMU measurements were less than 7.87 degrees for the lateral flexion plane, 11.14 degrees for the flexion-extension plane, and 25.38 degrees for the axial rotation plane.

We employed the paired *t*-test and the Wilcoxon signed-rank test to compare cervical angular motions measured by the SmartDX optoelectronic camera and the IMU sensors. This data was further analyzed based on the specific lifting and moving instrument and the activity undertaken, as detailed in Table 3. With the LSB, statistically significant differences

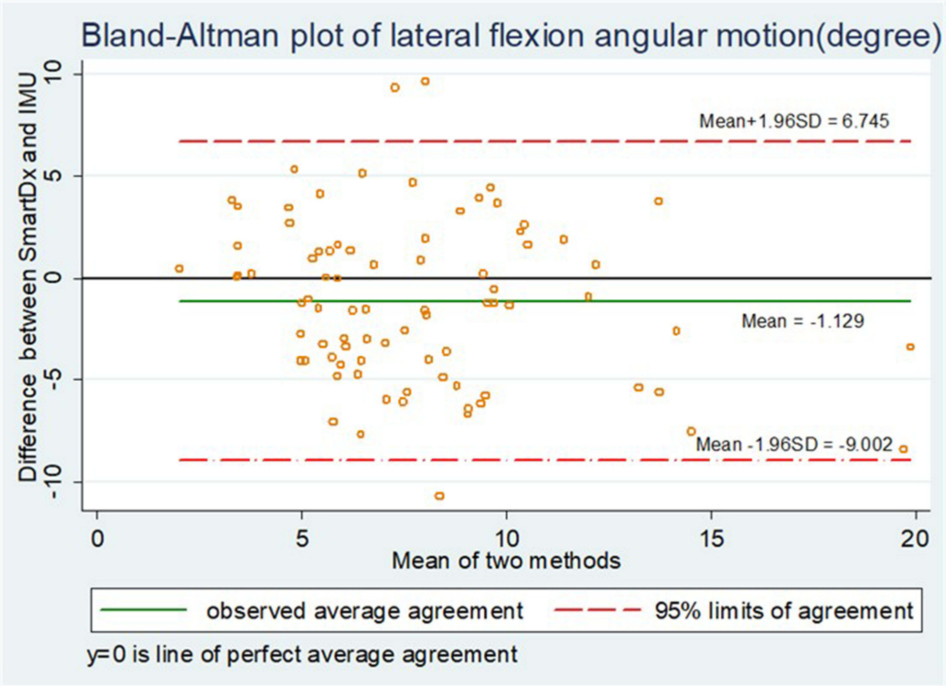

Figure 2 Bland-Altman plots of cervical spine angular motion measurement of lateral flexion.

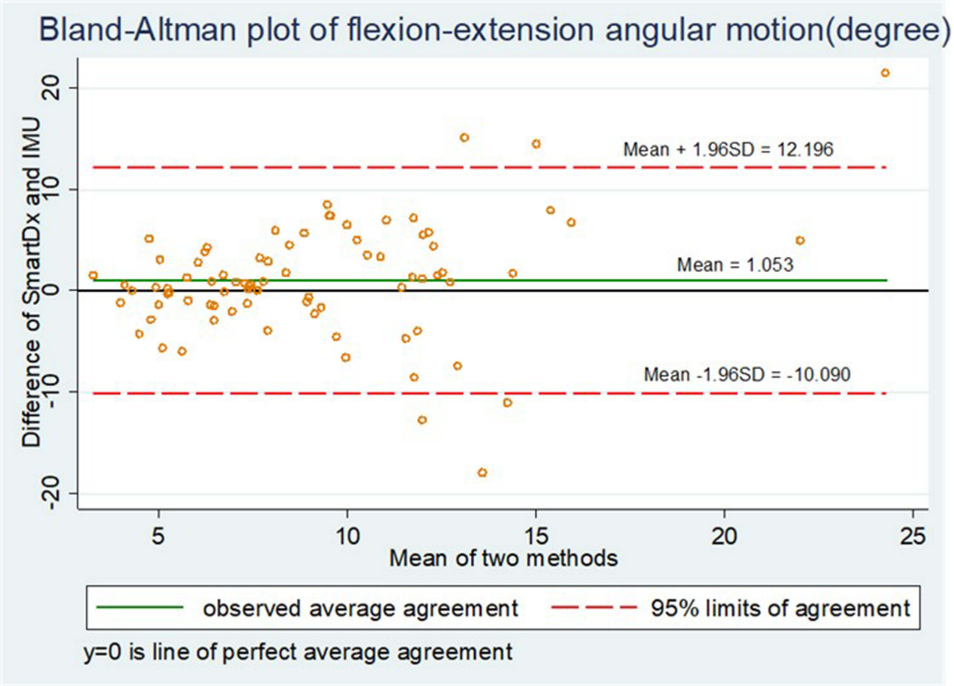

Figure 3 Bland-Altman plots of cervical spine angular motion measurement of flexion-extension.

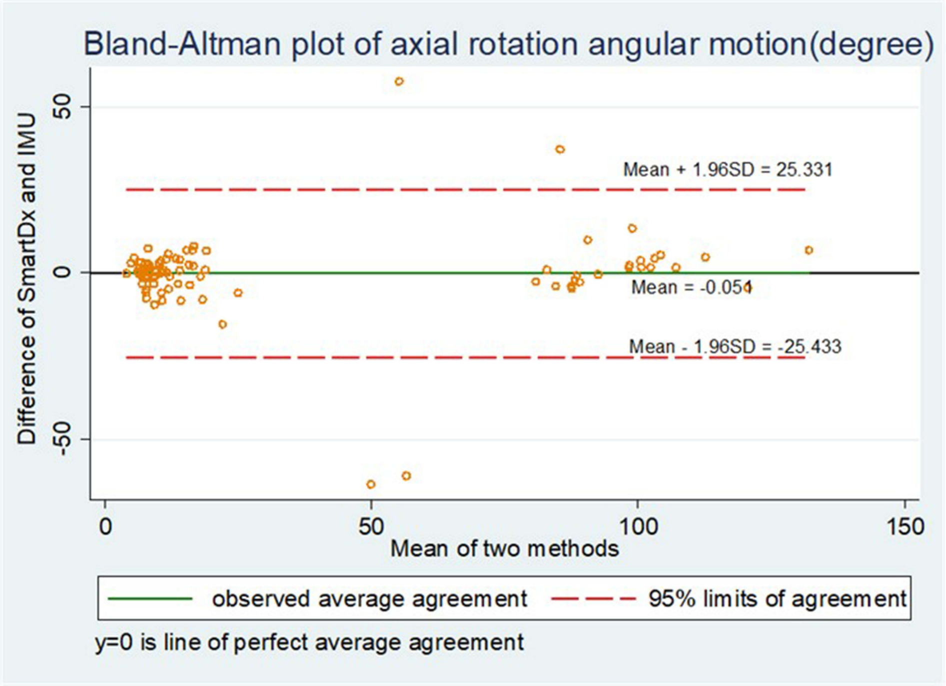

Figure 4 Bland-Altman plots of cervical spine angular motion measurement of axial rotation.

were observed in the lateral flexion plane during the lifting and transferring of the volunteers and in the flexion-extension plane during lifting. When using the Sked stretcher, significant differences were noted in the flexion-extension plane during lifting and the lateral flexion plane during the transfer of the volunteers. With the vacuum mattress, significant discrepancies were evident in both the lateral flexion and axial rotation planes during the transfer activities.

Table 3 Cervical Angular Motion Across Three Lifting and Moving Instruments, as Recorded by the SmartDX and the IMU Device, Was Compared Using Either the Paired *t*-Test or the Wilcoxon Signed-Rank Test

	Activities	Angle Planes	SmartDX		IMU		P-value
			N	(Mean ± SD Or Median (IQR))	N	(Mean ± SD Or Median (IQR))	
Long Spinal Board	Lifting	Lateral Flexion	12	6.34±3.00	12	3.19(1.98–5.48)	0.02
		Flexion-Extension		9.70±3.72		7.93±2.64	0.03
		Axial Rotation		9.63±3.49		6.67(4.55–10.94)	0.07
	Transferring	Lateral Flexion		5.60±2.49		8.14±2.53	0.03
		Flexion-Extension		7.3(2.63–10.7)		6.39±2.08	0.48
		Axial Rotation		9.59±4.52		9.28±2.34	0.77
	Tilting	Lateral Flexion		10.55(8.65–10.55)		9.83±4.11	0.24
		Flexion-Extension		6.65(5.23–10.94)		6.83(4.54–11.99)	0.65
		Axial Rotation		89.89±34.35		97.19±18.38	0.43
SKED	Lifting	Lateral Flexion		5.46(3.6–6.86)		7.73±2.80	0.11
		Flexion-Extension		11.17±4.09		8.49±3.33	0.01
		Axial Rotation		9.63(7.2–17.06)		12.43±4.64	0.77
	Transferring	Lateral Flexion		5.83±1.80		9.35±1.78	0.002
		Flexion-Extension		10.52±4.21		9.18±2.51	0.19
		Axial Rotation		9.8(6.5–10.9)		11.26±4.05	0.26
	Tilting	Lateral Flexion		12.28±4.08		14.12±6.70	0.52
		Flexion-Extension		5.6(5.05–7.5)		17.21(13.25–21.42)	0.24
		Axial Rotation		86.30±7.73		78.53±20.64	0.35
Vacuum Mattress	Lifting	Lateral Flexion		6.38(4.77–10.07)		6.19±2.81	0.07
		Flexion-Extension		11.33(9.17–14.75)		10.64±(4.82)	0.22
		Axial Rotation		13.04±4.98		15.54±7.77	0.11
	Transferring	Lateral Flexion		4.43(4.4–6.23)		9.97±2.89	0.04
		Flexion-Extension		9.35(5.3–12.23)		7.20±2.08	0.09
		Axial Rotation		11.65±4.05		9.35±1.65	0.05
	Tilting	Lateral Flexion		8.57±3.48		9.58±3.71	0.29
		Flexion-Extension		7.15(5.9–8)		7.39(5.09–9.87)	0.77
		Axial Rotation		99.01±8.93		96.57±8.11	0.07

Discussion

In our study, the agreement between the IMU and optoelectronics across all three angular planes was found to be reasonably acceptable Notably, the concentration of degree differences in the axial rotation plane indicated that both measurement techniques exhibited comparable precision in gauging cervical spine angular motion. This suggests that the axial rotation was the most reliable plane of the three evaluated.

When analyzed using paired *t*-tests and the Wilcoxon signed-rank test, the axial rotation plane demonstrated the least significant difference, observable primarily when transferring volunteers using a vacuum mattress. These findings suggest that the IMU device may offer greater accuracy and reliability in measuring the axial rotation plane compared to the other two planes. However, caution is advised when interpreting the IMU measurements in the flexion-extension plane. Additionally, our study's outcomes indicate potential measurement errors of undetermined origin, either from the IMU or optoelectronics.

Mjøsund HL et al evaluated the inclination motion of the lumbar region in both the sagittal and coronal planes using ViMove (an IMU system) in comparison with Vicon (an optical measurement system). Their findings, based on the Root Mean Squared Error and the Bland-Altman plot, suggested that the agreement between these two measurement methods was clinically acceptable.[16]

The study results are consistent with other research, such as the study by English DJ et al, which examined cervical active range of motion (AROM) using IMU devices compared to standard devices. This study measured cervical spine movements in flexion, extension, rotation (right and left), and lateral flexion (right and left), and found no statistically significant differences in measurement accuracy between the IMU devices and the standard devices.[19]

The study by Zong-Rong Chen et al was conducted with 19 healthy volunteers. IMU devices were attached to the occiput, cervical spine, thoracic spine, sacrum, and right radius to record movements, which were then compared to standard devices. The study found that IMU devices had an accuracy greater than 86%, with sensitivities over 90% and specificities over 91%.[20] The study by Tae-Lim Yoon et al involved 33 healthy volunteers and compared IMU devices with standard devices for measuring cervical spine movements in flexion, extension, side-bending, and rotation. The study found that IMUs demonstrated high reliability and reasonable validity, recommending them as standard devices for measuring cervical spine movements.[21]

Additionally, several studies have compared the use of IMU devices with standard devices for measuring torso and pelvis movements, demonstrating that IMUs are highly accurate.[22,23] A systematic review comparing the use of Inertial Measurement Units (IMUs) with standard devices, such as optoelectronic motion capture systems, found that IMUs provide accuracy and consistency in measuring lumbar spine movements comparable to those of standard devices.[24]

Foremost, the significant benefits of cost-effective portable devices should not be overlooked, especially when juxtaposed with traditional laboratory systems. These devices demonstrate a performance that is often on par with, if not superior to, their more established counterparts. Furthermore, a distinguishing feature of these portable instruments is their inherent potential for ongoing refinement and technological advancement in the years to come.

Limitation

Our study exclusively evaluated healthy volunteers without any cervical spine-related conditions and was conducted in a controlled laboratory setting. A notable limitation is that the findings may not directly apply to patients with cervical spine conditions. Additionally, as per a reference study the placement of the attached markers may not represent the most reliable position due to potential postural changes in volunteers when placed in the immobilization devices.[1]

Conclusion

Our findings indicate that the IMU device exhibited substantial when measuring the angular motion of the cervical spine in the axial rotation plane. While the device demonstrated commendable validity in both lateral flexion and the flexion-extension plane, its reliability was suboptimal when evaluated on healthy volunteers without cervical spine conditions. Despite this shortcoming, the portability and cost-effectiveness of the IMU device underscores its potential for clinical application, especially in prehospital scenarios. However, practitioners should exercise prudence when relying on this economical tool for measurements in the flexion-extension plane. Continued research is warranted to elucidate further the IMU's proficiency in capturing intricate kinematics.

Disclosure

The authors report no conflicts of interest in this work.

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