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Unveiling the Nexus of Cervical Proprioception, Postural Stability, and Impeding Factors in Cervical Spondylosis: Insights from Reposition Errors, Limits of Stability, and Mediation Analysis

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Abstract: Cervical proprioception and postural stability play crucial roles in maintaining optimal head and neck positioning, yet their relationship and implications in cervical spondylosis (CS) remain underexplored. This study aims to investigate cervical proprioceptive reposition errors, limits of stability, and their association in individuals with CS while considering the mediating effects of pain and kinesiophobia. The primary objectives are to compare cervical proprioceptive reposition errors and limits of stability variables between individuals with CS and age-matched healthy controls, explore their associations within the CS group, and determine the mediating roles of pain and kinesiophobia. A cross-sectional study recruited 60 individuals with CS and 60 healthy controls. Cervical joint reposition errors (JREs) were assessed using a cervical range-of-motion device, while limits of stability were evaluated using a computerized dynamic posturography system. Pain, kinesiophobia, and demographic data were collected. Parametric tests, correlation analyses, and multiple regression were employed for data analysis. Individuals with CS exhibited significantly higher cervical JREs in flexion, extension, and rotation compared with healthy controls ($p < 0.001$). Within the CS group, correlations revealed associations between JREs and limits-of-stability variables ($p < 0.05$). Mediation analysis demonstrated significant direct and indirect effects of pain and kinesiophobia on the relationship between JREs and limits-of-stability variables in the CS group ($p < 0.005$). CS is associated with impaired cervical proprioception, increased reposition errors, and compromised postural stability. This study highlights the interplay between proprioception, stability, pain, and psychological factors, emphasizing the need for comprehensive interventions in individuals with CS to enhance functional outcomes and quality of life.

Keywords: cervical spondylosis; proprioception; postural stability; joint reposition error; limits of stability; pain; kinesiophobia

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1. Introduction

The intricate interplay between the sensory system and musculoskeletal framework underpins the human body's ability to perceive and maintain its position in space [1]. Proprioception, a pivotal facet of this sensorimotor integration, is responsible for furnishing the central nervous system with crucial information about the position, movement, and orientation of body segments [2]. Specifically, cervical proprioception, which centers on the neck region, plays an indispensable role in preserving postural stability, coordinating head movements, and ensuring optimal spatial awareness [3].

Cervical proprioception is conferred through a network of specialized receptors, known as proprioceptors, dispersed throughout the muscles, tendons, ligaments, and joints of the cervical spine [4]. These proprioceptors continuously transmit feedback to the brain, providing real-time data about muscle length, tension, joint angles, and related parameters that govern neck positioning and motion [5]. As a result, individuals can effortlessly navigate their surroundings, maintain balance, and undertake complex

tasks that require synchronized head and neck movements [6,7]. The significance of cervical proprioception becomes particularly apparent in scenarios where its functionality is compromised [8,9]. Cervical spondylosis (CS), a degenerative condition affecting the cervical spine, can adversely impact the proprioceptive mechanisms that regulate the neck's position and movement [10]. This condition, characterized by the wear and tear of spinal discs, facet joints, and other structural components, can lead to proprioceptive deficits and subsequent challenges in maintaining postural stability and coordinating neck movements [11].

Prior research has elucidated the fundamental significance of cervical proprioception in maintaining postural stability and coordinating head movements [12]. Studies have highlighted the critical role of proprioceptive signals from cervical muscles and ligaments in modulating the activity of neck muscles to maintain an upright posture and stabilize the head during various tasks [10,13]. These studies underscore the essential contribution of cervical proprioception to the dynamic control of head position [13]. Moreover, cervical proprioceptive deficits are associated with various musculoskeletal conditions. Research by Shelke et al. [14] demonstrated that individuals with neck pain exhibit impaired cervical proprioception, characterized by increased joint position errors during head repositioning tasks. Similarly, studies by Sjölander et al. [15] and Madeleine et al. [16] reported altered proprioceptive function in individuals with whiplash-associated disorders, emphasizing the role of cervical proprioception in neck pain conditions. These findings collectively indicate that disturbances in cervical proprioception can have profound implications for musculoskeletal health and postural control.

Pain, often a prominent feature of CS, could potentially influence proprioceptive accuracy and stability [17,18]. Kinesiophobia, characterized by an irrational fear of movement due to the anticipation of pain, might also interact with proprioceptive function and postural stability in this population [17,19]. By delving into these mediating factors, a more nuanced understanding of the multifaceted relationship between cervical proprioception, stability, pain, and psychological factors can be obtained [20,21].

Despite the valuable insights provided by previous research, significant gaps remain in our understanding of cervical proprioception, particularly in the context of cervical spondylosis. Cervical spondylosis, a degenerative condition affecting the cervical spine, can adversely impact the proprioceptive mechanisms that regulate the neck's position and movement [22]. However, to date, there has been a notable scarcity of comprehensive studies that systematically investigate the relationship between cervical proprioception and postural stability in individuals with cervical spondylosis. Existing literature predominantly focuses on either proprioception or postural stability in isolation, overlooking the intricate interplay between these factors in the context of cervical spondylosis [22].

This research gap is significant as cervical spondylosis is a prevalent condition, particularly among older adults, and is often associated with neck pain and functional limitations. Understanding how cervical proprioception and postural stability are affected in cervical spondylosis is crucial for developing effective rehabilitation strategies tailored to the unique needs of this population. Additionally, while pain is a common symptom of cervical spondylosis, its potential mediating effect on the relationship between proprioception and postural stability remains underexplored. Furthermore, kinesiophobia, characterized by an irrational fear of movement due to the anticipation of pain, might interact with proprioceptive function and postural stability in individuals with cervical spondylosis, yet this relationship has not been thoroughly investigated.

In light of the aforementioned considerations, the primary objectives of this study are as follows: Firstly, to assess the disparities in cervical joint reposition errors (JREs) and limits-of-stability variables between individuals diagnosed with CS and age-matched healthy controls. Secondly, to explore the potential associations between cervical proprioceptive reposition errors and limits-of-stability variables in the CS group, thereby shedding light on the intrinsic relationship between these aspects. Lastly, the study aims to investigate the mediating effect of pain and kinesiophobia on the connection between cervical

proprioceptive reposition errors and limits-of-stability variables in individuals with CS. By addressing these objectives and hypotheses, this study aims to contribute to the growing body of knowledge surrounding cervical proprioception, stability impairments, and their potential determinants in individuals with CS. The findings have the potential to inform therapeutic interventions and rehabilitation strategies tailored to the unique needs of this population, ultimately enhancing their quality of life and functional abilities.

2. Materials and Methods

2.1. Study Design, Setting, Ethics

This study utilized a cross-sectional design to comprehensively investigate the relationship between cervical proprioception, stability parameters, and potential mediating factors in individuals with CS. The research was conducted within a controlled setting to ensure data accuracy and consistency while minimizing confounding variables. The study was conducted at a medical rehabilitation center equipped with state-of-the-art facilities, including a Cervical Range of Motion (CROM) device (Performance Attainment Associates, MN, USA) for assessing proprioception and an Iso-Free system (Techno body, Bergamo, Italy) for evaluating stability, pain, and psychological factors. The controlled environment of the rehabilitation center enabled standardized data collection, reducing the influence of external variables on the study outcomes. The research adhered to the principles outlined in the Declaration of Helsinki and was conducted with the approval of the KKU Institutional Review Board Committee. Confidentiality and anonymity of participants were strictly upheld throughout the study, with data coded and stored securely.

2.2. Participants

The participants included two distinct groups: individuals diagnosed with CS and age-matched healthy controls. Participants with CS were selected using a purposive sampling technique based on medical records and diagnostic criteria. Healthy controls were recruited from the general population and were matched for age to ensure a meaningful comparison. Participants eligible for inclusion in this study were those who met the criteria for CS. CS was defined as an individual experiencing neck pain with radiological evidence confirming cervical degeneration. The study focused on individuals aged over 40 years, encompassing both men and women. Participants were required to have been referred by a physician and to present with neck pain as their primary complaint. Moreover, individuals needed to have radiological confirmation of CS, as indicated by degenerative changes in the cervical spine, such as intervertebral disc degeneration, osteophyte formation on vertebral bodies, hypertrophy of facets and laminal arches, and evidence of ligamentous and segmental instability. To ensure specificity and consistency, participants were subjected to Spurling's test, and a positive result was considered part of the inclusion criteria. Additionally, individuals with limitations in the range of motion of the cervical spine were eligible for inclusion. This limitation in cervical spine movement was to have been established through clinical assessment.

For the age-matched healthy control group, inclusion criteria mandated age-matched subjects with normal cervical spine range of motion in all planes. Furthermore, these control subjects must have had no history of cervical spine injury, dizziness, vertigo, or other musculoskeletal complaints. The rigorous application of these inclusion and exclusion criteria aimed to assemble a homogeneous group of individuals with confirmed CS and age-matched healthy controls, ensuring the validity and reliability of the study's findings.

2.3. Cervical Proprioceptive Reposition Sense Measurement

The evaluation of cervical JREs using the CROM device followed the established protocols [23]. Cervical JREs refer to the discrepancies between an individual's perceived or intended head position and the actual head position in space, and these errors are quantified in degrees (°). The participant assumed an upright seated position, maintaining a straight back, with their head oriented straight ahead and their feet planted firmly on the

ground. This neutral head position was adopted as the baseline for the assessment. All participants were provided with comprehensive instructions about the study procedure, and standardized guidelines were administered during the testing phase. To eliminate visual and extraneous physical cues, participants were blindfolded using a travel eye mask, and a Velcro strap was utilized to minimize unnecessary movements of the trunk and shoulders throughout the cervical JRE testing (Figure 1).



Figure 1. Cervical joint reposition error assessment using CROM unit.

To maintain uniform measurement conditions, the examiner firmly affixed the CROM unit to the participant's head with the help of a Velcro strap. Simultaneously, the magnetic yoke of the CROM device was positioned on the participant's shoulder, aligning the arrow symbol with the north direction. This setup allowed for the calibration of the CROM device to establish a neutral position. The CROM device, well known for its accuracy in quantifying cervical range of motion, demonstrated consistent intratester reliability, with values ranging from 0.62 to 0.91, and inter-tester reliability, with values ranging from 0.74 to 0.87 [24].

To evaluate the cervical JREs, the examiner took charge of directing the participant's head to a specific target position, precisely set at 50% of the maximum cervical range of motion range previously determined by the examiner. The participant received instructions to maintain their head in this designated position consistently for a duration of 3 s. After this period, participants were asked to mentally note this target position. Following that, the examiner gradually guided the participant's head back to the initial neutral position. Subsequently, the participant was instructed to actively replicate the target position by adjusting their head. The degree of disparity between the participant's repositioned head and the actual target position was measured as the repositioning accuracy error, quantified in degrees.

Cervical JRE testing encompassed two planes of motion: sagittal (flexion and extension) and transverse (right and left rotation). The order of testing across these directions

was randomized using a straightforward chit method. To ensure robustness, each direction of cervical JRE testing was conducted in triplicate, and the mean error derived from these trials was employed for subsequent analysis. To maintain consistency, the testing process was overseen by a single investigator, and participants received no feedback during the testing procedure.

2.4. Limits of Stability Assessment

The assessment of limits of stability employed computerized dynamic posturography through the Iso-Free system (Techno body, Bergamo, Italy). Limits of Stability pertain to the maximum extent to which an individual can intentionally lean or sway their body while maintaining a stable base of support without losing balance or taking a step and the value is expressed as a percentage. This technique offers a comprehensive analysis of the area within which an individual can safely move while maintaining their base of support intact. The system consists of a circular platform integrated with several key components, including a stabilometric posture platform, a touch screen, a 3D camera, and specialized software. The stabilometric force platform plays a pivotal role in this assessment by analyzing the center of pressure when an individual is in a standing posture, effectively detecting the pressure exerted on the platform [25]. The entire limits-of-stability assessment was conducted in a serene and well-ventilated environment. Participants were instructed to position themselves on the stabilometric force platform with both feet together, adhering to standardized protocols (Figure 2).

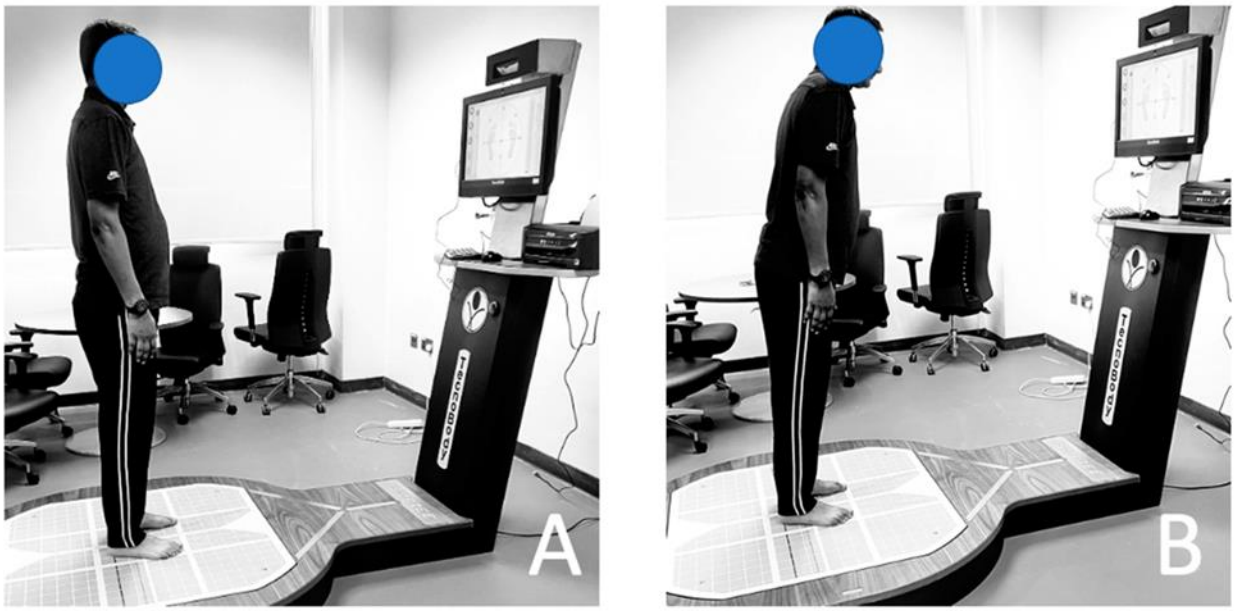


Figure 2. Limits-of-stability assessment using stabilometric force platform; (**A**) starting and (**B**) moving to limits-of-stability target.

The participant's gaze was directed toward the screen located in front of them, focusing on the targets presented by the posturography device. Randomly appearing in all eight directions, these targets appeared momentarily on the screen. Participants were tasked with shifting their center of mass toward the target while maintaining their feet stationary. The posturography instrument meticulously recorded the degree of sway required for the individual to attain the target position from the center, following the shortest vertical or horizontal path. The scoring system assigned a maximum score of 100 for each direction, where lower scores indicated increased sway. The assessed limits-of-stability parameters encompassed reaction time, maximum excursion, and directional control.

2.5. Kinesiophobia

We assessed kinesiophobia using the Tampa Scale of Kinesiophobia (TSK), a well-established and validated self-report questionnaire [26]. The TSK comprises 17 items designed to measure the fear of movement or re-injury in individuals with musculoskeletal pain conditions [26]. Each item is rated on a 4-point Likert scale, with responses ranging from "strongly disagree" to "strongly agree". The total score on the TSK provides an indication of an individual's level of kinesiophobia, with higher scores reflecting a greater fear of movement [26–30].

2.6. Sample Size Calculation

The sample size calculation was conducted using G*Power (version 3.1.4), a software tool that employs established statistical methods. To detect meaningful differences between the two groups, a statistical power of 0.80 (80%) was targeted, along with a significance level (alpha) of 0.05. The anticipated effect size was estimated based on the study by Reddy et al. [22]. Given the complexity and multifaceted nature of the study's assessments, a larger sample size was deemed necessary to account for potential variations and confounding factors. Additionally, the inclusion of 60 subjects in each group would enhance the generalizability of the study's findings and increase the statistical robustness of the results. By meticulously considering these factors and employing a sample size of 60 subjects in each group, the study aimed to minimize the likelihood of type II errors, ensuring that meaningful differences and associations, if present, would be accurately detected and reported.

2.7. Data Analysis

The dataset collected from the study exhibited a normal distribution, enabling the utilization of parametric statistical tests for the data analysis. With a sample size of 60 subjects in each group, the application of parametric tests was deemed appropriate to draw meaningful conclusions regarding cervical proprioceptive reposition sense and limits of stability. Descriptive statistics were initially employed to succinctly summarize the demographic characteristics of participants in both the CS group and the age-matched healthy control group. Mean values accompanied by standard deviations are presented for continuous variables, while frequencies and percentages were used for categorical variables. In order to address the primary research objectives, independent t-tests were conducted to compare continuous variables between the CS group and the healthy control group. These tests aimed to discern any statistically significant differences in cervical proprioceptive reposition errors and limits-of-stability parameters between the two groups.

Moreover, within the CS group, correlation analyses were performed using Pearson correlation coefficients to explore potential associations between cervical proprioceptive reposition errors and limits-of-stability variables. In the mediation analysis, we employed a model to examine whether pain and kinesiophobia act as mediators in the relationship between cervical JREs and limits-of-stability variables in individuals with CS. This analysis comprised several steps (Figure 3). First, we established a significant relationship between JREs and limits-of-stability variables. Second, we demonstrated a significant relationship between JREs and the mediator variables, which were pain and kinesiophobia. Third, we showed that the mediator variables, while controlling for JREs, significantly predicted the limits-of-stability variables. Finally, we assessed whether the direct impact of JREs on limits-of-stability variables was diminished or rendered non-significant when the mediator variables (pain and kinesiophobia) were included in the model. Multiple regression analysis facilitated a comprehensive exploration of how these mediating factors influenced the relationship between proprioception and postural control in individuals with CS. For the data analysis, the Statistical Package for the Social Sciences (SPSS) version 20 was utilized.

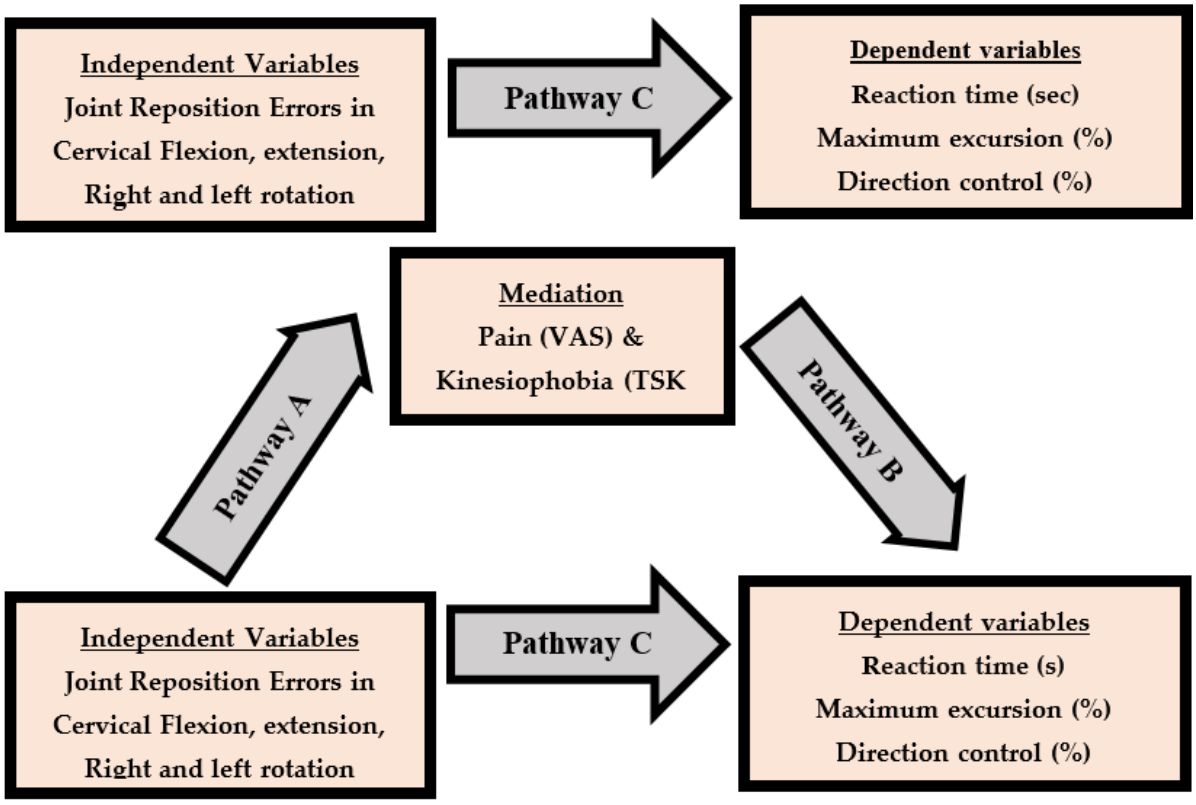


Figure 3. Illustrating the possible mediating role of kinesiophobia in the connection between cervical joint reposition sense and limits-of-stability variables among individuals with cervical spondylosis.

3. Results

3.1. Demographic Characteristics

The demographic characteristics of the study participants are detailed in Table 1, showing distinctions between the CS group and the healthy control group.

Table 1. Demographic characteristics of study subjects.

	CS Group (*n* = 60) Mean ± SD	**Healthy Control Group (*n* = 60) Mean ± SD**	***p*-Value**
Age	54.36 ± 5.29	33.94 ± 3.64	0.246
Gender: M:F	36:24	38:22	0.456
BMI	24.36 ± 2.36	23.12 ± 1.76	0.256
Neck pain intensity (VAS) (0–10 cm)	4.69 ± 1.41	-	-
Neck disability (NDI) %	31.48 ± 8.63	-	-

CS, cervical spondylosis; BMI, body mass index; VAS, visual analog scale; NDI, neck disability index.

Notably, the CS group (n = 60) displayed a mean age of 54.36 ± 5.29 years, contrasted with the healthy control group's (n = 60) younger mean age of 33.94 ± 3.64 years (p = 0.246). Gender distribution included 36 males and 24 females in the CS group and 38 males and 22 females in the healthy control group (p = 0.456). BMI showed a minor variance, with the CS group's mean BMI at 24.36 ± 2.36 and the healthy control group at 23.12 ± 1.76 (p = 0.256). The CS group reported neck pain intensity of 4.69 ± 1.41 on the visual analog scale (VAS), while the neck disability index (NDI) was 31.48 ± 8.63 for this group. These findings highlight the baseline characteristics and disparities between the groups, contributing to the contextual understanding of subsequent analyses.

3.2. Differences in Cervical JREs and Limits of Stability Variables between Individuals with CS and Healthy Individuals

The comparison of cervical JREs between individuals with CS and healthy individuals revealed significant differences across all directions, and various stability parameters are summarized in Table 2.

Table 2. Comparison of cervical joint reposition errors in four directions between CS and asymptomatic subjects.

	CS Group (n = 60) Mean ± SD	Healthy Group (n = 60) Mean ± SD	df	p-Value
JREs in cervical flexion (°)	4.43 ± 1.43	2.45 ± 0.23	265.12	<0.001
JREs in cervical extension (°)	5.12 ± 1.55	2.56 ± 0.31	233.23	<0.001
JREs in cervical rotation left (°)	4.01 ± 1.37	2.78 ± 0.45	236.34	<0.001
JREs in cervical rotation right (°)	4.03 ± 1.29	2.67 ± 0.81	217.45	<0.001
Reaction time (s)	2.39 ± 0.42	0.82 ± 0.40	139.85	<0.001
Maximum excursion (%)	5.60 ± 0.49	8.27 ± 0.43	963.33	<0.001
Direction control (%)	62.77 ± 4.64	86.80 ± 3.93	345.51	<0.001

CS, cervical spondylosis; JREs, joint reposition errors.

In cervical flexion, the CS group exhibited a significantly higher mean JREs of 4.43 ± 1.43 degrees compared with the healthy group's mean JREs of 2.45 ± 0.23 degrees (F = 265.12, $p < 0.001$). Similarly, in cervical extension, the CS group displayed a mean JREs of 5.12 ± 1.55 degrees, significantly greater than the healthy group's mean JREs of 2.56 ± 0.31 degrees (F = 233.23, $p < 0.001$). For cervical rotation to the left, the CS group had a mean JRE of 4.01 ± 1.37 degrees, while the healthy group showed a mean JRE of 2.78 ± 0.45 degrees (F = 236.34, $p < 0.001$). Similarly, in cervical rotation to the right, the CS group demonstrated a mean JRE of 4.03 ± 1.29 degrees, contrasting with the healthy group's mean JRE of 2.67 ± 0.81 degrees (F = 217.45, $p < 0.001$).

Furthermore, the CS group exhibited significant differences in stability parameters compared with the healthy group. Figure 4 illustrates that the CS group exhibited larger values for limits-of-stability variables and increased trunk sway, while the healthy control group had a higher percentage of achievement (eight directions—A1 to A8) in limits of stability compared with the CS group.

In terms of reaction time, the CS group demonstrated a mean reaction time of 2.39 ± 0.42 s, considerably higher than the healthy group's mean reaction time of 0.82 ± 0.40 s (F = 139.85, $p < 0.001$). Similarly, the CS group displayed reduced maximum excursion with a mean of 5.60 ± 0.49%, whereas the healthy group exhibited a higher mean maximum excursion of 8.27 ± 0.43% (F = 963.33, $p < 0.001$). Moreover, in terms of directional control, the CS group showed diminished control with a mean of 62.77 ± 4.64%, compared with the healthy group's mean directional control of 86.80 ± 3.93% (F = 345.51, $p < 0.001$). These results collectively highlight the significant differences in cervical JREs and stability parameters between individuals with CS and asymptomatic subjects, underscoring the impact of cervical spondylosis on proprioceptive accuracy and postural stability.

3.3. Correlation Analysis: Associations between Cervical Joint Reposition Errors (JREs) and Limits-of-Stability Variables in Individuals with CS

The correlation analysis between cervical JREs and limits-of-stability variables among individuals with CS revealed significant associations (Table 3).

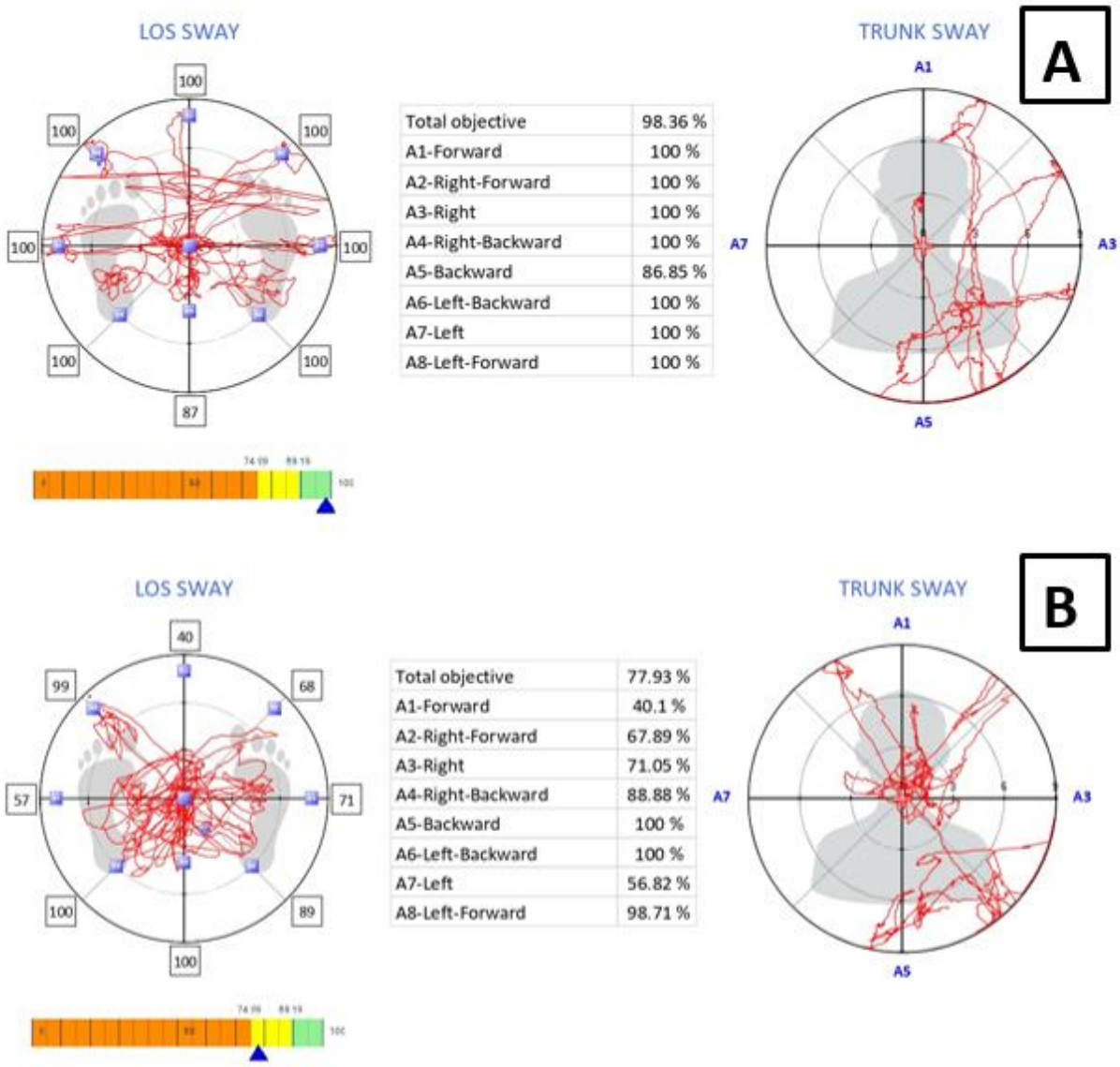


Figure 4. Limits of stability and trunk sway in (**A**) healthy and (**B**) CS individuals.

Table 3. Relationship between cervical joint reposition errors and limits-of-stability variables in CS individuals.

Variables		Reaction Time (s)	Maximum Excursion (%)	Direction Control (%)
JREs in cervical flexion (°)	r	0.31 **	−0.31 **	−0.41 **
JREs in cervical extension (°)	r	0.42 **	−0.36 **	−0.42 **
JREs in cervical rotation left (°)	r	0.46 **	−0.35 **	−0.45 **
JREs in cervical rotation right (°)	r	0.41 **	−0.41 **	−0.47 **

CS, cervical spondylosis; JREs = joint reposition errors; ** = correlation is significant at the 0.05 level (two-tailed).

In the CS group, JREs in cervical flexion were positively correlated with reaction time (r = 0.31, $p < 0.05$) and inversely correlated with both maximum excursion (r = −0.31, $p < 0.05$) and directional control (r = −0.41, $p < 0.05$). Similarly, JREs in cervical extension exhibited a positive correlation with reaction time (r = 0.42, $p < 0.05$) and a negative correlation with both maximum excursion (r = −0.36, $p < 0.05$) and directional control (r = −0.42, $p < 0.05$). For JREs in cervical rotation to the left, positive correlations were found with reaction time (r = 0.46, $p < 0.05$) and directional control (r = −0.45, $p < 0.05$),

while an inverse correlation was observed with maximum excursion (r = −0.35, $p < 0.05$). Similarly, JREs in cervical rotation to the right were positively correlated with reaction time (r = 0.41, $p < 0.05$) and negatively correlated with both maximum excursion (r = −0.41, $p < 0.05$) and directional control (r = −0.47, $p < 0.05$). These findings indicate that greater joint reposition errors in various cervical movements are associated with delayed reaction times and reduced limits-of-stability variables in individuals with cervical spondylosis, highlighting the interconnected nature of proprioceptive accuracy and postural stability in this population.

3.4. Mediation Analysis: The Role of Pain and Kinesiophobia in Mediating the Relationship between Cervical JREs and Limits-of-Stability Variables

Table 4 presents the results of the mediation effect analysis examining the role of kinesiophobia in mediating the relationship between cervical JREs and limits-of-stability variables.

Table 4. Mediation effect of kinesiophobia on the relationship between cervical JREs and limits-of-stability variables in CS individuals.

Variables	Direct and Indirect Effect (Total Effect)			Direct Effect			Indirect Effect		
	B	**SE**	***p*-Value**	**B**	**SE**	***p*-Value**	**B**	**SE**	***p*-Value**
Pain × JREs in flexion (°) X RT	0.53	0.04	<0.001	0.52	0.03	<0.001	0.18	0.03	0.002
Pain × JREs in extension (°) X RT	0.49	0.02	<0.001	0.61	0.02	<0.001	0.17	0.03	0.003
Pain × JREs in left rotation (°) X RT	0.51	0.04	<0.001	0.52	0.04	<0.001	0.19	0.04	0.004
Pain × JREs in right rotation (°) X RT	0.59	0.02	<0.001	0.56	0.04	<0.001	0.19	0.04	0.003
Pain × JREs in flexion (°) X RT	0.53	0.04	<0.001	0.51	0.03	<0.001	0.18	0.03	0.001
Pain × JREs in extension (°) X ME	0.53	0.04	<0.001	0.52	0.03	<0.001	0.18	0.03	0.002
Pain × JREs in left rotation (°) X ME	0.49	0.02	<0.001	0.61	0.02	<0.001	0.17	0.03	0.003
Pain × JREs in right rotation (°) X ME	0.51	0.04	<0.001	0.52	0.04	<0.001	0.19	0.04	0.004
Pain × JREs in flexion (°) X DC	0.59	0.02	<0.001	0.56	0.04	<0.001	0.19	0.04	0.003
Pain × JREs in extension (°) X DC	0.53	0.04	<0.001	0.51	0.03	<0.001	0.18	0.03	0.001
Pain × JREs in left rotation (°) X DC	0.59	0.02	<0.001	0.56	0.04	<0.001	0.19	0.04	0.003
Pain × JREs in right rotation (°) X DC	0.53	0.04	<0.001	0.51	0.03	<0.001	0.18	0.03	0.001
Kinesiophobia × JREs in flexion (°) X RT	0.53	0.02	<0.001	0.52	0.03	<0.001	0.18	0.03	0.003
Kinesiophobia × JREs in extension (°) X RT	0.58	0.01	<0.001	0.62	0.02	<0.001	0.16	0.03	0.004
Kinesiophobia × JREs in left rotation (°) X RT	0.51	0.04	<0.001	0.49	0.04	<0.001	0.29	0.04	0.003
Kinesiophobia × JREs in right rotation (°) X RT	0.49	0.04	<0.001	0.48	0.04	<0.001	0.18	0.04	0.004
Kinesiophobia × JREs in flexion (°) X ME	0.53	0.04	<0.001	0.52	0.03	<0.001	0.18	0.03	0.002
Kinesiophobia × JREs in extension (°) X ME	0.49	0.02	<0.001	0.61	0.02	<0.001	0.17	0.03	0.003
Kinesiophobia × JREs in left rotation (°) X ME	0.51	0.04	<0.001	0.52	0.04	<0.001	0.19	0.04	0.004
Kinesiophobia × JREs in right rotation (°) X ME	0.59	0.02	<0.001	0.56	0.04	<0.001	0.19	0.04	0.003
Kinesiophobia × JREs in flexion (°) X DC	0.53	0.04	<0.001	0.51	0.03	<0.001	0.18	0.03	0.001
Kinesiophobia × JREs in extension (°) X DC	0.49	0.04	<0.001	0.61	0.02	<0.001	0.17	0.03	0.001
Kinesiophobia × JREs in left rotation (°) X DC	0.51	0.03	<0.001	0.49	0.04	<0.001	0.18	0.04	0.002
Kinesiophobia × JREs in right rotation (°) X DC	0.63	0.04	<0.001	0.68	0.04	<0.001	0.19	0.04	0.001

RT, reaction time; ME, maximum excursion; DC, direction control; CS, cervical spondylosis; JREs, joint reposition errors; B, unstandardized coefficients; SE, standard error.

For each combination of explanatory variables, the total effect, direct effect, and indirect effect were evaluated. Notably, significant effects were observed across the board. In instances where pain interacted with JREs in various directions (flexion, extension, left and right rotation) in conjunction with reaction time, the total effect was consistently significant ($p < 0.001$), with respective total effects ranging from 0.49 to 0.59. Similarly, for the interactions involving maximum excursion and directional control, the total effects were significant ($p < 0.001$), with values ranging from 0.49 to 0.63. Direct effects remained consistently significant ($p < 0.001$) across all combinations, showcasing the direct influence of the explanatory variables on the outcome variables. Indirect effects, representing the mediating influence of kinesiophobia, were also statistically significant (*p*-values ranging

from 0.001 to 0.004), elucidating the role of kinesiophobia in mediating the relationship between cervical JREs and limits-of-stability variables.

4. Discussion

The current study provides a comprehensive analysis of cervical proprioception and stability parameters in the context of CS, yielding valuable insights into the intricate relationship between these variables and their potential mediators. The objectives of this investigation were threefold: to compare cervical proprioceptive reposition errors and limits-of-stability variables between individuals with CS and age-matched healthy controls, to explore the associations between cervical proprioceptive reposition errors and limits-of-stability variables within the CS group, and to examine the mediating effect of pain and kinesiophobia on the connection between cervical proprioceptive reposition errors and limits-of-stability variables.

The significance of cervical proprioception and its contribution to postural stability cannot be overstated. The present study underscores the impact of CS on proprioceptive function, as evidenced by significantly higher cervical JREs in the CS group compared with the healthy controls across all directions—flexion, extension, left and right rotation. These findings resonate with previous research that has highlighted the compromised proprioceptive accuracy observed in musculoskeletal conditions. Moreover, the documented reductions in limits-of-stability variables among individuals with CS underline the challenges they face in maintaining postural stability and coordinating head movements. Notably, the CS group displayed higher reaction times, reduced maximum excursions, and diminished directional control compared with the healthy controls. These limitations are likely to stem from the degenerative changes and biomechanical alterations associated with CS.

The significance of cervical proprioception and its integral role in maintaining postural stability gains further validation through the inclusion of various pertinent studies [5,31,32]. Our findings align with previous research, emphasizing the profound impact of CS on proprioceptive function. In consonance with the study conducted by Reddy et al. [22] that delved into the intricate relationship between cervical proprioception and neck pain intensity in individuals with CS, our findings resonate with their assertion that cervical proprioception plays a pivotal role in maintaining posture and movements. Their cross-sectional study involving 132 CS subjects and 132 healthy age-matched controls, underscores the impaired proprioceptive function in individuals with CS [22]. Similar to our study, they employed the measurement of JREs using a cervical range-of-motion device, assessing repositioning accuracy in various planes. The outcomes of the study by Reddy et al. [22] mirror our findings, demonstrating that CS subjects exhibited significantly larger JREs in all directions tested compared with the healthy control subjects. Their results highlight the extent of proprioceptive deficits in CS, with joint position errors ranging from 6.27° to 8.28° in the CS group and 2.36° to 4.48° in the control group. Moreover, their study unearthed a significant and positive correlation between neck pain intensity and cervical proprioception in the CS group, a result akin to our exploration of the mediating effects of pain and kinesiophobia on the relationship between cervical proprioceptive reposition errors and limits-of-stability variables. Also, studies conducted by Blanc et al. [33] and Li et al. [10] both reported compromised proprioceptive accuracy in individuals with musculoskeletal conditions such as whiplash-associated disorders and cervical pain. This consistency underscores the broader implications of musculoskeletal conditions on the intricate proprioceptive mechanisms that regulate posture and movement.

Furthermore, the observed reductions in limits-of-stability variables among individuals with CS indicate the complex challenges they face in maintaining postural stability. Our study's outcomes parallel the work of Abdelkader et al. [34], who investigated postural stability in patients with cervical pain. They found that individuals with neck pain with muscle fatigue exhibited diminished postural stability, a finding akin to our own results. Moreover, the diminished limits-of-stability variables, including increased reaction times,

reduced maximum excursions, and decreased directional control in the CS group align with the findings of Celenay et al. [35] and Hsu et al. [36]. Those studies highlighted the interplay between spinal degeneration and compromised postural stability, emphasizing that the biomechanical changes associated with CS may contribute to these limitations. In conclusion, the present study substantiates the profound impact of CS on cervical proprioception and postural stability, with its findings corroborated by studies that emphasize the intricate connection between musculoskeletal conditions and proprioceptive impairments. The evident limitations in limits-of-stability variables underscore the multifaceted challenges individuals with CS encounter in maintaining postural equilibrium. These insights contribute to the growing body of evidence that underscores the importance of addressing proprioceptive deficits and stability impairments in rehabilitation and management strategies for individuals with CS.

Of particular significance is the interplay between cervical proprioceptive reposition errors, limits-of-stability variables, and their potential mediators [37]. The current study reveals the mediating role of pain and kinesiophobia in shaping the relationship between cervical proprioceptive reposition errors and limits-of-stability variables. Pain, a hallmark of CS, emerges as a potential influencer of both proprioceptive accuracy and stability [38,39]. The integration of pain into the mediation analysis substantiates its role as a driving factor in this relationship. Furthermore, the significant mediating effect of kinesiophobia underscores the psychological dimension of the proprioception–stability continuum. Kinesiophobia's influence extends beyond biomechanical constraints, demonstrating its capacity to impact postural control among individuals with CS [17]. This underscores the importance of a holistic approach that addresses psychological factors alongside biomechanical interventions in managing CS [40]. This study's findings align with the existing body of research that underscores the multifaceted nature of CS, highlighting the intricate interactions between biomechanical, physiological, and psychological factors [41,42]. The implications for clinical practice are noteworthy. Integrated interventions that acknowledge the nuanced relationship between cervical proprioception, stability, pain, and kinesiophobia have the potential to enhance the efficacy of rehabilitation strategies for individuals with CS [43]. A personalized approach that targets both physical and psychological components is paramount in fostering functional improvements and enhancing the quality of life of these individuals [44,45].

4.1. Clinical Significance

The clinical significance of this study lies in its comprehensive exploration of cervical proprioception, stability, and their mediating factors among individuals with CS. By revealing the compromised proprioceptive accuracy and reduced stability parameters in these individuals, along with the mediating roles of pain and kinesiophobia, the study underscores the multifaceted challenges that impact their postural control and functional abilities. These findings emphasize the need for holistic rehabilitation approaches that consider both the biomechanical and psychological aspects of CS. The integrated interventions informed by this study have the potential to enhance the efficacy of rehabilitation strategies, leading to improved postural control, reduced pain, and enhanced quality of life for individuals affected by this condition.

4.2. Areas of Future Research

In light of the insights gained from this study, several avenues for future research emerge. Longitudinal studies could elucidate the temporal progression of cervical proprioceptive deficits and stability impairments in individuals with CS, shedding light on the dynamic nature of these relationships over time. Exploring the effectiveness of targeted interventions that address both biomechanical and psychosocial aspects and their impact on improving proprioceptive accuracy, stability, and pain management in this population could provide valuable clinical guidelines. Additionally, investigating the potential influence of other mediating factors, such as muscle strength, cognitive factors, and psychosocial

determinants, on the proprioceptive–stability continuum among individuals with CS could deepen our understanding of the underlying mechanisms. Furthermore, extending the study's scope to encompass larger and more diverse samples, considering variations in age, gender, and severity of CS, could enhance the generalizability of the findings. Incorporating advanced neuroimaging techniques to explore the neural pathways underlying cervical proprioception and stability deficits could also contribute to a more comprehensive understanding of the condition. Ultimately, these future research endeavors have the potential to inform tailored interventions, advance clinical practice, and improve the overall well-being of individuals navigating the challenges posed by CS.

4.3. Limitations of the Study

The interpretation of this study's findings must consider several limitations. Firstly, due to the cross-sectional design, it was not possible to establish causal relationships, and the findings only offer a momentary glimpse of the observed connections. Conducting longitudinal studies would be more suitable for gaining deeper insights into how cervical proprioception, stability, and mediating factors change over time. Secondly, relying on self-reported pain and kinesiophobia measures introduces the possibility of response bias and subjectivity. To improve the results' accuracy, incorporating objective measures of pain and psychological factors would be advisable. Thirdly, since the study focused on a specific age group and a population with moderate to severe CS, the generalizability of the findings to broader demographics or individuals with milder conditions may be limited. Encompassing a more diverse range of participants could provide a more comprehensive understanding of the relationship between proprioception, stability, and associated factors. Lastly, although the study explored the mediating effects of pain and kinesiophobia, it did not investigate other potentially influential variables. Therefore, future research should examine these unexplored variables to gain a more comprehensive understanding of the complex interplay in this context.

5. Conclusions

In conclusion, this comprehensive study sheds light on the intricate interplay between cervical proprioception, postural stability, and associated factors in individuals with CS. The findings underscore the significant impact of CS on proprioceptive reposition errors and limits-of-stability variables, highlighting the compromised sensory–motor integration in this population. The examination of correlations within the CS group reveals inherent relationships between proprioceptive reposition errors and postural stability measures, underlining the complex interdependence of these aspects. Moreover, the mediating effects of pain and kinesiophobia on the connection between proprioception and stability offer valuable insights into the multifaceted nature of this relationship. The study's outcomes have clinical implications, emphasizing the importance of addressing proprioceptive deficits and stability impairments in individuals with CS to improve functional outcomes and quality of life. However, it is important to acknowledge the study's limitations, including its cross-sectional design, reliance on self-reported measures, and specific population focus. These findings contribute to the growing body of knowledge in the field and provide a foundation for future research aimed at refining interventions and rehabilitation strategies tailored to the unique needs of individuals with CS. Ultimately, this study deepens our understanding of the intricate interplay between cervical proprioception, stability impairments, and related factors, paving the way for enhanced therapeutic approaches and improved patient outcomes in this population.

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