Wearable Motion Analysis System for Thoracic Spine Mobility With Inertial Sensors

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***Abstract*—This study presents a wireless wearable portable system designed for the automatic quantitative spatio-temporal analysis of continuous thoracic spine motion across various planes and degrees of freedom (DOF). This includes automatic motion segmentation, computation of the range of motion (ROM) for six distinct thoracic spine movements across three planes, tracking of motion completion cycles, and visualization of both primary and coupled thoracic spine motions. To validate the system, this study employed an Inter-days experimental setting to conduct experiments involving a total of 957 thoracic spine movements, with participation from two representatives of varying age and gender. The reliability of the proposed system was assessed using the Intraclass Correlation Coefficient (ICC) and Standard Error of Measurement (SEM). The experimental results demonstrated strong ICC values for various thoracic spine movements across different planes, ranging from 0.774 to 0.918, with an average of 0.85. The SEM values ranged from 0.64° to 4.03°, with an average of 1.93°. Additionally, we successfully conducted an assessment of thoracic spine mobility in a stroke rehabilitation patient using the system. This illustrates the feasibility of the system for actively analyzing thoracic spine mobility, offering an effective technological means for non-invasive research on thoracic spine activity during continuous movement states.**

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***Index Terms*—Thoracic spine mobility, continuous movement, quantitative analysis, reliability, wearable sensors.**

I. INTRODUCTION

WITH the advent of the era of digitization, people's lifestyles are undergoing changes. Prolonged usage of computers and mobile phones, coupled with reduced physical activity, has become increasingly common, especially in economically developed societies [1]. Additionally, factors like maintaining poor sitting posture, improper body alignment, and lack of exercise are contributing to the exacerbation of back issues [2], [3]. Particularly, the incidence of upper and middle back pain stemming from thoracic spine pain (TSP) is gradually becoming more prevalent. Furthermore, TSP may also serve as an external manifestation of certain underlying diseases, further emphasizing its significance in health issues [6], [7], [8], [9]. This type of pain not only significantly impacts physical health but also influences psychological well-being, leading individuals into a suboptimal state of health, thereby resulting in adverse consequences for overall life [4], [5]. It markedly diminishes the quality of life, directly impairs work efficiency, and subjects individuals enduring pain to additional mental stress [10]. However, despite back pain becoming increasingly prevalent in modern society, in comparison to the lower back pain (LBP) caused by the lumbar spine (commonly known as "lumbago") [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], there is relatively limited targeted research within the health field concerning the upper-middle back pain caused by TSP associated with thoracic spine [2]. This has led to a lack of in-depth understanding of the root causes and mechanisms behind TSP.

As a vital and complex region of the human spine, the thoracic spine holds crucial significance. Situated between the cervical (neck) and lumbar (lower back) regions, it serves as a bridge connecting the upper cervical and lower lumbar. Uniquely, the thoracic spine is the only spinal region linked to the rib cage, playing a key role in stabilizing the rib cage and safeguarding internal organs. Furthermore, as an integral part of the body's structural support, the thoracic spine's flexibility and stability are imperative for maintaining bodily balance, ensuring an upright posture, aligning the head and neck properly, assisting in upper limb movements, and facilitating respiration, which are essential for the smooth execution of daily activities. The muscles, nerves, and other structures in the upper and middle back are intricately intertwined with thoracic spine. Therefore, a range of factors such as prolonged poor posture, muscle tension, injuries or strain, herniated discs, vertebral arthritis, nerve compression, or damage, can contribute to thoracic spine issues, consequently giving rise to upper-middle back pain.

Studying the mobility of thoracic spine has become highly essential, as it contributes to uncovering the underlying mechanisms of TSP issues and provides robust support for targeted intervention measures [24]. By utilizing convenient systematic technological approaches, a better understanding of the intricate factors underlying TSP can be gained, offering an effective path to enhance individuals' health and quality of life. Currently, hospitals typically rely on radiographic imaging, such as X-rays, alongside goniometers or inclinometers, patient-reported questionnaires, and the subjective experience of medical professionals for standard spinal diagnoses. This includes evaluations conducted by medical professionals following pertinent physical examinations and tests, as well as the use of scoring scales [38]. However, these methods come with certain limitations. Radiographic imaging, for instance, cannot capture the dynamic and continuous motion of the spine, providing only limited information at specific time points [25], [26], [27]. Goniometers or inclinometers do not account for the dynamic kinematics of movement, and the measurements obtained with these tools are operator-dependent, requiring significant time and effort [39]. Meanwhile, on-site assessments by doctors suffer from a one-time and non-reproducible drawback, potentially introducing subjective errors. In laboratory settings, research on spinal mobility predominantly relies on optical capture systems [28], [29], [30], [31]. However, these systems are expensive and constrained by site-specific limitations. Establishing marker sets for optical motion capture systems is a complex, time-consuming process that typically requires numerous markers [30]. Ensuring accuracy with these systems demands strict experimental conditions, including the precise control of lighting conditions and background complexity. These factors can potentially interfere with target capture and tracking, leading to inaccurate outcomes.

Moreover, current research on spine mobility predominantly focuses on the lumbar region [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [32], [33], [34], with comparatively less effort being dedicated to investigating the mobility of the thoracic spine [46], [54], [55], [56], [61], [62]. Despite extensive literature searches, no published studies have undertaken automatic active spatio-temporal quantitative analysis of thoracic spine mobility in continuous motion across all anatomical planes, particularly in effectively distinguishing between proprioceptive and objective movements [57], [58], and utilizing wireless wearable strategies. Given the limited research on the thoracic spine, only a few non-radiographic methods currently explore measuring its ROM, including the thoracolumbar spine, across all anatomical planes. Mousavi et al. employed an opto-electronic motion capture system to measure the 3-D ROM of the thoracolumbar spine, evaluating its stability through analyses of ICC and SEM [30]. However, this approach required nearly 100 markers, and the measurements involved only non-continuous motion, with each action performed only once per trial and repeated three times in experiments. Narimani et al. attempted to measure the ROM in three DOF of the thoracic spine using inertial tracking devices [46]. However, this protocol had limitations, notably in the measurement of non-continuous movements. In each trial, participants performed each action only once and repeated it three times. Additionally, the wired nature of the devices might have induced unnatural movements during the experiments. Furthermore, the study lacked an analysis of measurement stability.

Given the aforementioned issues, this study introduces a wireless, portable, wearable inertial-sensor-based system for automatically and quantitatively analyzing dynamic thoracic spine mobility during continuous movements across all anatomical planes and DOFs. In contrast to traditional radiographic methods, our system enables real-time capture and active analysis of the continuous dynamic motion of thoracic spine across its complete anatomical plane, effectively distinguishing between proprioceptive and objective movements. Notably, it not only extends the temporal scope of thoracic spine mobility assessment but also offers easy accessibility to individuals without specialized expertise, allowing for self-monitoring and mobility assessment. Furthermore, the system offers convenient wearability. Leveraging wireless communication technology enhances its practicality in daily life, overcoming the cost, space, and environmental limitations faced by optical capture systems in controlled experimental settings [30]. This empowers the system to assess thoracic spine mobility in real-world conditions, free from temporal, spatial, and environmental constraints. By liberating itself from these constraints and offering convenient and flexible usability, the system enables continuous monitoring of daily thoracic spine activity. It equips medical professionals with objective, comprehensive, long-term, and stable thoracic spine mobility data, thereby facilitating more precise diagnoses and treatment planning. The proposed system introduces new possibilities for thoracic spine health management and furnishes patients and healthcare practitioners with valuable information.

The remaining sections are organized as follows: Section II introduces the methods used in this study. Section III presents the experimental results, which are discussed in Section IV, and our conclusions are presented in Section V.

II. METHODS

A. Interested Target Motions Definition

In this paper, we described and defined thoracic spine movements based on anatomical position and planes (Fig. 1(a)). Anatomical position serves as the reference point for all movements (Fig. 1(b)).

Based on human anatomical structure, a human spine is categorized into five regions: cervical, thoracic, lumbar, sacral, and coccyx (Fig. 2). The thoracic spine consists of 12 vertebrae stacked together, labeled as T1 to T12, and lies at the center of the upper and middle back (Fig. 2). It starts just below the cervical spine (neck region) and ending where it meets the lumbar spine (lower back). The thoracic vertebrae have prominent spinous processes, which are easily identifiable upon palpation. Additionally, each thoracic vertebra is typically

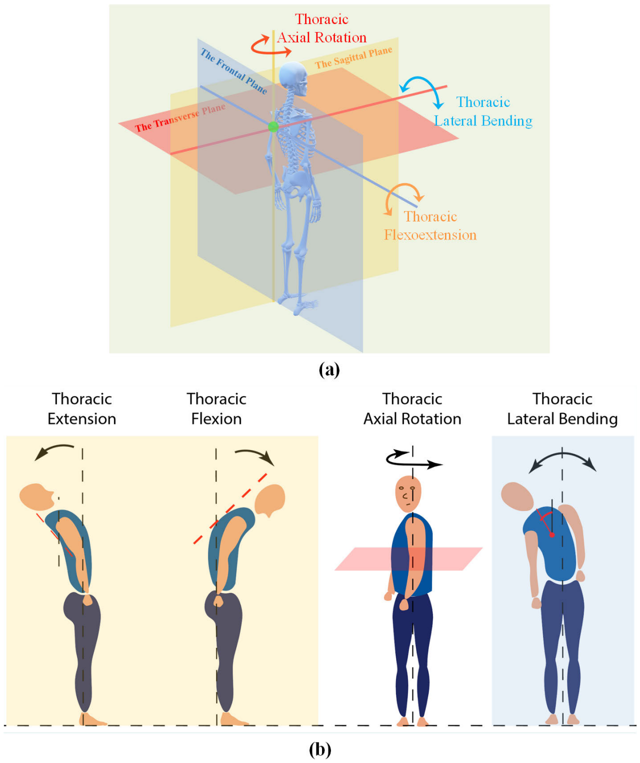


Fig. 1. (a) The anatomical plane used in this study and (b) thoracic spine movements defined in the study.

connected to a pair of ribs, aiding in the identification of each vertebral level. Compared to the cervical and lumbar regions, thoracic spine exhibits more restricted mobility, posing challenges for its study. Our study focuses on investigating the movement capabilities of thoracic spine in three DOF across three anatomical planes. This covers six distinct thoracic spine movements: flexion and extension in sagittal plane, lateral bending in frontal plane, and axial rotation in transverse plane (Fig. 1(b)).

Thoracic flexion initiates from a neutral upright position, inducing a forward curvature of thoracic spine by bending the upper-middle back within sagittal plane. In contrast, thoracic extension originates from a neutral upright position, resulting in a backward extension of thoracic spine as the upper-middle back bends backward in sagittal plane. Thoracic lateral bending tilts thoracic spine to the left or right side, away from the body's midline within the frontal plan, achieved by shifting the upper torso to the left or right. Thoracic axial rotation turns the torso to the left or right in transverse plane, accomplished by rotating thoracic spine along the body's midline in either direction.

B. System Hardware Description

Fig.3(a) shows our system schematic design, a fully portable and wearable wireless system for capturing thoracic spine kinematics data. The system consists of four inertial sensing units, and a control box unit designed by our team (Fig. 4). The system has all logic elements required for monitoring continuous kinematics signals in real-time based on the inertial sensor readings onboard. Our system is convenient to carry and wear and a user can don it in less than two minutes.

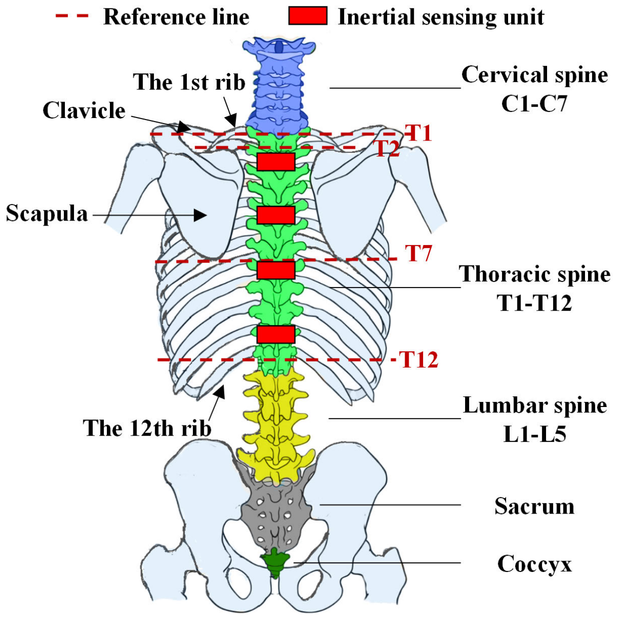
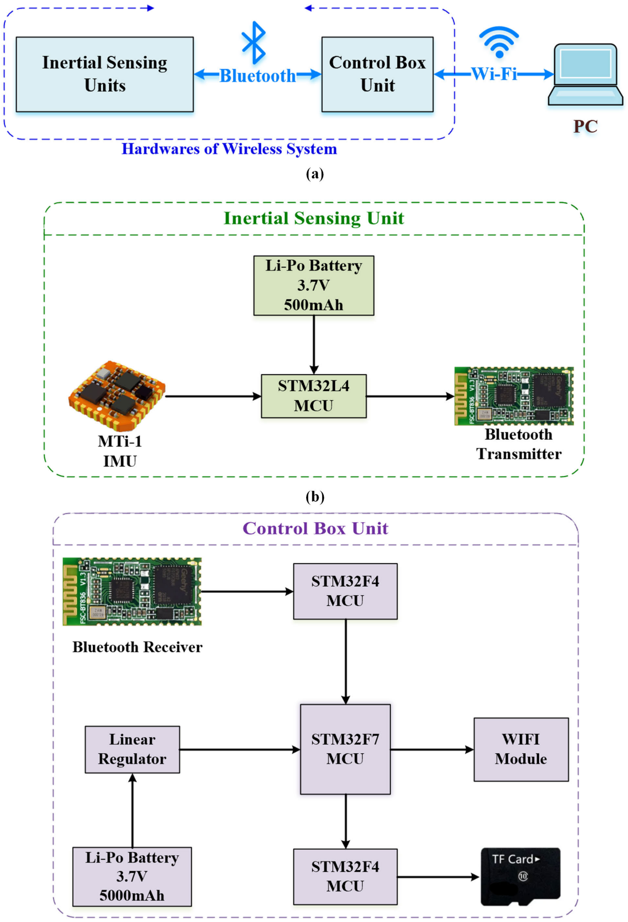


Fig. 2. This illustration portrays the spine regions and major anatomical landmarks, using reference lines drawn from the clavicle, scapula, first rib, and twelfth rib to assist the placement of inertial sensing units in experiments. The cervical spine is labeled C1-C7, the thoracic spine T1-T12, and the lumbar spine L1-L5. Red blocks represent the inertial sensing units aligned along the thoracic spine.

The inertial sensing unit of the system (Fig.3(b)) employs a 9-axis Inertial Measurement Unit (IMU), specifically the Xsens MTi 1-series model. This IMU has dimensions of $12 \times 12 \times 2.5$ millimeters and weights 0.6 grams. It comprises a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis magnetometer to enhance heading angle measurement accuracy. According to its specifications, in typical application scenarios, the accuracy range evaluated under GNSS (Global Navigation Satellite System)/INS (Inertial Navigation System) is 0.5° in the Roll/Pitch direction and 2.0° in the Yaw direction. The design architecture of the inertial sensing unit also comprises a logic unit, a Bluetooth communication module, signal acquisition and processing circuits, and power management circuits. The signal acquisition and processing circuit of the inertial sensing unit utilizes a dedicated IMU acquisition chip to collect kinematic signals collected by the IMU. These signals are further analyzed and processed by the microcontroller unit (MCU) in the logic unit. The signals from the 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer are integrated to derive real-time accurate human kinematic angle signals using proprietary algorithms for signal correction and multi-sensor fusion. The MCU processes the kinematic angle signals and transmits them to the Bluetooth communication module of the inertial sensing unit at a frequency of 100 Hz. The Bluetooth transmitter within the module employs wireless Bluetooth® technology to transmit the kinematic angle signals to the corresponding Bluetooth receiver on the control box unit. The power management circuit is designed to provide the required voltage, voltage monitoring, battery charging and discharging protection, as well as switch control for the inertial sensing unit. A reliable and stable V lithium-polymer battery supplies power independently to the inertial sensing unit.

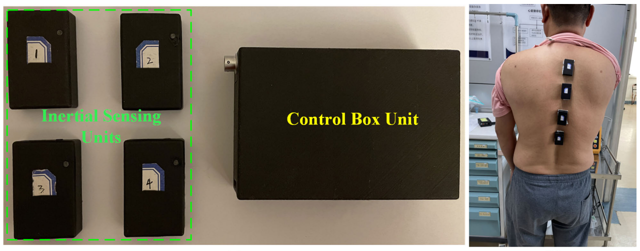


(a)

(b)

(c)

Fig. 3. (a) The system schematic. (b) The architecture of the inertial sensing unit. (c) The architecture of the control box unit.



(a) (b)

Fig. 4. (a) Real image of the system hardware. (b) A stroke rehabilitation patient wearing the wireless system.

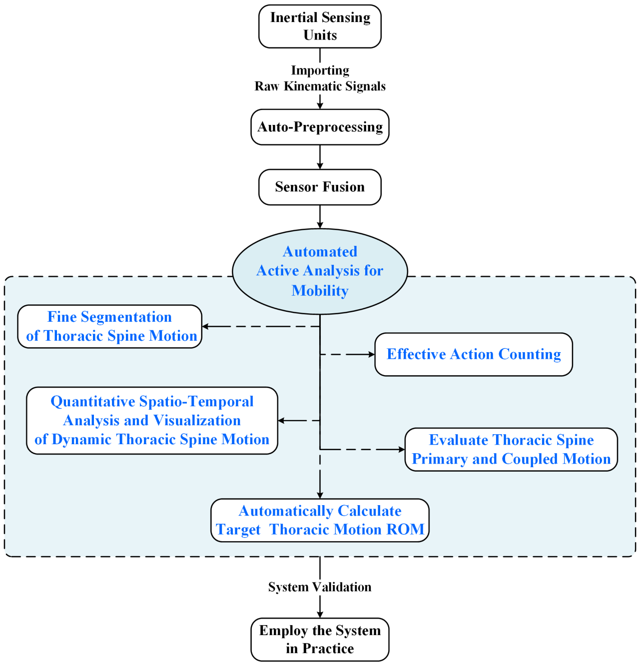


Fig. 5. The flowchart depicts the algorithm design strategy for Thoracic Spine Mobility analysis. The dashed box indicates the execution contents within the Automated Active Analysis for Mobility phase, with dotted lines connecting these items to signify concurrent processes.

The control box unit of the system (Fig.3(c)), functions as the central hub, responsible for collecting, synchronously processing signals, transmitting the synchronized data to the upper computer in real-time via Wi-Fi at a frequency of 100 Hz, and storing multi-channel wireless kinematic signals on a Trans-Flash Card (TF card) for subsequent analysis. The design architecture of the control box unit consists of a wireless Bluetooth communication module, three logic units, a Wi-Fi wireless communication module, data analysis and storage circuits, and power management circuits. The wireless Bluetooth communication module serves as the corresponding Bluetooth receiver, capturing signals transmitted by the Bluetooth transmitters of the four inertial sensor units. Within the first logic unit, the MCU receives kinematic signals from the inertial sensor units through the Bluetooth receiver, encapsulating all these signals for subsequent transmission to the MCU housed in the second logic unit. The MCU of the second logic unit receives all the signals packaged by the first MCU, synchronizes them, and conducts further parsing and processing. The processed signals are then packaged and sent via UART to the Wi-Fi wireless communication module. The Wi-Fi wireless communication module reliably and stably transmits the processed signals via a WLAN to the user's computer in real-time. Simultaneously, the processed signals from the second logic MCU are sent to the third MCU, which is responsible for storing signals on the TF card for future analysis. The power management circuit converts the voltage of the 3.7V rechargeable lithium battery into the required 3.3V DC voltage for subsequent circuits using a linear regulator. The control box unit is powered by a rechargeable 3.7V, 5000mAh lithium battery and can also be powered in real-time using a portable power source. These features enable the control box unit to function wirelessly and independently from the inertial sensor units. The wearer can either wear the main control unit wirelessly or place it within a range of up to 50 meters from the wearer.

C. Algorithm Protocol

Fig. 5 illustrates the design strategy of the active analysis algorithm for thoracic spine mobility.

1) Auto-Preprocessing: This step is crucial for enhancing signal quality by reducing noise and extracting the most pertinent signals for subsequent thoracic movement analysis. The raw signals from the four inertial sensor units of the system, sampled at a frequency of 100 Hz, were directed to our custom preprocessing algorithm. Initially, the algorithm selects the required kinematic channels from the raw signals. Subsequently, a sliding window with a duration of 0.1 seconds was employed for continual identification and substitution of outliers within the selected channels. To attenuate noise, a Gaussian filter was implemented, and the continuous quadratic trend in the signals from the inertial sensor units, caused by drift, was ameliorated. Finally, the preprocessed signals are forwarded for primary motion analysis.

2) Sensor Fusion: We employ the concept of sensor fusion to enhance the performance and robustness of thoracic spine mobility analysis during dynamic continuous processes. Our system has the capability to strategically position multiple inertial sensing units uniformly across the T1-T12 region of thoracic spine, ensuring a well-balanced signal source. Given the unidirectional nature of the system's sensing units and the imperative to optimize computational efficiency, we utilize signal averaging to merge kinematic angle signals from multiple inertial sensing units.This process yields representative kinematic angle signals characterizing the entire thoracic spine, the T1-T12 segment. This process can be described using the following mathematical model ······ (1)-(2). Ultimately, these signals are automatically transmitted to subsequent active analysis algorithms.

$$\boldsymbol{T}^{1-12} = \frac{\sum_{i=1}^{j} \boldsymbol{I}_i}{j}$$

$$i = 1, 2, 3, \ldots, j, \ \ j \in \mathbb{N}^{+} \tag{1}$$

$$\boldsymbol{T}_t^{1-12} = \left[\boldsymbol{K}_t^{Transverse}, \ \boldsymbol{K}_t^{Frontal}, \ \boldsymbol{K}_t^{Sagittal} \right], \ \ t \in \mathbb{R}^{+} \tag{2}$$

Here, $\boldsymbol{j}$ represents the number of used inertial sensor units, while $\boldsymbol{i}$ signifies the serial number of the inertial sensing unit. The uppercase $\boldsymbol{I}$ denotes a matrix representing the captured kinematic signals by the inertial sensing units. The uppercase $\boldsymbol{T}^{1\text{-}12}$, in matrix form, signifies the kinematic angle signals of the entire thoracic spine, the T1-T12 segment, across three anatomical planes. $\boldsymbol{K}$ stands for a vector representing the kinematic information of thoracic spine on the corresponding anatomical plane. $\boldsymbol{t}$ serves as a time parameter, reflecting moments within continuous dynamic motion.

3) Active Analysis for Thoracic Spine Mobility : The design of the active analysis algorithm employed in this system is grounded in the following core idea: by identifying changes in direction during dynamic continuous movements and considering both the duration of these changes and a specific threshold of movement amplitude, irrelevant fluctuations and disturbances are excluded. Here irrelevant fluctuation is defined as minor physiological motions that do not contribute to intentional experimental movements of the thoracic spine, such as postural adjustments or swaying. The mathematical model of the design idea can be expressed as ······ (3)-(6).

$$f'(K^{Primary}) = \frac{dK^{Primary}}{dt}, \ \ t \in \mathbb{R}^{+} \tag{3}$$

$$f''(K^{Primary}) = \frac{d^2 K^{Primary}}{d^2 t}, \ \ t \in \mathbb{R}^{+} \tag{4}$$

$$\begin{gathered} M = \{\, m : m \in f'(K^{Primary}) = 0 \\ \wedge\, m \in f''(K^{Primary}) < 0 \\ \wedge\, m \in \lim_{t \to \delta} f(K^{Primary}) > \varepsilon \,\} \\ m = 0, 1, 2, 3, \ldots, \ m \in \mathbb{N}, \ t, \delta, \varepsilon \in \mathbb{R}^{+} \end{gathered} \tag{5}$$

$$\begin{gathered} L = \{\, l : l \in f'(K^{Primary}) = 0 \\ \wedge\, l \in f''(K^{Primary}) > 0 \\ \wedge\, l \in \lim_{t \to \delta} f(K^{Primary}) > \varepsilon \,\} \\ l = 0, 1, 2, 3, \ldots, \ l \in \mathbb{N}, \ t, \delta, \varepsilon \in \mathbb{R}^{+} \end{gathered} \tag{6}$$

Here, $\boldsymbol{K}^{Primary}$ represents the kinematic angle signal of the target (primary) motion by the wearer. $\boldsymbol{t}$ denotes the moment during the continuous movement process. δ is used to indicate the time threshold, and ε represents the angle threshold. $\boldsymbol{m}$ signifies the moments when the wearer reaches the maximum ROM during the execution of continuous target movements, and $\boldsymbol{M}$ is the set of these moments. Similarly, $\boldsymbol{l}$ indicates the moments when the wearer returns to the neutral position during the execution of continuous target movements, and $\boldsymbol{L}$ is the set of these moments. To differentiate intentional thoracic spine movements from static postures or minor, physiologically inconsequential movements (e.g., postural adjustments or slight shifts), the algorithm determines that a movement is considered to have started when the angle exceeded 5° from the neutral position and is sustained for at least 200 milliseconds. The thresholds were selected based on references to relevant literature [35], [47] and preliminary tests, further validated through manual inspection of a random selection of motion samples using a subset of data not included in the main study.

This design enables the algorithm to autonomously analyze the entire process of continuous dynamic thoracic spine movements executed by the wearer. Through accurately capturing and extracting key information and moments from continuous thoracic spine motions, comprehensive analysis of thoracic spine mobility is achieved. This active analysis involves identifying the initiation moment of voluntary thoracic spine movements by the wearer, determining the moment at which the maximum ROM is achieved, returning to the neutral position, tallying the count of effective thoracic spine movements completed by the wearer. Additionally, it includes performing automated fine segmentation of the target thoracic spine motion during dynamic continuous movements executed by the wearer, as well as analyzing the primary thoracic spine motion along with its associated coupled movements. Additionally, it includes performing automated fine segmentation of the target thoracic spine motion during dynamic continuous movements executed by the wearer, as well as analyzing the primary thoracic spine motion along with its associated coupled movements.

D. Experimental Protocol

This study primarily focused on conducting experimental tests on system stability and feasibility in healthy individuals. Subsequently, to further evaluate the system's suitability for a broader population, particularly in disease-specific applications, we assessed the thoracic mobility of a stroke rehabilitation patient. This approach is grounded in the understanding that stroke is a globally widespread disease and a leading cause of disability [40]. Patients recovering from a

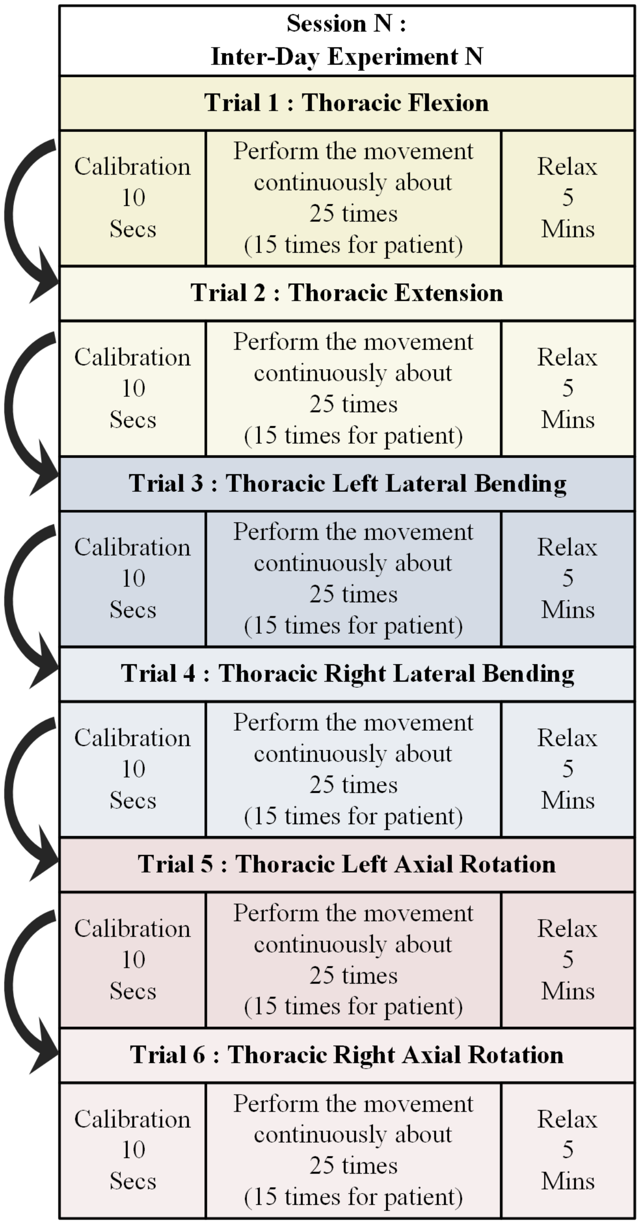


Fig. 6. Experimental protocol. N represents the session number, which can range from 1 to 3.

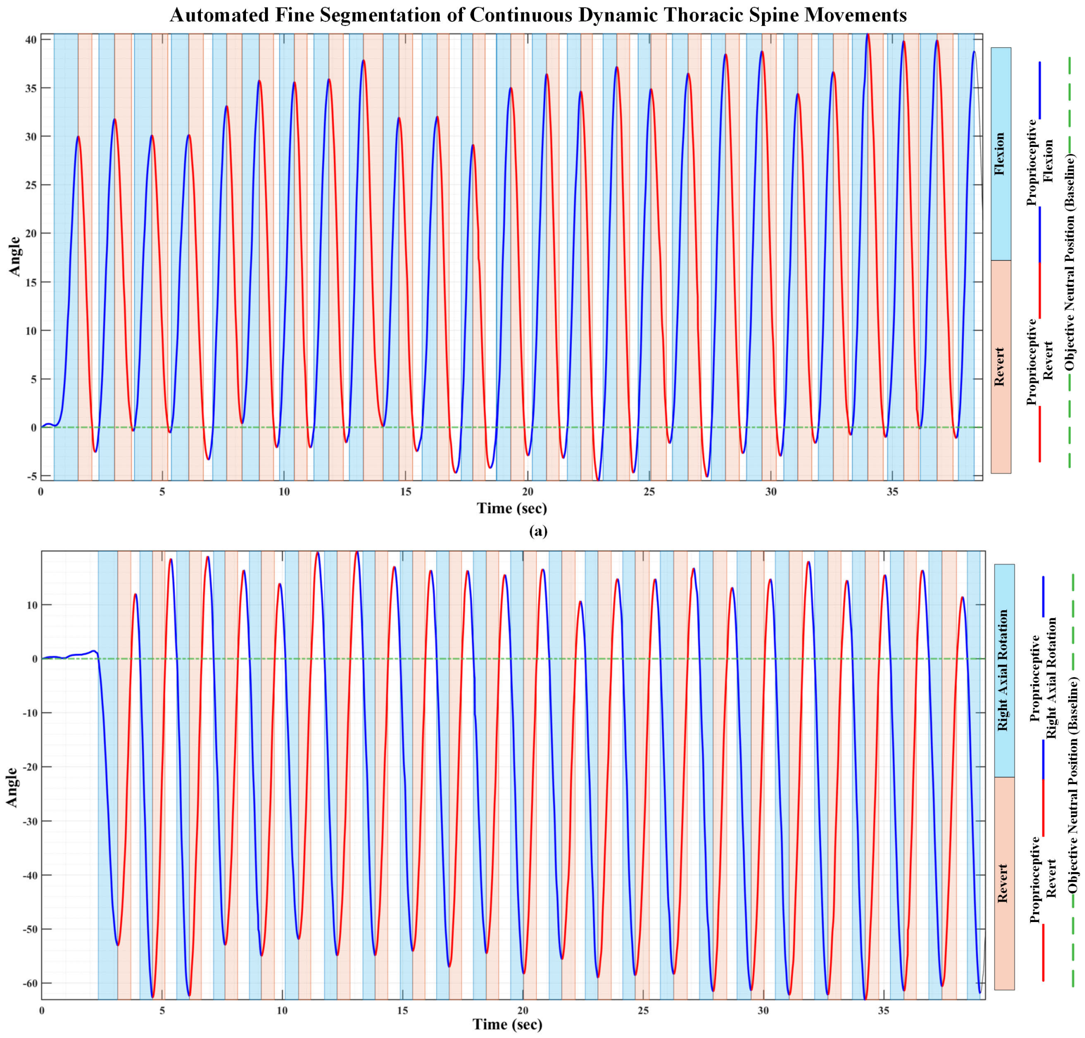
stroke often experience various degrees of motor function impairment, affecting their overall motor abilities [41], [42]. This includes not only restricted limb movement and challenges in coordinating body movements but also compromised balance abilities.

1) Participants: The study randomly selected two eligible healthy adult participants one representing a healthy male (approximately 35 years old) and the other representing a healthy female (approximately 55 years old), along with a stroke rehabilitation patient. The aim was to assess the feasibility of active analyzing thoracic spine movements in this diverse population. Participants were excluded from the healthy group if they faced limitations in actively performing pain-free spine movements, were obese, had orthopedic, neurological, or vestibular conditions, or experienced recent back pain, a history of spinal surgery, traumatic fracture, thoracic deformity, or any conditions affecting balance, movement, or the ability to stand. The female healthy participant is 56 years old, 162 cm in height, and weighs 55 kg. The male healthy participant, aged 37, stands at 177 cm and weighs 80 kg. Additionally, there is a 39-year-old male stroke rehabilitation patient who measures 175 cm in height, weighs 65.6 kg, and has a Berg Balance Scale (BBS) score of 49 as well as a Modified Ashworth Scale score of 1 [43], [44]. The patient, who presents with right-sided hemiplegia, had suffered an ischemic stroke approximately six to seven months prior to the onset of the study. All subjects in this study were right-hand dominant. The Local Ethics Committee of Peking University approved the study protocol, and all participants provided informed consent before participating in the experimental sessions.

2) Procedures: We ensured the accurate placement of inertial sensing units along the thoracic spine (T1-T12) by utilizing major anatomical landmarks, palpation techniques, reference lines, and the positional relationship with the ribs [45], as illustrated in Fig. 2. Specifically, we began by locating the spinous process of T1 directly below C7—the most prominent process at the base of cervical spine, which is particularly noticeable when the head is flexed forward. The position of T1 could also be verified by the location of the 1st rib or the clavicle. T12 was identified adjacent to the 12th rib, marking the end of the thoracic spine. The scapula's relation to the thoracic spine provided further guidance, with its upper angle corresponding to T2 and the lower angle aligning with T7. Throughout the experiment, four inertial sensing units were evenly positioned along the midline of participants' thoracic spines, from T1 to T12 (Fig. 2). These units were securely affixed to participants' skin using double-sided adhesive to ensure precise analysis (Fig. 4(b)). We also had a professional rehabilitation physician who provided guidance and assistance during the experiment. After becoming familiar with the procedure, even individuals without a professional background can quickly apply sensors to the subjects, ensuring they are placed on the thoracic spine.

Before the experiment, participants received comprehensive training, which included verbal instructions and live demonstrations for each movement pattern, as detailed in Section A and depicted in (Fig. 1(b)). This preparatory phase involved practice to ensure participants' proficiency and confidence in executing the maneuvers. Participants were instructed to replicate the movements, receiving immediate feedback and corrections from instructors to confirm their understanding. All experimental trials were conducted only after ensuring that the participants could adequately follow instructions.

Fig. 6 outlines the experiment's procedures, which include six trials. Each trial focuses on a unique thoracic spine movement pattern, with participants executing each pattern approximately 25 times in succession. Trials are conducted with participants standing, arms hanging naturally, and begin from an objective neutral position. This position reflects the participant's natural standing body alignment at rest, without any imposed posture or movement, serving as the baseline. Participants then perform continuous target movements, moving to achieve maximal ROM and then returning to their proprioceptively determined neutral position [57], [58], before moving back to achieve maximal ROM again in a cycle,



(a)

(b)

Fig. 7. The solid blue line represents the participant's proprioceptively target thoracic spine motion, while the solid red line indicates the proprioceptive return motion. In contrast, the light blue and light red shaded regions highlight phases of objective motion; within these, the solid blue and solid red lines represent the objectively measured target and return motions, respectively. The dashed green line denotes the participant's objective neutral position, serving as the baseline throughout the continuous movement trial. (a) presents continuous flexion movements of the thoracic spine, (b) presents continuous right axial movements of the thoracic spine.

all at their own pace until a trial concludes. This approach authentically captures their natural movement characteristics in continuous motion. The system undergoes calibration before each trial to ensure accurate motion tracking. Participants rest for 5 minutes between trials for muscle adjustment and relaxation. Meanwhile, a technician monitors real-time kinematic signals from the system's inertial sensing units during each trial and has the authority to interrupt and restart a trial if any issues arise, thus guaranteeing each trial's integrity.

For the healthy participants, an Inter-Day experimental arrangement is employed, in which the same participant completes an additional full experiment on a different day (usually spaced around 2-3 days apart) for replication. Each participant completes a cumulative total of 3 full experiments, all adhering to the same protocol, resulting in 3 experimental sessions.

After the system was validated through experiments conducted with healthy participants, a stroke rehabilitation patient participated in a single experiment session. In this session, each movement was repeated continuously 15 times.

E. Reliability Assessment

Aligned with our research objectives, we aim to develop an objective, stable, and automated system for quantifying thoracic spine movement during continuous motion. In this study, the reliability of the system in actively analyzing thoracic spine mobility was assessed using the ICC and SEM [30], [35], [36], [37], [48], [49], [49], [50], [51]. ICC and SEM are widely acknowledged as tools for assessing the performance of measurement methods through the evaluation of measurement reliability [49], [50], [51].

Although ICC analysis does not strictly require data normality or homogeneity of variance, incorporating these considerations can enhance the robustness and accuracy of the ICC outcomes. Before implementing ICC, the data were verified to meet the necessary prerequisites by conducting normality checks using the Shapiro-Wilk test and evaluated homoscedasticity through Levene's test. The results, with p-values above 0.05, confirm normality and consistent variance across sessions, supporting the validity of the ICC calculations.

TABLE I
RANGE OF MOTION FOR PRIMARY THORACIC SPINE MOTION (WITH STANDING POSITION)

Anatomical Planes DOF	Target Motions	Mean	SD	Range	Min	Max	ICC	95% CI	P value	SEM	Total of Measures
In Sagittal Plane	Flexion	33.52°	4.94°	24.9°	21.26°	46.16°	0.895	(0.81, 0.95)	< 0.001	1.6°	170
	Extension	13.74°	3.2°	14.8°	6.91°	21.7°	0.808	(0.657, 0.909)	< 0.001	1.4°	146
In Frontal Plane	Left Lateral Bending	17.1°	2.23°	11.24°	11.26°	22.5°	0.918	(0.846, 0.962)	< 0.001	0.64°	172
	Right Lateral Bending	16.43°	1.71°	8.84°	12.23°	21.07°	0.774	(0.6, 0.892)	< 0.001	0.81°	171
In Transverse Plane	Left Axial Rotation	42.97°	8.91°	41.35°	22.69°	64.04°	0.878	(0.773, 0.942)	< 0.001	3.11°	149
	Right Axial Rotation	49.91°	9.66°	45.93°	18.82°	64.74°	0.826	(0.671, 0.918)	< 0.001	4.03°	149

The 95% CI (Confidence Interval) is (Lower bound, Upper bound).

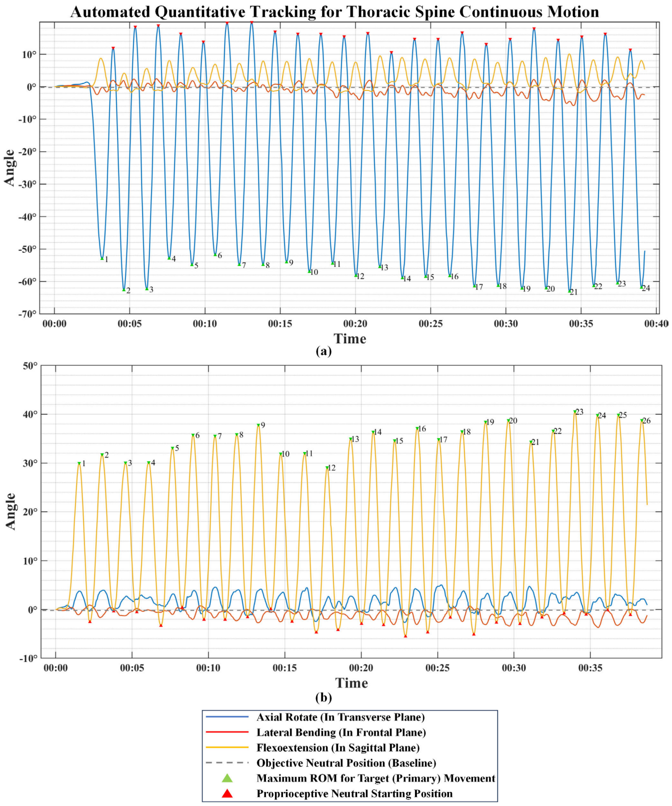


Fig. 8. Visualizing primary and coupled movements of continuous thoracic spine motion, along with key event tracking. (a) Continuous thoracic spine flexion motion. (b) Continuous thoracic spine right axial motion.

A two-way random-effects model for ICC was adopted, referred to as ICC(C,k) [37], [48]. This approach was specifically focused on evaluating both the inter-day consistency and the reliability of single measurements, emphasizing the importance of consistency agreement. An ICC score below 0.5 suggests poor reliability, between 0.5 and 0.75 signifies moderate reliability, between 0.75 and 0.9 represents good reliability, and values exceeding 0.9 indicate excellent reliability [37]. Furthermore, a smaller SEM value indicates a higher level of reliability [35], [49].

III. RESULTS

In this study, we considered flexion, left lateral bending, and left axial rotation directions as positive, while regarding extension, right lateral bending, and right axial rotation directions as negative. The plus and minus signs are used to indicate the direction on a specific plane or DOF. The '+' sign represents the positive direction, while the '-' sign represents the negative direction.

A. Active Detection of Key Events

We randomly selected experimental outcomes encompassing diverse directional thoracic spine maneuvers to exemplify the system's ability in automating the segmentation of actions and capturing key events in uninterrupted dynamic thoracic spine movements.

Fig. 7 depicts the system's automated tracking and fine segmentation of continuous flexion thoracic spine motion, primarily occurring in sagittal plane (Fig. 7(a)), as well as continuous right rotation thoracic spine motion, which primarily occurs in transverse plane (Fig. 7(b)). The 'Revert' indicates the process where the wearer returns to the proprioceptive neutral starting position after completing the target thoracic spine movement. In the same experimental trials, Fig. 8 visualizes the active spatio-temporal analysis, including the capture of key events with target motion counting, for continuous dynamic thoracic spine motions. The results demonstrate that our system can actively and effectively track, partition, and capture the key events of thoracic spine motion in different planes and directions during continuous movement, including effectively distinguishing between proprioceptive motion events and objective motion.

B. Active Computation of ROM

Table I presents the system's active computational results of the primary ROM for distinct target thoracic spine motions in inter-day continuous thoracic spine movement experiments. A total of 957 effective thoracic spine movements have been included. Here, 'SD' stands for Standard Deviation, and the significance level α of the 'P value' is set at 0.05. Fig. 9 illustrates a visual comparison of experimental outcomes, depicting the ROM values for distinct primary thoracic spine motions during dynamic continuous movements across different groups. Fig. 10 presents the results of the system's assessment of the ROM for primary thoracic spine motion along with its accompanying coupled motions during continuous movement.

C. Automatic Temporal Quantification

Tables II and III present active temporal computations for distinct thoracic target motions in various planes and DOFs during continuous movement for both the healthy and stroke rehabilitation group.

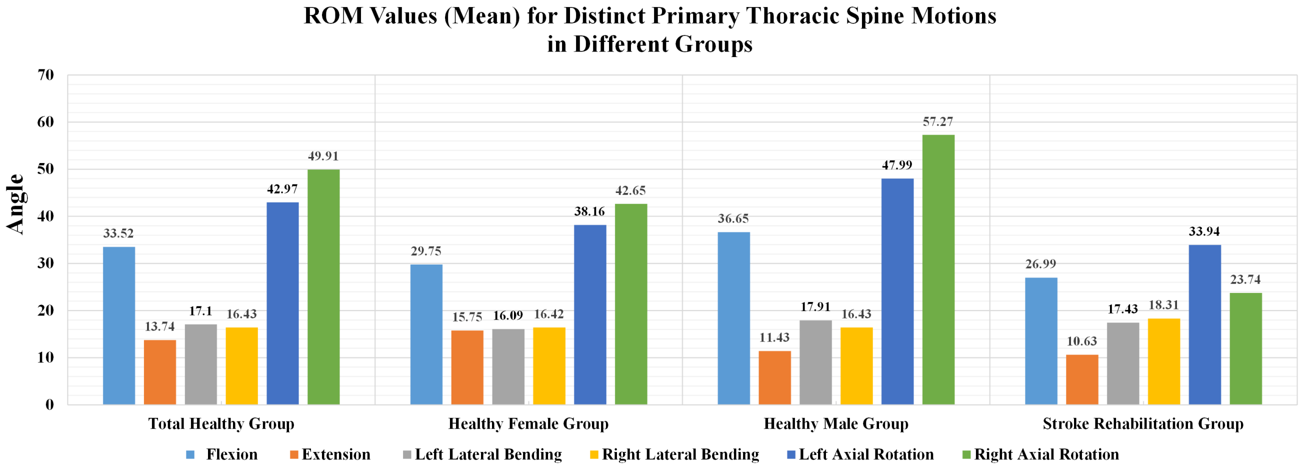


Fig. 9. Comparison of primary ROM: Here, 'group' represents different categories of sample sets derived from dynamic continuous thoracic spine movement experiments, with the sample size indicating the number of thoracic spine movements collected across all sessions.

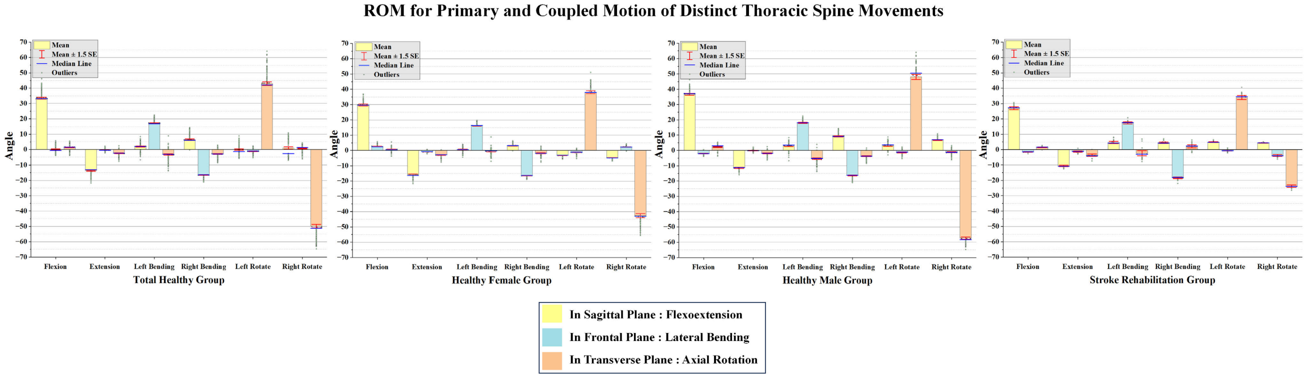


Fig. 10. Comparison of the primary ROM and their corresponding coupled motions: Here, 'group' represents different categories of sample sets derived from dynamic continuous thoracic spine movement experiments, with the sample size as the number of thoracic spine movements collected across all sessions.

TABLE II
TARGET THORACIC SPINE MOTIONS TIMING FOR HEALTHY GROUP IN DYNAMIC CONTINUOUS MOVEMENTS (UNIT: SEC)

Target Motions	Execution		Revert		Cycle Completion	
	Mean	SD	Mean	SD	Mean	SD
Flexion	0.72	0.1	0.76	0.11	1.48	0.2
Extension	0.82	0.16	0.85	0.23	1.67	0.39
Left Lateral Bending	0.78	0.2	0.79	0.21	1.56	0.41
Right Lateral Bending	0.71	0.19	0.77	0.27	1.47	0.46
Left Axial Rotation	0.85	0.1	0.86	0.13	1.71	0.23
Right Axial Rotation	0.86	0.08	0.91	0.15	1.77	0.23

TABLE III
TARGET THORACIC SPINE MOTIONS TIMING FOR STROKE REHABILITATION GROUP IN DYNAMIC CONTINUOUS MOVEMENTS (UNIT: SEC)

Target Motions	Execution		Revert		Cycle Completion	
	Mean	SD	Mean	SD	Mean	SD
Flexion	1.77	0.18	1.81	0.15	3.58	0.19
Extension	1.37	0.11	1.76	0.16	3.13	0.23
Left Lateral Bending	1.20	0.08	1.29	0.08	2.49	0.13
Right Lateral Bending	1.36	0.10	1.42	0.09	2.77	0.14
Left Axial Rotation	1.16	0.07	1.30	0.08	2.46	0.19
Right Axial Rotation	1.27	0.11	1.29	0.06	2.54	0.14

IV. DISCUSSION

As a significant contribution, this study introduces a wireless wearable portable system designed to perform active spatio-temporal analysis of continuous thoracic spine movements across three distinct anatomical planes and DOFs. This innovative system provides a convenient and efficient method for the automated analysis of thoracic spine mobility during continuous motion, capable of effectively distinguishing between proprioceptive motion events and objective motion, enabling objective, quantitative, and reliable assessments. It not only enhances our comprehension of thoracic mobility patterns but also offers an effective technological means for evaluating upper and middle back pain caused by thoracic spine issues, thus filling the current gap.

A. Active Motion Analysis Capability

We propose a novel wireless, portable, wearable system capable of conducting quantitative spatio-temporal analysis of thoracic spine mobility during continuous movement across all anatomical planes and DOFs, effectively distinguishing between proprioceptive and objective movements. This study utilized an inter-day experimental setup with healthy participants from various age groups and genders, analyzing a total of 957 thoracic spine movements. Additionally, we tested thoracic spine mobility in a stroke rehabilitation patient to evaluate the system's performance for individuals with spinal-related issues. As illustrated in Fig. 7 and Fig. 8, the system effectively segments movements and detects key motion events during continuous movements, distinguishing between proprioceptive and objective movements. This method lays the foundation for spatio-temporal quantitative analysis. Specifically designed to capture natural thoracic spine movement patterns, our system enables an authentic reflection of volunteers' individual movement traits during continuous motions. It captures and quantifies each thoracic spine movement event, with deviations from the baseline position during continuous movements highlighting individual variations in proprioception, encompassing aspects of body control and movement habits. Our system calculates the target thoracic spine ROM from the objective neutral position, excluding deviations, while accurately reflecting proprioceptive neutral starting points during motion.

We applied the ICC and SEM to assess the reliability of system strategies. The ICC values for primary ROM calculation of thoracic movements in all anatomical planes exceeded the established criteria for good reliability (ICC >0.75) [36], [37]. Specifically, the ICC values for flexion (0.895) and extension (0.808) in the sagittal plane, left lateral bending (0.918) and right lateral bending (0.774) in the frontal plane, and left axial rotation (0.878) and right axial rotation (0.826) in the transverse plane, all demonstrated high reliability. According to previous research [35], goniometry measurements commonly used in clinical practice typically allow for an acceptable error of $\pm 5°$. In this study, the average SEM for the ROM calculation of thoracic movements in all planes was 1.94°, with specific values for flexion (1.6°), extension (1.4°), left lateral bending (0.64°), right lateral bending (0.81°), left axial rotation (3.11°), and right axial rotation (4.03°). These findings provide strong evidence for the reliability of the active analysis system and its feasibility in clinical applications.

Literature reviews conducted by Pan et al. and Esteban-González et al. indicate that due to the current lack of standardized measurement criteria in assessing thoracic spine movement and the heterogeneity observed when employing various type tools and protocols [52], [53], direct comparison of thoracic spine ROM across different studies becomes impractical. However, we conducted comparisons between our system experimental results and several scientific research findings related to thoracic spine mobility reported in current studies [46], [52], [54], [55], [56], [59], [60], [61], [62], [63]. Fig. 9 illustrates the variations in the primary ROM of the thoracic spine across anatomical planes. Notably, among healthy individuals, the highest ROM were observed during axial rotation, followed by flexion, lateral bending, and extension. In the overall healthy group, the mean primary ROM across different planes and DOFs is ranked from largest to smallest as follows: right axial rotation, left axial rotation, flexion, left lateral bending, right lateral bending, and extension. Upon examining the 35-year-old male and 55-year-old female groups, it becomes apparent that female thoracic spine mobility is notably lower than that of males. These observations are consistent with previous research emphasizing age-related impacts on thoracic spine mobility [52], [54], [55], [56], [59]. In the primary motion of the thoracic spine in one plane, coupled movements are observed in the other two planes. Fig. 10 illustrates that coupled movements are most prominent during lateral bending and axial rotation of the primary thoracic spine, with minor coupled motions occurring during primary flexoextension motions in the sagittal plane among the healthy individuals. This phenomenon aligns with established research in the field [46], [52], [60], [61], [62], [63]. The experimental results demonstrate that the ROM obtained through our system is reasonable and consistent with existing research conclusions and previous studies on thoracic spine mobility, reflects compatibility with established scientific findings.

When comparing thoracic spine mobility between the healthy group and the stroke rehabilitation group, Fig. 9 and Fig. 10 clearly show that the male of similar age who has experienced a stroke exhibit significantly lower activity levels than the healthy male, especially in axial rotation. Achieving thoracic axial rotation also requires more coupling movements. Additionally, a noticeable asymmetry can be observed in left/right axial rotation. This asymmetry may result from inherent anatomical differences, functional dominance between body sides, or factors such as muscle strength disparities, flexibility, coordination, previous injuries, postural habits, and neurological conditions. Notably, all subjects in this study were right-hand dominant, highlighting the case of a stroke patient with right-sided hemiplegia.This patient's asymmetrical mobility, showing a reduced range of right axial rotation compared to the left, contrasts with healthy individuals, who typically exhibit a greater range of right axial rotation. This suggests that the observed asymmetry may also relate to the natural distribution of left- and right-handedness in humans. This comparison validates the effectiveness of the system, while our study also contributes valuable objective outcomes to the knowledge base for thoracic spine mobility in stroke patients.

As shown in the results of section III-C, in addition to calculating primary and coupled ROM of the thoracic spine across various planes and DOFs during continuous movements, the active analysis system enables quantitative assessment of the key timing of thoracic spine events. This capability sets it apart from previous studies. It is evident from Tables II and III that the individual with spinal-related issues who has experienced a stroke exhibits a notably slower performance in executing thoracic spine target movements across all planes, necessitating a longer duration compared to healthy individuals.

B. Portable Wireless Characteristics

Through the utilization of the active analysis algorithm developed within this study, an autonomous analysis of wearer thoracic spine movements has been realized. This advancement serves as a robust foundation for a comprehensive evaluation of thoracic spine mobility performance. Furthermore, the attributes of the system enhance its practically for individuals. These attributes include its wireless design and absence of wiring, its capacity to function without environmental limitations, and the flexibility to position the control box unit up to 50 meters away from the inertial sensing units. This collective configuration creates an environment that allows wearers to execute movements without constraints, resulting in smoother and more natural motions. As a result, the system is well-positioned to offer more authentic feedback on the inherent natural state of thoracic spine movement. The inherent wireless nature, operational simplicity and cost-effectiveness of this system contribute significantly to its versatility and practical utility.

C. Limitations

The developed active analysis system has demonstrated promising capabilities in assessing thoracic spine mobility through continuous movements. Nonetheless, our study is subject to several limitations. Firstly, it aims to design a stable, objective, and convenient method for measuring thoracic spine mobility in motion. Our emphasis has been on system feasibility and effectiveness, specifically focusing on the frequency of individual thoracic spine movements. Consequently, our analysis prioritizes the quantity of movements over the diversity of participant demographics, aiming to underscore the motions themselves rather than providing a comprehensive demographic analysis. This approach confines our investigation to individual thoracic spine mobility tests and assessments, rather than characterizing thoracic spine mobility in a specific population or delving into the interplay among additional relevant parameters.

Secondly, the experiments predominantly involve healthy individuals and include only one representative case of thoracic mobility issues with post-stroke conditions. The clinical application of this system in special populations, such as the elderly and those potentially experiencing thoracic mobility issues, remains unexplored due to a lack of comprehensive and targeted research. While this pilot study laid the foundation, future research should explore various scenarios to unveil system versatility.

Thus, as our work progresses, we aim to undertake more comprehensive and focused research to gain valuable insights by analyzing system's performance across diverse demographics. Currently, we are utilizing a stroke patient as a pilot for preliminary exploration. Moving forward, we will conduct targeted evaluations of thoracic spine mobility in stroke patients, including measurements of trunk movement smoothness. This will deepen our understanding of the rehabilitation needs and progress of these patients. Adopting this holistic approach will enable us to fully leverage the system's potential in both research and clinical settings.

V. CONCLUSION

In this study, we first introduce an objective, stable, and automated system for automatic quantifying thoracic spine mobility during continuous movements across all anatomical planes and DOFs. The effectiveness of our active analysis system was demonstrated through Inter-day experiments involving 957 thoracic spine motions from healthy participants, as well as one representative case of thoracic mobility issues with post-stroke conditions. This non-invasive, portable, wireless wearable thoracic spine active analysis system, proposed in this paper, empowers individuals to self-assess and monitor their thoracic spine mobility, offering an effective approach for analyzing upper and middle back pain. Moreover, with its attributes of cost-effectiveness, convenience, and efficiency, this system can aid doctors in the clinical diagnosis and evaluation of spine-related disorders. Beyond these advantages, this innovative system holds the potential to enhance our understanding of thoracic mobility patterns.

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REFERENCES

[1] World Health Organization. *Physical Activity*. Accessed: Dec. 29, 2023. [Online]. Available: https://www.who.int/health-topics/physical-activity#tab=tab_1

[2] N. Fouquet et al., "Prevalence of thoracic spine pain in a surveillance network," *Occupational Med.*, vol. 65, no. 2, pp. 122–125, Mar. 2015.

[3] N. Z. Ratzon, T. Yaros, A. Mizlik, and T. Kanner, "Musculoskeletal symptoms among dentists in relation to work posture," *Work*, vol. 15, no. 3, pp. 153–158, 2001.

[4] P. Leino, "Symptoms of stress predict musculoskeletal disorders," *J. Epidemiol. Community Health*, vol. 43, no. 3, pp. 293–300, 1989.

[5] K. Hasegawa, M. Okamoto, S. Hatsushikano, H. Shimoda, M. Ono, and K. Watanabe, "Normative values of spino-pelvic sagittal alignment, balance, age, and health-related quality of life in a cohort of healthy adult subjects," *Eur. Spine J.*, vol. 25, no. 11, pp. 3675–3686, Nov. 2016.

[6] P. Brigatto, J. C. Carbinatto, C. M. Costa, M. I. L. Montebelo, I. Rasera-Júnior, and E. M. Pazzianotto-Forti, "Application of positive airway pressure in restoring pulmonary function and thoracic mobility in the postoperative period of bariatric surgery: A randomized clinical trial," *Brazilian J. Phys. Therapy*, vol. 18, no. 6, pp. 553–562, Dec. 2014.

[7] H.-J. Jang, M.-J. Kim, and S.-Y. Kim, "Effect of thorax correction exercises on flexed posture and chest function in older women with age-related hyperkyphosis," *J. Phys. Therapy Sci.*, vol. 27, no. 4, pp. 1161–1164, 2015.

[8] D. M. Kado, M. Huang, A. S. Karlamangla, E. Barrett-Connor, and G. A. Greendale, "Hyperkyphotic posture predicts mortality in older community-dwelling men and women: A prospective study," *J. Amer. Geriatrics Soc.*, vol. 52, no. 10, pp. 1662–1667, Oct. 2004.

[9] F. Magerl, M. Aebi, S. D. Gertzbein, J. Harms, and S. Nazarian, "A comprehensive classification of thoracic and lumbar injuries," *Eur. Spine J.*, vol. 3, no. 4, pp. 184–201, Aug. 1994.

[10] H. Hemingway, M. Shipley, S. Stansfeld, and M. Marmot, "Sickness absence from back pain, psychosocial work characteristics and employment grade among office workers," *Scandin. J. Work, Environ. Health*, vol. 23, no. 2, pp. 121–129, Apr. 1997.

[11] E. Clays, D. De Bacquer, F. Leynen, M. Kornitzer, F. Kittel, and G. De Backer, "The impact of psychosocial factors on low back pain: Longitudinal results from the belstress study," *Spine*, vol. 32, no. 2, pp. 262–268, Jan. 2007.

[12] S. Dagenais, J. Caro, and S. Haldeman, "A systematic review of low back pain cost of illness studies in the United States and internationally," *Spine J.*, vol. 8, no. 1, pp. 8–20, Jan. 2008.

[13] N. M. Dunk and J. P. Callaghan, "Lumbar spine movement patterns during prolonged sitting differentiate low back pain developers from matched asymptomatic controls," *Work*, vol. 35, no. 1, pp. 3–14, 2010.

[14] A. Hernandez, K. Gross, and S. Gombatto, "Differences in lumbar spine and lower extremity kinematics during a step down functional task in people with and people without low back pain," *Clin. Biomechanics*, vol. 47, pp. 46–52, Aug. 2017.

[15] D. Hoy et al., "The global burden of low back pain: Estimates from the global burden of disease 2010 study," *Ann. Rheumatic Diseases*, vol. 73, no. 6, pp. 968–974, Jun. 2014.

[16] M. S. Kerr et al., "Biomechanical and psychosocial risk factors for low back pain at work," *Amer. J. Public Health*, vol. 91, no. 7, p. 1069, 2001.

[17] J. K. Lee, G. T. Desmoulin, A. H. Khan, and E. J. Park, "Comparison of 3D spinal motions during stair-climbing between individuals with and without low back pain," *Gait Posture*, vol. 34, no. 2, pp. 222–226, Jun. 2011.

[18] J. K. Lee and E. J. Park, "3D spinal motion analysis during staircase walking using an ambulatory inertial and magnetic sensing system," *Med. Biol. Eng. Comput.*, vol. 49, no. 7, pp. 755–764, Jul. 2011.

[19] T. Mitchell, P. B. O'Sullivan, A. F. Burnett, L. Straker, and A. Smith, "Regional differences in lumbar spinal posture and the influence of low back pain," *BMC Musculoskeletal Disorders*, vol. 9, no. 1, pp. 1–11, Dec. 2008.

[20] R. Müller, T. Ertelt, and R. Blickhan, "Low back pain affects trunk as well as lower limb movements during walking and running," *J. Biomechanics*, vol. 48, no. 6, pp. 1009–1014, Apr. 2015.

[21] L. R. Van Dillen, S. P. Gombatto, D. R. Collins, J. R. Engsberg, and S. A. Sahrmann, "Symmetry of timing of hip and lumbopelvic rotation motion in 2 different subgroups of people with low back pain," *Arch. Phys. Med. Rehabil.*, vol. 88, no. 3, pp. 351–360, Mar. 2007.

[22] W. Van Hoof, K. Volkaerts, K. O'Sullivan, S. Verschueren, and W. Dankaerts, "Comparing lower lumbar kinematics in cyclists with low back pain (flexion pattern) versus asymptomatic controls–field study using a wireless posture monitoring system," *Manual Therapy*, vol. 17, no. 4, pp. 312–317, Aug. 2012.

[23] J. M. Fritz and S. R. Piva, "Physical impairment index: Reliability, validity, and responsiveness in patients with acute low back pain," *Spine*, vol. 28, no. 11, pp. 1189–1194, Jun. 2003.

[24] L. Bissolotti, M. Gobbo, J. H. Villafane, and S. Negrini, "Spinopelvic balance: New biomechanical insights with clinical implications for Parkinson's disease," *Eur. Spine J.*, vol. 23, pp. 576–583, Mar. 2014.

[25] S. J. Edmondston, M. M. Christensen, S. Keller, L. B. Steigen, and L. Barclay, "Functional radiographic analysis of thoracic spine extension motion in asymptomatic men," *J. Manipulative Physiological Therapeutics*, vol. 35, no. 3, pp. 203–208, Mar. 2012.

[26] S. Iyer et al., "Variations in sagittal alignment parameters based on age: A prospective study of asymptomatic volunteers using full-body radiographs," *Spine*, vol. 41, no. 23, pp. 1826–1836, 2016.

[27] S. Edmondston, A. Ferguson, P. Ippersiel, L. Ronningen, S. Sodeland, and L. Barclay, "Clinical and radiological investigation of thoracic spine extension motion during bilateral arm elevation," *J. Orthopaedic Sports Phys. Therapy*, vol. 42, no. 10, pp. 861–869, Oct. 2012.

[28] B. Mazzone, R. Wood, and S. Gombatto, "Spine kinematics during prone extension in people with and without low back pain and among classification-specific low back pain subgroups," *J. Orthopaedic Sports Phys. Therapy*, vol. 46, no. 7, pp. 571–579, Jul. 2016.

[29] F. M. Rast, E. S. Graf, A. Meichtry, J. Kool, and C. M. Bauer, "Between-day reliability of three-dimensional motion analysis of the trunk: A comparison of marker based protocols," *J. Biomechanics*, vol. 49, no. 5, pp. 807–811, Mar. 2016.

[30] S. J. Mousavi, R. Tromp, M. C. Swann, A. P. White, and D. E. Anderson, "Between-session reliability of opto-electronic motion capture in measuring sagittal posture and 3-D ranges of motion of the thoracolumbar spine," *J. Biomechanics*, vol. 79, pp. 248–252, Oct. 2018.

[31] S. M. Beaudette, D. P. Zwambag, R. B. Graham, and S. H. M. Brown, "Discriminating spatiotemporal movement strategies during spine flexion-extension in healthy individuals," *Spine J.*, vol. 19, no. 7, pp. 1264–1275, Jul. 2019.

[32] M. Dreischarf, E. Pries, M. Bashkuev, M. Putzier, and H. Schmidt, "Differences between clinical 'snap-shot' and 'real-life' assessments of lumbar spine alignment and motion–what is the 'real' lumbar lordosis of a human being?" *J. Biomechanics*, vol. 49, no. 5, pp. 638–644, Mar. 2016.

[33] J. M. Williams, I. Haq, and R. Y. Lee, "A novel approach to the clinical evaluation of differential kinematics of the lumbar spine," *Manual Therapy*, vol. 18, no. 2, pp. 130–135, Apr. 2013.

[34] T.-H. Ha, K. Saber-Sheikh, A. P. Moore, and M. P. Jones, "Measurement of lumbar spine range of movement and coupled motion using inertial sensors—A protocol validity study," *Manual Therapy*, vol. 18, no. 1, pp. 87–91, Feb. 2013.

[35] A. Bruton, J. H. Conway, and S. T. Holgate, "Reliability: What is it, and how is it measured?" *Physiotherapy*, vol. 86, no. 2, pp. 94–99, Feb. 2000.

[36] J. L. Fleiss, "Analysis of data from multiclinic trials," *Controlled Clin. Trials*, vol. 7, no. 4, pp. 267–275, Dec. 1986.

[37] T. K. Koo and M. Y. Li, "A guideline of selecting and reporting intraclass correlation coefficients for reliability research," *J. Chiropractic Med.*, vol. 15, no. 2, pp. 155–163, Jun. 2016.

[38] M. A. Seffinger et al., "Reliability of spinal palpation for diagnosis of back and neck pain: A systematic review of the literature," *Spine*, vol. 29, no. 19, pp. E413–E425, Oct. 2004.

[39] R. Bravi et al., "An inertial measurement unit-based wireless system for shoulder motion assessment in patients with cervical spinal cord injury: A validation pilot study in a clinical setting," *Sensors*, vol. 21, no. 4, p. 1057, Feb. 2021.

[40] V. L. Feigin et al., "Global, regional, and national burden of stroke and its risk factors, 1990–2019: A systematic analysis for the global burden of disease study 2019," *Lancet Neurol.*, vol. 20, no. 10, pp. 795–820, 1990.

[41] M. C. Cirstea and M. F. Levin, "Compensatory strategies for reaching in stroke," *Brain*, vol. 123, no. 5, pp. 940–953, May 2000.

[42] D. de Kam, A. C. Geurts, V. Weerdesteyn, and G. Torres-Oviedo, "Direction-specific instability poststroke is associated with deficient motor modules for balance control," *Neurorehabilitation Neural Repair*, vol. 32, nos. 6–7, pp. 655–666, Jun. 2018.

[43] K. Berg, S. Wood-Dauphine, J. I. Williams, and D. Gayton, "Measuring balance in the elderly: Preliminary development of an instrument," *Physiotherapy Canada*, vol. 41, no. 6, pp. 304–311, Nov. 1989.

[44] R. W. Bohannon and M. B. Smith, "Interrater reliability of a modified Ashworth scale of muscle spasticity," *Phys. Therapy*, vol. 67, no. 2, pp. 206–207, Feb. 1987.

[45] S. van Sint Jan, *Color Atlas of Skeletal Landmark Definitions E-book: Guidelines for Reproducible Manual and Virtual Palpations*. Amsterdam, The Netherlands: Elsevier, 2007.

[46] M. Narimani and N. Arjmand, "Three-dimensional primary and coupled range of motions and movement coordination of the pelvis, lumbar and thoracic spine in standing posture using inertial tracking device," *J. Biomechanics*, vol. 69, pp. 169–174, Mar. 2018.

[47] D. L. Woods, J. M. Wyma, E. W. Yund, T. J. Herron, and B. Reed, "Factors influencing the latency of simple reaction time," *Frontiers Human Neurosci.*, vol. 9, p. 131, Mar. 2015.

[48] K. O. McGraw and S. P. Wong, "Forming inferences about some intraclass correlation coefficients," *Psychol. Methods*, vol. 1, no. 1, pp. 30–46, 1996.

[49] J. P. Weir, "Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM," *J. Strength Conditioning Res.*, vol. 19, no. 1, pp. 231–240, 2005.

[50] G. Atkinson and A. M. Nevill, "Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine," *Sports Med.*, vol. 26, no. 4, pp. 217–238, Oct. 1998.

[51] J. E. Lexell and D. Y. Downham, "How to assess the reliability of measurements in rehabilitation," *Amer. J. Phys. Med. Rehabil.*, vol. 84, no. 9, pp. 719–723, Sep. 2005.

[52] F. Pan, A. Firouzabadi, S. Reitmaier, T. Zander, and H. Schmidt, "The shape and mobility of the thoracic spine in asymptomatic adults—A systematic review of in vivo studies," *J. Biomechanics*, vol. 78, pp. 21–35, Sep. 2018.

[53] P. Esteban-González, E. A. Sánchez-Romero, and J. H. Villafañe, "Analysis of the active measurement systems of the thoracic range of movements of the spine: A systematic review and a meta-analysis," *Sensors*, vol. 22, no. 8, p. 3042, Apr. 2022.

[54] D. Ignasiak, A. Rüeger, and S. J. Ferguson, "Multi-segmental thoracic spine kinematics measured dynamically in the young and elderly during flexion," *Hum. Movement Sci.*, vol. 54, pp. 230–239, Aug. 2017.

[55] N.-G. Lee, J.-A. Lee, and J.-B. Kim, "A comparison of three-dimensional spine kinematics during multidirectional trunk movement between elderly subjects with degenerative spine disease and healthy young adults," *J. Phys. Therapy Sci.*, vol. 25, no. 1, pp. 21–26, 2013.

[56] D. Morita et al., "Range of motion of thoracic spine in sagittal plane," *Eur. Spine J.*, vol. 23, no. 3, pp. 673–678, Mar. 2014.

[57] G. O. Glofcheskie and S. H. M. Brown, "Athletic background is related to superior trunk proprioceptive ability, postural control, and neuromuscular responses to sudden perturbations," *Human Movement Sci.*, vol. 52, pp. 74–83, Apr. 2017.

[58] M. Vaugoyeau, H. Hakam, and J.-P. Azulay, "Proprioceptive impairment and postural orientation control in Parkinson's disease," *Human Movement Sci.*, vol. 30, no. 2, pp. 405–414, Apr. 2011.

[59] H. O'gorman and G. Jull, "Thoracic kyphosis and mobility: The effect of age," *Physiotherapy Pract.*, vol. 3, no. 4, pp. 154–162, Jan. 1987.

[60] S. J. Edmondston et al., "Influence of posture on the range of axial rotation and coupled lateral flexion of the thoracic spine," *J. Manipulative Physiological Therapeutics*, vol. 30, no. 3, pp. 193–199, Mar. 2007.

[61] T. Fujimori et al., "Kinematics of the thoracic spine in trunk rotation: In vivo 3-dimensional analysis," *Spine*, vol. 37, no. 21, pp. E1318–E1328, Oct. 2012.

[62] T. Fujimori et al., "Kinematics of the thoracic spine in trunk lateral bending: In vivo three-dimensional analysis," *Spine J.*, vol. 14, no. 9, pp. 1991–1999, Sep. 2014.

[63] J. Willems, G. Jull, and J.-F. Ng, "An in vivo study of the primary and coupled rotations of the thoracic spine," *Clin. Biomechanics*, vol. 11, no. 6, pp. 311–316, Sep. 1996.