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RESEARCH ARTICLE

Assessment of Spinal Motion in Young Adults (15 to 26 Years of Age) Without Spine Deformity Using Inertial Sensor and Manual Measurements

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ABSTRACT

Introduction: The evaluation of spinal range of motion is paramount in the context of spinal disorders, especially considering emerging surgical techniques focused on motion preservation and circumventing spinal fusion. Manual measurement techniques, which utilize a goniometer and tape measure, demand proficiency to accurately assess spinal motion. This becomes further complicated in patients with spinal deformities. Inertial sensors emerge as a potential clinical solution. By assessing electronic inertial sensor performance in capturing thoracolumbar spinal range of motion, this study evaluates the level of association observed between the range of motion measurements captured by manual and sensor methods.

Methods: Participants included 19 healthy young adults (74% female, average age 20 years [range 15-26]) without spinal conditions. Each performed a series of manual spinal motion evaluations quantified using a standard goniometer and a tape measure. Participants repeated the motions with an electronic inertial sensor attached to their C7 spinous process. Each manual and electronic motion sequence was performed three times. Data were analyzed with a Pearson's correlation to assess congruence between the datasets, and a paired t-test compared the mean values between the two groups to examine the two motion measurement methodologies.

Results: Association between the different planes of motion for manual and electronic repeated clinical motions were moderate ($r=0.44$) to strong ($r=0.70$). Manual measurements showed similar levels of variation to that of the electronic measurements. Upon comparing the manual and electronic measurement sets through a paired t-test, the mean values exhibited no statistically significant differences.

Conclusion: The electronic motion measurements were congruent with manual measurements based on the correlation values and t-tests presented. Thus, inertial sensors can approximate the measurements of manual methods in assessing spinal range of motion. This demonstrates the potential for clinical adaptation of these sensors into spine centers to objectively assess patient outcomes in spinal motion preserved surgeries.

Key Terms: Thoracolumbar spine, clinical range of motion, electronic inertial sensor, goniometer

1.0 Introduction

Thoracolumbar spinal range of motion (ROM) plays a pivotal role in diagnosing and monitoring various spinal conditions, ranging from scoliosis and degenerative disc disease to disc herniations. Essentially, any ailment impacting an individual's ROM can be examined using these metrics. This evaluation is vital, especially in outcome-based studies examining the perioperative ROM when contemplating surgeries that either rectify spinal conditions or alleviate pain from disc degeneration. Assessing ROM serves multiple purposes, from gauging a patient's quality of life[1] to determining their participation capabilities in sports activities.[2] Innovations in surgical approaches, such as Anterior Scoliosis Correction,[3] now emphasize preserving ROM by using a muscle sparing thoracotomy approach that builds upon the principles of Vertebral Body Tethering (VBT). This is an option for treatment of stabilizing scoliotic curves rather than fusing them. The efficacy of these novel techniques will be gauged using ROM measurements. Thus, there is a burgeoning demand for ROM devices amenable to clinical adaptation, emphasizing user-friendly data collection.[4]

Although X-rays can capture precise intersegmental spinal images, the overarching clinical significance rests in assessing the total trunk's ROM. Traditional methods like the goniometer[5] are employed for this purpose but possess inherent limitations, especially when compared to extremity joint measurements.[6] The spine's segmented nature requires a generalized trunk position estimation during goniometric assessments.[7] Parameters such as flexion, extension, lateral bending, and axial rotation, each depicting specific movement capabilities, provide invaluable insights into spinal health and subsequently inform clinical decision-making.

Flexion of the spine can be described as the ability of an individual to maximally bend forward above the level of their hips. Extension refers to the backward spinal movement above the level of the hips. Lateral bending refers to the bending of an individual directly downwards to their left and right with the pelvis remaining still. Axial rotation is a measure of spinal trunk rotation left and right occurring with the pelvis remaining still.[7] These parameters give insight into the health of the spine and are useful as an aid in making decisions about patient care.

The advent of electronic devices gives clinicians the opportunity of more streamlined ROM assessments. Optical scanning, for instance, captures trunk images during peak ROM, thereby quantifying movement.[8] Meanwhile, inertial sensors offer real-time 3-dimensional (3-D) motion tracking as patients do specific movements. Our study set out to present data on the mean, range, and standard deviation from both inertial sensors and clinical measurement devices to identify correlations between them and compare these with established norms for thoracolumbar spinal motion. This comparison aims to demonstrate the inertial sensor's viability in routine clinical procedures. By adopting such advanced tools, clinicians can achieve consistent measurements[7] that would complement other diagnostic modalities like radiographs. This would facilitate more informed decisions regarding surgical strategies to uphold or enhance patient mobility.

2.0 Materials and Methods

In this prospective study, we evaluated healthy volunteers without any spinal conditions. Prior to recruiting participants, we secured approval from our Institutional Review Board (IRB). The study encompassed a cohort of 19 participants, comprised of 14 women and 5 men. The subjects had a mean age of 20 years (range, 15 to 26 years). A single examiner, proficient in both manual and electronic trunk measurements, conducted all assessments to ensure uniformity across the study. The methodology for determining clinical ROM was rooted in the procedures outlined by Johnson and Mulcahey (2021).[5] Participants were instructed to flex their trunk maximally and comfortably in six directions: flexion, extension, left lateral bend, right lateral bend, left twist, and right twist. These motions were quantified using either a goniometer or a tape measure, as depicted in Figures 1-3. The anatomical landmarks of C7 to the posterior superior iliac spine (PSIS) represent the superior and inferior points of the thoracolumbar spine, respectively. Lateral bending and twisting angular measurements were conducted with a goniometer employing a standard technique. Initially, one arm of the goniometer was aligned with the participant's anatomical features (the moving arm), while the other arm stayed parallel to the ground (stationary arm). As the subjects rotated or bent their trunk, the other goniometer arm was adjusted correspondingly. This technique offers insights into the average propensity of the sampled population to achieve maximal anterior and posterior bending without flexion at the knees. This process is depicted in Figures 1 and 2.

Figure 1. Lateral Bending: The participant laterally flexes the spine, and the angle formed between the horizontal plane of the pelvis and the line extending to the C7 spinous process is quantified using a goniometer.

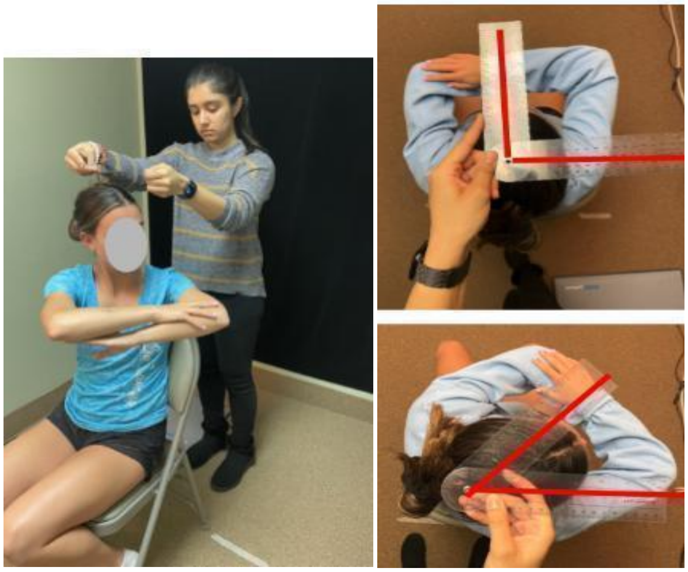

Figure 2. While seated, the participant rotates the trunk, squeezing their knees together to minimize excessive rotation. The goniometer quantifies the angle of rotation.

Using the Modified Schober test, we assessed the spinal flexion and extension with a flexible tape measure, as shown in Figure 3 and Figure 4.

Figure 3. The distance resulting from skin elongation between the posterior superior iliac spine (PSIS) and C7 landmarks is quantified.

Figure 4. The distance resulting from extension of the spine between the posterior superior iliac spine (PSIS) and C7 landmarks is shown. The flexible tape measure aligns with the curvature of the spine.

To accurately identify the C7 location, participants were instructed to lower their chin, allowing for palpation, to pinpoint the C7 site. A surgical marker was used to draw a horizontal line at C7 and between the PSIS landmarks for manual measurement. The span between the midpoint of the PSIS dimples and the C7 spinous process was quantified in a neutral standing posture, followed by measurements during flexion and extension. Alterations in this length, whether contraction or elongation, serve as indirect indicators of angular movement, attributed to the skin's adaptation over the spinous processes. This procedure was replicated twice more, ensuring a total of 3 measurement sets were acquired via both manual and electronic techniques for every directional motion.

The electronic inertial sensor, depicted in Figure 5, is a component of the Formetric surface topography system produced by DIERS International GmbH (Schlangenbad, Germany; www.DIERS.eu). Equipped with a skin adhesive property, these sensors firmly attach to the subject's posterior spine at the C7 spinous process. Communication between the sensor and the system's computer is facilitated through Bluetooth connectivity, permitting the documentation of spinal range of motion across 6 distinct directions. Subsequently, the same range of motion activities were executed and documented by the manual goniometer.

Figure 5. The inertial sensor used in this study (size: 4cm by 4cm).

2.1 Data Management - Statistical Analysis

Data for the inertial sensor measurements were initially recorded on the software and then manually entered in a protected and deidentified Microsoft Excel spreadsheet for analysis. Manual clinical range of motion data were recorded on individual handwritten sheets and then entered onto the same spreadsheet. Descriptive statistics were used to calculate the mean, range, and standard deviation of the planes of motions as recorded by the various methods outlined in this study. Each specific parameter for range of motion was measured 3 times. To calculate the means, all 57 trials, (19 participants x 3 trials x 1 rater) yielded the values shown in Tables 1-3 (see Results). These data were used to calculate a Pearson Product Moment Correlation Coefficient to critically assess the congruence between the two datasets. A paired student's t-test was utilized to compare the mean values derived from manual methods and electronic method. These findings are shown in Table 3. In this study the pairs are the mean value recorded by manual measurements (goniometer or tape measurer) paired with the electronic sensor measurements. For each subject, the standard deviation stemming from their 3 trials was computed, serving as a metric for the variability of the measurements.

3.0 Results

Tables 1-2 delineate the mean, range and standard deviation of spine motions obtained by manual and inertial sensors. Each of the 19 subjects assessed underwent the measurement process 3 times.

The presented range for each metric signifies the minimum and maximum values pertaining to overall spinal motion of the subjects evaluated. Table 1 shows the average total spinal movement as captured by the electronic sensor, whereas Table 2 shows the outcomes from manual evaluations. Table 3 compares the electronic sensor measurements and manual measurements side by side.

Table 1: Electronic Inertial Sensor Results (n=19)

Plane of Motion	Electronic Mean (SD)	Range
Forward Flexion	86.9° (7.7°)	54° - 114°
Extension	51.4° (5.7°)	24° - 108°
Lateral Bend Right	50.7° (5.6°)	20° - 75°
Lateral Bend Left	52.9° (5.3°)	26° - 80°
Axial Rotation Right	57.5° (5.1°)	42° - 86°
Axial Rotation Left	59.04° (5.5°)	32° - 78°

Table 2 summarizes the manual measurements done by a single rater across all subjects. The values are comparable to those seen in Table 1.

Table 2: Clinical Range of Motion Manual Measurements Using Flexible Tape Measure and Goniometer (n=19)

Plane of Motion	Manual Mean (SD)	Range
Forward Flexion	54.4 cm (0.35)	45 cm - 64 cm
Extension	41.1 cm (0.38)	29.6 cm - 51 cm
Lateral Bend Right	57.9° (1.4)	38° - 74°
Lateral Bend Left	56.7° (1.8)	44° - 76°
Axial Rotation Right	58.1° (1.8)	48° - 74°
Axial Rotation Left	60.9° (1.8)	40° -74°

Table 3 provides a combined side by side view of the summary of the means in both Table 1 and Table 2 followed by the standard deviation and comparative analyses.

Table 3: Comparison of Means, Correlation, and t-test Between Manual and Electronic Sensor

Plane of Motion	Electronic	Manual	Compared		
	Mean (SD)	Mean (SD)	Correlation Between Manual and Electronic Means	t-test	t-test p value
Flexion	86.9° (7.7)	54.4 cm (0.35)	*		
Extension	51.4° (5.7)	41.1 cm (0.38)	*		
Lateral Bend Right	50.7° (5.6)	57.9° (1.4)	r = 0.70	Not Sig	1
Lateral Bend Left	52.9° (5.3)	56.7° (1.8)	r = 0.68	Not Sig	1
Axial Rotation Right	57.5° (5.1)	58.1° (1.8)	r = 0.54	Not Sig	0.58
Axial Rotation Left	59.04° (5.5)	60.9° (1.8)	r = 0.44	Not Sig	0.87

*Unable to compare centimeters of flexion and extension of manual to electronic methods in degrees

Manual measurements for flexion and extension were executed using a flexible tape measure in a skin stretch test, spanning the anatomical landmarks from C7 to the PSIS.

The consistency of measurements, denoted by the average standard deviation from repeated trials, was higher in the electronic approach (approximately 5° vs. 2°). The correlation between lateral bending measurements done manually and electronically was strong (r = 0.70), but the correlation between the axial rotation measurements was only moderate for the right (r = 0.54) and the left (r=0.44).

Measuring motion in flexion and extension was done using two different methods, so they cannot be compared using a t-test. The difference between the mean range of motion collected by the sensor and hand measurements differs by 1 to 6° across all ranges of motion, except for flexion and extension values (Table 4).

Table 4. Comparison of the average difference between the means of measured ROM from an electronic sensor and manual measurements.

Plane of Motion	Average Value (°)
Lateral Bend Right	6.00°
Lateral Bend Left	5.00°
Axial Rotation Right	0.6°
Axial Rotation Left	1.86°

The difference between the means was calculated by subtracting the electronic mean from the manual mean for each plane of motion seen in Table 4. Flexion and Extension values were not included here due to the units for those planes of measurements being incomparable across electronic and manual methodologies used in this study.

4.0 Discussion

The primary objective of this study was to appraise the level of association of the inertial sensor technology in assessing the clinical range of motion by collecting data from typically developing subjects. The manual measurements served as a basis for comparison. Clinical range of motion evaluations have long been a keystone in discerning limitations potentially stemming from injuries or illnesses. By gauging joint or muscle movement capacities, invaluable insights are availed to healthcare practitioners for mobility assessment. For example, Asher, et al.[9] showed that individuals with scoliosis reflected a significant influence of their scoliotic curves on their perception of self and their motion capabilities, indicating the importance of recording and analyzing these parameters at different phases of patient care.

Thus, there has been a recent increase in the development of different wearable monitoring systems for various types of clinical motion, both pertaining to spinal motion and posture.[10,11] This knowledge becomes important in tracking postoperative recovery following procedures like Anterior Scoliosis Correction. These parameters not only underscore muscle potency, joint flexibility, and overall function, but are traditionally gauged using tools like goniometers and tape measures.

While the Modified Schober test provided a semblance of angular flexion, it may not be the best method to evaluate flexion of the thoracolumbar spine. While some studies underscore its reliability,[5] others indicate a tenuous link between angular flexion and skin stretch.[4] Trunk rotation measurement also grapples with the issue of reliability. The literature describes diverse methods, yet none deliver consistent reproducibility or pinpoint accuracy.[6,12]

Trunk rotation measurements frequently yield varying levels of reliability—a sentiment echoed in existing literature that targets trunk motion evaluation.[13] In the context of trunk range of motion, a deviation of +/- 5° may be acceptable. The methodology used in this study was straightforward to perform, but the results of our study report that it delivers only moderate reliability (Table 3). Udoekwere et al.[12] delineated a trunk movement assessment where participants, while maintaining an upright posture, maximized trunk movement in the transverse plane, utilizing their hands on their hips for spinal stabilization. Despite the numerous methodologies, a universal standard remains unestablished for goniometer placements during trunk rotation measurements.[5] The diverse methodologies described in the literature render it challenging to create a unified protocol, increasing the complexity of evaluating and comparing different patient groups. Introducing electronic sensors could potentially bridge this gap, as it has a consistent method of measuring these planes of motion. This is crucial in considering the methods used in the study because being able to solidify a procedure that yields accurate trunk rotation measurements can be extremely useful in clinical settings. Thus, this study used a method that did not restrict the subject in an uncomfortable position but was still able to gauge a sense of the individual's range of motion.

Preliminary findings from a research group[7] posited that an inertial sensor adeptly quantified angles in mechanical settings, suggesting their applicability to the human thoracolumbar spine. However, the consistency in capturing a human six-directional bending when repeated 6 times may vary among repeated trials due to factors such as muscle stretching.[14] Consequently, variability in measurements may not solely emanate from manual techniques or sensor inaccuracies but also physiological factors. Variability in this study was evaluated by the magnitude of the standard deviation. A smaller standard deviation indicates enhanced consistency in measurements across subjects.

Recent research that evaluated the interrelated reliability of tape measures and goniometers in recording thoracolumbar range of motion demonstrated the strong association observed in our study, especially when measurements were executed by a singular examiner.[7] Inertial sensor technology overall has been systematically reviewed for its reliability and validity in both static and dynamic motion in healthy adults.[15] Notably, while our study emphasized thoracolumbar motion, prevalent research predominantly focuses on the lumbar range, specifically targeting the T12-sacrum or L1-sacrum regions, excluding the C7 to PSIS span.[16] This delineation is paramount since spinal segmental motion varies based on factors like age, gender, and specific health conditions impeding motion. Investigation into the use of a noninvasive electrogoniometer, torsiometer, and other 3D motion capture tools have been investigated but primarily on the lumbar spine, not the entire thoracolumbar region.[17] Clinical range of motion also has many applications outside of measuring the thoracolumbar spine; thus, finding ways to optimize these measurements for other regions of the body such as with thoracic posture can also benefit a care team in developing a treatment plan.[18]

This study does not purport to summarize typical thoracolumbar spinal motion across all demographics but rather underscores the potential of the tools in evaluating spinal movement. The electronic sensor objectively requires less training and can provide numerous benefits for spine centers to obtain motion data without the need for extensive training of the locations of anatomical processes. By creating devices that unobtrusively attach to the body, these devices could be further developed to evaluate clinical data in settings other than the clinic, such as in a home or community setting.[19] In addition to obtaining data pertaining to 3D movement, these devices also provide electromyography (EMG) data[20] that can be used to measure factors such as muscle tightness. This is particularly relevant to patients with scoliosis in regards to monitoring paraspinal muscles but also can be further expanded to use in physical therapy and rehabilitation.[21]

In comparing electronic and manual methods, while the electronic sensor exhibited a slightly higher magnitude in standard deviation across measurements, it requires less training, simplifying the process by obviating the need to identify multiple anatomical landmarks. This is because it primarily necessitates proficiency in locating the C7 vertebra to position the sensor.

It has been shown that manual measurements of clinical range of motion require extensive training to be accurate.[5] This comprehensive training can prolong the process of assessing ROM and could render it somewhat subjective. As mentioned, preliminary findings regarding the capability of this inertial sensor have been evaluated and showed high accuracy for measuring angular displacement as measured by placing the sensor to an affixed spot on a bicycle wheel to mimic spinal motion.[7] These findings build upon the notion that these sensors have levels of association like that of manual measurements and upon conducting further investigation can eventually be adapted permanently into clinical care universally. Further research into increasing the reproducibility, reliability, and validity of this technology could have multiple applications for relying on these methods to evaluate thoracolumbar ROM for different purposes in clinical care.

Average motion values across the 6 planes offer a glimpse into expected postoperative outcomes following spinal corrective surgeries, bolstering clinical evaluations during recovery stages. Quantifying trunk range of motion remains pivotal, especially since structural spine adjustments are often captured in static radiographs. However, a patient's functional movement is arguably the paramount outcome. Thus, ensuring the availability and applicability of tools that meticulously measure a patient's range of motion, without undermining comfort, is vital for clinical implementation.

The data procured can effectively monitor pre-surgical and post-surgical progression of a patient’s range of motion or overall functional movement. Evaluating the duration required to achieve a "normal" range of motion postoperatively is a direct application of these observations. Such evaluations are pivotal for healthcare professionals in assessing the state of spinal deformities and in determining optimal care strategies to either maintain or enhance an individual's mobility.

5.0 Conclusion

This study evaluated a novel and developing technology – inertial sensors – against traditional longstanding methods of manually measuring thoracolumbar clinical range of motion. The electronic inertial sensor measures in a similar capacity to traditional manual spine motion measurements, and this study provides encouraging evidence that technology can be permanently adopted into spine centers for future use. Evaluating clinical range of motion with the inertial sensor ultimately optimizes the measurement process and, if further developed, could be used outside of clinical settings for further information on an individual's functional capabilities. This would provide insight into important real life considerations such as function in activities of daily living, ability to participate in sports, and overall comfort.

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None

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