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Thoracic Kyphosis Screening and Its Relationship with Spinal Mobility and Postural Stability Assessed Through Center of Pressure Behavior

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Abstract: The spinal deviations, kyphoscoliosis represents a sagittal plane deviation of the vertebral column and may generate trunk balance disturbances and reduced spinal flexibility. This observational cross sectional study aims to examine sagittal plane vertebral column static behavior within an adolescent cohort and establish correlations with CoP displacement patterns. Our subject cohort comprised 32 female students from Ethos School in Craiova, with mean age 11.23 years (±0.60).Evaluation include clinical assessment, spinal deformities assessment using Spinal Mouse(thoracic and lumbar angles and mobility) and evaluation of center of pressure (COP). We found that increased weight or elevated BMI may exhibit greater postural oscillations, potentially elevating imbalance and fall risk. Observations reveal that mean COP oscillation surface magnitude, total displacement values, along with antero-posterior and latero-medial displacement patterns, demonstrate elevated measurements within the subject cohort presenting dorsal kyphosis beyond reference interval thresholds. Mean ThSp measurements registered 29.66° and 46.42° respectively for the cohort exhibiting values outside reference parameters, whereas LSp measurements recorded 12.66° and 11° respectively for the moderate kyphosis-identified cohort. Clinical consequences indicate that accentuated kyphosis may restrict thoracic segment mobility, reflected through negative correlations with lumbar mobility and flexion movement amplitude, elevating overload risk or functional imbalance. The demonstrated correlations indicate that postural stability is influenced by multiple factors, and clinical interpretation must account for both anthropometric parameters and segmental body interaction.

Keywords: kyphoscoliosis, balance; mobility

1. Introduction

The The vertebral column serves a fundamental role in sustaining postural equilibrium under both static and dynamic conditions. Consequently, postural modifications arising from spinal curvature affect body alignment and may induce alterations in locomotor typology [1].

Postural balance denotes the organism's capability to maintain the gravitational line within the support base, representing a cornerstone element for daily activity performance. The human body possesses the capacity to preserve proper posture under static and dynamic circumstances while counteracting gravitational forces. Adequate posture ensures normal biomechanical functioning of the locomotor apparatus. Nevertheless, inappropriate postural misalignment and trunk instability-including asymmetric pelvic tilting across three distinct planes (frontal, sagittal, transverse) alongside exaggerated spinal curves such as lordosis, kyphosis, and scoliosis, may generate spinal deformations and adversely impact the equilibrium system. Research investigations have demonstrated that balance function abnormalities stemming from progressive curves correlate with pelvic deformations in both sagittal and frontal planes [2].

Among spinal deviations, kyphoscoliosis represents a sagittal plane deviation of the vertebral column, typically three-dimensional in nature, generating trunk balance disturbances observable in upright standing and frequently associated with vertebral rigidity development evidenced through reduced spinal flexibility [3].

Kyphoscoliosis is characterized as a combination of kyphosis with scoliosis, affecting vertebral statics in sagittal and frontal planes, considering kyphosis with angles >50° and scoliosis <10° [4].

Starting from physiological values-specifically 20-35° for cervical lordosis in children aged 10-18 years, 20-35° for thoracic kyphosis (which increases angularly with age), and 30-45° for lumbar lordosis-kyphoscoliosis most commonly occurs in the thoracolumbar region, primarily referenced by the number of vertebrae involved in the spinal deviation and its localization.

Regarding incidence, kyphoscoliosis is estimated to occur in approximately 1 per 1,000 individuals, depending on age and etiology [5].

Generally, the percentage incidence is estimated at 0.4-8.3%, with increased frequency occurring between ages 10-12 years, predominantly affecting boys more than girls at a ratio of 2/1-7/1.

The severity of kyphotic deviation depends on the affected segment length and the timing of onset relative to growth. The highest incidence has been observed at the T10-L2 level [6].

Studies examining spinal deviations have primarily focused on idiopathic scoliosis and less on thoracic kyphosis. Therefore, researchers [7] maintain that regarding adolescent idiopathic scoliosis (AIS), it constitutes a three-dimensional structural deformation of the spine, commonly encountered among the general population worldwide, with frequencies ranging between 0.93 and 12% [8].

One critical question concerning sagittal plane spinal deviations involves understanding body balance implications. Within this framework, plantar pressure analysis currently represents a widely utilized method for investigating potential biomechanical mechanisms of spinal disorders [9], as it provides relevant data regarding foot posture, functionality, and the organism's overall postural control capacity [10]. Consequently, numerous researchers have integrated this technique into studies dedicated to spinal deviations, identifying significant correlations between diverse scoliotic morphologies and multiple plantar pressure parameters. For instance, Ma and colleagues [11] demonstrated that static plantar pressure indicators, such as forefoot contact surface area and loading ratio on the curve side, enable partial estimation of both segmental and global balance in juvenile idiopathic scoliosis patients. Yi and team [12] established a close relationship between sagittal plane balance and static plantar pressure distribution. St-Georges and colleagues [13] revealed that, compared to other scoliotic curve types, pressure exerted on the right foot directly relates to right thoracic Cobb angle magnitude. Gao and collaborators [14] examined center of pressure (CoP) trajectory in patients diagnosed with idiopathic kyphoscoliosis with dextroconvex curves, finding leftward CoP displacement in both feet among kyphoscoliosis groups compared to healthy subjects, with moderate Cobb angulation patients exhibiting the most pronounced CoP deviation. These investigations suggest plantar pressure analysis may serve as a pertinent indicator of postural control deficit and is susceptible to influence by spinal morphology in adolescent idiopathic scoliosis patients. However, some investigations appear to overlook the impact of single or double scoliotic curves on plantar pressure distribution [15]. Most studies related to spinal deviation impact on human body balance have focused on scoliosis with minimal attention to kyphosis. Thus, plantar pressure parameter variations suggest that both curve placement and typology influence foot postural distribution, center of gravity displacement, and body stability in this patient category [7]. One parameter evidencing postural equilibrium is the center of pressure (COP), which reflects dynamic fluctuations of pressure distribution during displacement and permits assessment of foot and trunk balancing capacity during gait [16]. The aforementioned authors' investigation did not identify statistically significant differences between groups but highlighted certain trends in the coronal plane. Patients with single thoracic curvature appear to manifest abnormal center of pressure displacement toward the main curve side. These observations align with Chockalingam and colleagues' findings, emphasizing that during locomotion, patients with severe adolescent idiopathic scoliosis forms present marked lateral CoP deviation in the coronal plane without notable sagittal plane modifications [17]. Nevertheless, the precise orientation of this lateral center of pressure displacement was not explicitly defined in the mentioned research. The authors suggested that variation amplitude might be attributed to participant compensatory curve condition diversity. This finding highlights potential impact of single versus double curves on plantar pressure parameters and requires further in-depth investigations.

Within this same framework, Jung and colleagues [18] mentioned that asymmetric pressure distribution induced by spinal deformations was associated with poor body balance during gait. Previous studies referenced by the authors examined gait particularities in scoliosis participants utilizing force platforms and three-dimensional motion analysis equipment, concluding that abnormal vertebral morphology encountered in scoliosis patients would modify the center of mass (COM) during displacement [19].

Gianuzzi and colleagues in their work [20] demonstrated that most research has targeted frontal plane vertebral static disorders-namely, adolescents with scoliosis-revealing that center of pressure (COP) trajectory in patients diagnosed with adolescent idiopathic scoliosis presents differences compared to healthy subjects without this condition [21].

A recent 2021 study demonstrated that severe and moderate scoliotic curves negatively influence gait parameters [15]. Other investigations concentrating on untreated adolescent idiopathic scoliosis patients revealed discrepancies in gait patterns compared to healthy adolescents; however, certain research has not identified statistically significant differences in gait analyses [22].

Currently, specialized literature data regarding adolescent idiopathic scoliosis patients indicates that plantar pressure and gait are influenced by multiple factors including age, gender, body mass index, and displacement velocity [23].

The center of pressure represents the application point of the instantaneous ground reaction force vector upon plantar surface contact [14]. This constitutes a two-dimensional positioning parameter whose localization continuously modifies throughout upright posture maintenance and gait. CoP oscillation magnitude, defined as postural sway, represents a widely accepted indicator of standing stability and reflects neuronal command intensity for stability control originating from higher nervous centers [24]. Its behavior has represented a challenge for all pathological aspects targeting static and dynamic human body balance, such a concern engaging Mahaudens and collaborators [25] who observed CoP might represent a valid and reliable functional marker for identifying subjects with different adolescent idiopathic scoliosis severity grades.

In adolescents diagnosed with idiopathic scoliosis, a significantly higher number of cases with negative sagittal plane trunk imbalance compared to positive imbalance cases is observed. Comparing with the normal balance group, patients with trunk instability manifest more accentuated local deformations, more pronounced head deviation, greater percentage differences regarding pressure load distribution between left and right feet or between anterior and posterior foot zones, a more extensive center of pressure oscillation area, diminished head and body stability in vertical position, alongside accentuated trunk imbalance [26]. Center of pressure oscillation area represents a widely accepted method for evaluating standing stability controlled by higher brain centers, while center of pressure variations reflect nervous function impairment during gait. The more extensive the center of pressure oscillation zone, the more accentuated the body instability. Wen and colleagues' investigation[26] revealed that patients with severe scoliosis forms and those with coronal or sagittal plane trunk imbalance presented extensive center of pressure oscillation zones, thus indicating that organism stability is affected by both scoliosis severity and trunk balance in coronal and sagittal planes.

Analyzing COP deviations in scoliosis, Jung and colleagues [27] observed that the scoliosis patient group manifested accentuated center of pressure (COP) and center of mass (COM) trajectory displacements [28].

Current specialized literature reveals insufficient understanding of the mechanisms underlying the relationship between spinal deformity severity (measured in degrees) among adolescents presenting sagittal plane vertebral column deviations and plantar support characteristics, particularly regarding center of pressure (CoP) behavior during static stance and ambulation.

Our research hypothesis posits a potential correlation between CoP deviations and the degree of thoracic kyphotic curvature, its anatomical location, pelvic positioning, and vertebral column mobility. We theorize that plantar CoP progression patterns may demonstrate modifications proportional to kyphosis severity. The research questions we aimed to clarify included: Do variations in CoP behavior manifest across different kyphosis severity levels? Do bilateral plantar surface CoP progressions demonstrate correlation with kyphotic degree?

This observational study aims to examine sagittal plane vertebral column static behavior within an adolescent cohort and establish correlations with CoP displacement patterns. Through this synthetic analysis, we additionally sought to investigate potential relationships and connections between body mass index and idiopathic sagittal plane vertebral column statics, recognizing that comprehending risk factors and specific clinical particularities could facilitate both screening phases and early diagnostic establishment.

2. Materials and Methodology

2.1. Participants

Our subject cohort comprised 32 female students from Ethos School in Craiova, with mean age 11.23 years (±0.60), average height 148.77cm (±5.23), mean weight 44.38kg (±10.23), and body mass index (BMI) 20.06 (±4.54). These individuals underwent somatic evaluation during a screening initiative designed to identify and assess sagittal plane vertebral column static disorders.

The screening process proceeded with complete parental consent and school staff approval, following presentation of the evaluation procedures to be implemented, with parents providing signed informed consent. Furthermore, the study received registration and approval from the UCV-FEFS Ethics Committee under number 514/16.09.2025, adhering to the Declaration of Helsinki principles (2013 version).

2.2. Inclusion parameters:

- Children without associated locomotor or neurological pathology;
- Children demonstrating cooperation during procedure completion;
- Children aged 10-12 years.

2.3. Exclusion parameters:

- Children previously investigated or participating in kinesiotherapy sessions;
- Children presenting thoracic malformations;
- Children experiencing communication and comprehension difficulties;
- Children exhibiting scoliotic attitude or pattern.

2.4. Subject Assessment Methodology:

- Clinical evaluation via somatoscopy to exclude subjects presenting severe and clinically evident vertebral column malformations;
- Assessment of sagittal plane vertebral column deviation across the entire lumbar spine, tracking curvatures at thoracic and lumbar vertebral column levels;
- Evaluation of center of pressure (CoP) behavior.

Vertebral column deviation assessment utilized Spinal Mouse equipment (IDIAG M360, Fehraltorf, Switzerland) available at the INCESA facility (Laboratory of Innovative Techniques and Processes in Bioengineering - www.incesa.ro).

This equipment enables both postural determination and vertebral column mobility evaluation at segmental levels through dedicated software. Notably, the equipment operates non-invasively. Each child received explanation of the evaluation procedure.

2.5. Procedure Protocol:

Subjects assumed a standard orthostatic position without clothing, wearing only shorts for assessment, under thermal comfort and habitual conditions, with uniform and equal body weight distribution across both lower limbs. Evaluation occurred in orthostatic position and during trunk flexion conditions. The C7 vertebra spinous process was marked as the starting point for Spinal Mouse palpator examination, proceeding across all spinous processes down to the S3 sacral vertebra level (Figures 1, 2, 3).

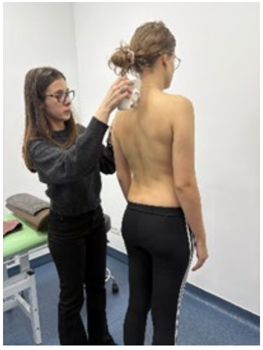

Figure 1. Spinal Mouse sensor positioning at C7 vertebra level

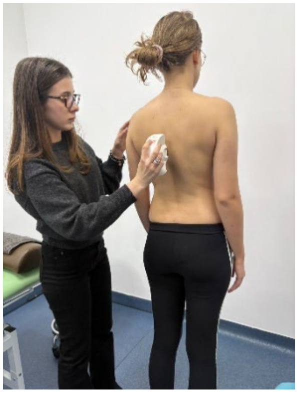

Figure 2. Conducting spinal assessment along the spinous process trajectory

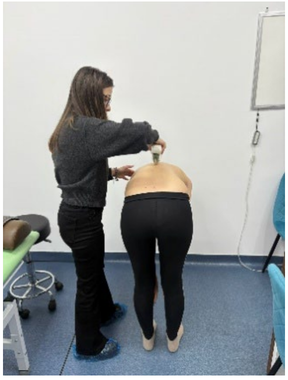

Figure 3. Vertebral column assessment during trunk flexion maneuver

Sagittal plane assessment yielded data concerning thoracic kyphotic curvature, lumbar lordotic configuration, and pelvic tilt orientation (Figure 4), with angular measurements computed through specialized software [29]. Recorded angular measurements included: the thoracic angle expressing thoracic region curvature magnitude (ThSp fixed at Th12) and the lumbar angle (LSp fixed at Th12) representing lumbar curvature magnitude, both documented during orthostatic stance utilizing the T12 thoracic vertebra as anatomical reference. Mobility assessment additionally encompassed sagittal plane motion through maximal trunk flexion maneuvers, simultaneously evaluating hip joint mobility to determine whether trunk flexion movement demonstrates compensatory execution from this anatomical level (Figure 5).

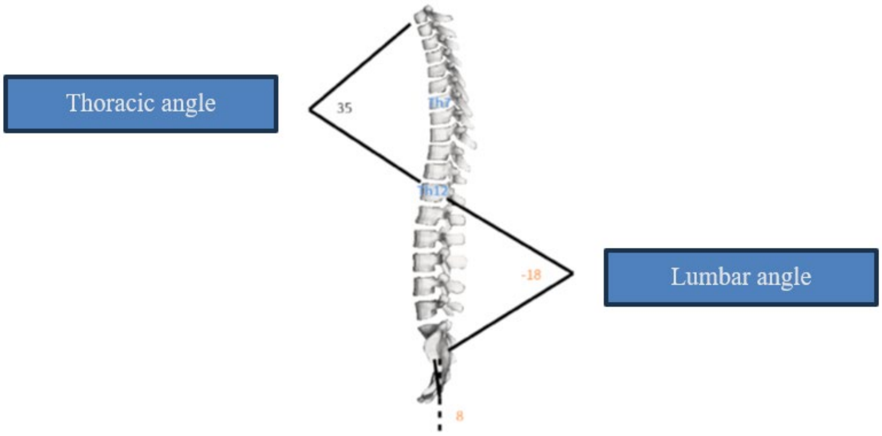

Figure 4. Angular measurements of thoracic and lumbar curvatures with pelvic inclination

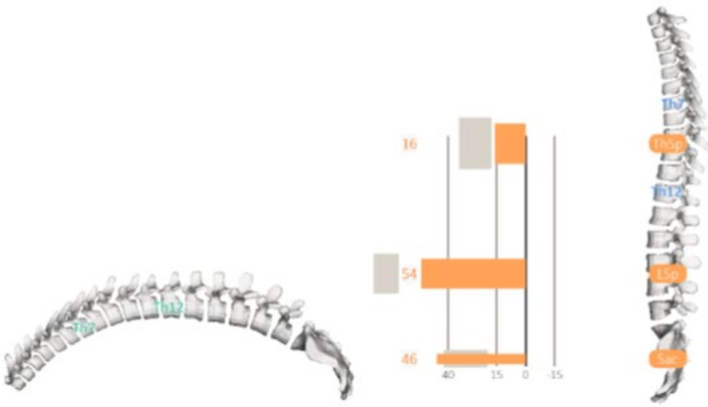

Figure 5. Spinal mobility evaluation during trunk flexion

Reference parameters considered for our study established thoracic kyphosis at 20-35° and lumbar curvature at 30-45° [30].

CoP Behavioral Assessment utilized Kinvent Physio equipment (Portable and lightweight, K-Force Plates are designed to measure static and dynamic balance). This system's force platforms function as devices measuring forces exerted by body weight upon the ground surface during orthostatic stance. Data collected from these force platforms provides information regarding static equilibrium, enabling visualization of how sagittal plane spinal alignment disturbances may influence balance through CoP mechanisms. CoP represents the intersection point where vertical ground reaction force meets the force platform, indicating the patient's center of mass location. Through CoP analysis, detailed information emerges concerning patient balance and postural control capabilities. CoP displacement serves as the element enabling static equilibrium evaluation through assessment of CoP oscillation, CoP oscillation surface area, and displacement along both X-axis (COPx) and Y-axis (COPy). Within our applied evaluation protocol, Kinvent measurement implementation required no warm-up period, with stability steps proceeding as follows: Subject positioned on platforms, executed 3-4 stationary steps to adopt optimal equilibrium position; arms relaxed alongside body; established focal reference point at 3-5m distance for subject visual fixation; recording initiated (Figure 6).

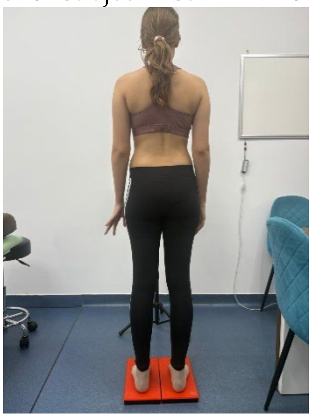

Figure 6. CoP recording on Kinvent platform

Assessment procedures occurred exclusively under eyes-open conditions, with acquisition frequency established at 50 Hz as recommended by Net CoP values along medial-lateral (CoPx) and antero-posterior (CoPy) axes underwent subsequent calculation utilizing corresponding formulas (Figures 7, 8).

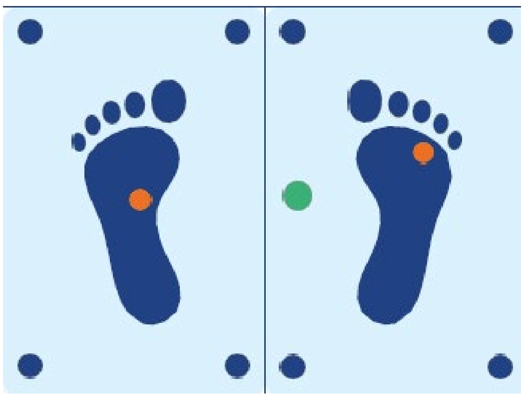

Figure 7. CoP position recording

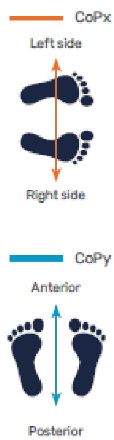

Figure 8. CoP displacement recording across both axes

Quantified metrics obtained and examined within our investigation comprised: elliptical surface area (mm^2), CoP displacement magnitude along the X-axis (Width Amplitude -mm) and Y-axis (Height Amplitude-mm). Statistical analysis implementation utilized XLStat software.

3. Results

3.1. Vertebral Column Assessment

Findings derived from lumbar spinal static evaluation and mobility assessment during trunk flexion maneuvers are displayed in Table 1.

Table 1. Morphofunctional characteristics of thoracic and lumbar vertebral column with hip mobility parameters

Statistical parameters	H	W	BMI	U S/H	U Th	U L	F S/H	F Th	F L
Minimum	143	32	15.2	-15	26	-25.00	16.00	-3.00	23.00
Maximum	156	60	26.5	16	52	12.00	67.00	33.00	68.00
1st Quartile	145	34	16	-6	30	-16.00	33.00	5.00	35.00
Median	148	41	18.7	2	40	-7.00	42.00	13.00	46.00
3rd Quartile	155	54	24.6	8	48	-3.00	50.00	20.00	54.00
Mean	148.7	44.38	20	0.54	38.69	-8.38	41.85	12.46	44.62
Standard deviation	5.23	10.23	4.54	9.33	9.79	10.99	15.47	10.04	13.82

* **Legend**: H- Height [cm], W- Weight [Kg], BMI-body mass index, U S/H- standing upright Sac/Hip, U Th- standing upright ThSp fixed at Th12, U L- standing upright LSp fixed at Th12, F S/H- standing flexion Sac/Hip, F Th- standing flexionThSp fixed at Th12, F L- standing flexion LSp fixed at Th12.

Clinical classification based on thoracic angular measurements revealed two distinct clusters (53.85% demonstrated values exceeding the 35° reference threshold, while 46.15% remained within age-appropriate normal parameters). Lumbar angular analysis identified a single subject among all participants presenting values beyond reference boundaries with a mean of 11.76°, with cluster stratification established through comparison against previously mentioned reference standards. Data examination indicates predominance of moderate thoracic kyphotic presentation alongside lumbar curvature effacement, likely representing compensatory adaptation. Mean ThSp measurements registered 29.66° and 46.42° respectively for the cohort exhibiting values outside reference parameters, whereas LSp measurements recorded 12.66° and 11° respectively for the moderate kyphosis-identified cohort. Data interpretation demonstrates thoracic-level kyphotic accentuation tendency, while lumbar region exhibits progression toward extension positioning and pelvic retroversion patterns, findings corroborated by substantially reduced hip angle measurements within the thoracic kyphosis subject cohort.

3.2. CoP Behavioral Parameter Assessment

CoP displacement evaluation is documented in Tables 2 and 3.

Table 2. Descriptive statistical analysis of subjects with dorsal kyphosis within reference interval parameters

Statistical parameters	SCOP	DSCOP	W A	H A	S/D	W/H	U S/H	U Th	U L
Minimum	43.44	49.30	4.77	7.36	0.51	0.39	-15.00	26.00	-18.00
Maximum	185.08	142.82	11.38	21.06	1.30	0.80	16.00	35.00	12.00
1st Quartile	54.17	77.36	5.71	12.09	0.77	0.48	-9.50	27.25	-16.75
Median	88.19	84.47	8.14	12.77	1.01	0.62	1.50	29.00	-9.50
3rd Quartile	101.78	116.23	9.54	14.67	1.21	0.71	10.25	31.50	6.75
Mean	92.34	93.81	7.89	13.52	0.97	0.60	0.67	29.67	-5.33
Standard deviation	52.02	34.63	2.63	4.50	0.31	0.16	12.72	3.39	13.79

* **Legend**: SCOP- CoP Surface (mm²), DSCOP- Total Displacement [mm], WA- Width Amplitude [mm], HA- Height Amplitude [mm], S/D- COP Surface/Displacement [mm²/mm], W/H- COP Width/Height [mm/mm], U S/H- standing upright Sac/Hip, U Th- standing upright ThSp fixed at Th12, U L - standing upright LSp fixed at Th12.

Table 3. Descriptive statistical analysis of subjects with dorsal kyphosis exceeding reference interval boundaries

Statistical parameters	SCOP	DSCOP	W A	H A	S/D	W/H	U S/H	U Th	U L
Minimum	50.53	85.26	4.98	10.81	0.59	0.46	-9.00	40.00	-25.00
Maximum	1060.25	230.56	53.26	25.88	4.60	2.10	9.00	52.00	-1.00
1st Quartile	113.75	103.24	10.47	11.28	1.04	0.80	-3.50	41.00	-15.50
Median	134.60	125.98	13.62	11.60	1.20	0.93	2.00	48.00	-7.00
3rd Quartile	376.74	146.25	17.85	20.53	2.59	1.16	4.00	51.50	-6.50
Mean	318.05	134.40	18.36	15.99	1.95	1.06	0.43	46.43	-11.00
Standard deviation	362.89	48.55	16.05	6.77	1.53	0.52	6.27	5.56	8.10

* **Legend**: SCOP- CoP Surface (mm²), DSCOP - Total Displacement [mm], WA- Width Amplitude [mm], HA- Height Amplitude [mm], S/D- COP Surface/Displacement [mm²/mm], W/H- COP Width/Height [mm/mm], U S/H- standing upright Sac/Hip, U Th- standing upright ThSp fixed at Th12, U L - standing upright LSp fixed at Th12.

Observations reveal that mean CoP oscillation surface magnitude, total displacement values, along with antero-posterior and latero-medial displacement patterns, demonstrate elevated measurements within the subject cohort presenting dorsal kyphosis beyond reference interval thresholds. Additionally, the index derived from the X-axis CoP displacement to Y-axis displacement ratio registers values exceeding 1, signifying medio-lateral displacement predominance (X-axis). Instability quantification through CoP Surface measurement appears primarily governed by transverse component characteristics (Width).

3.3. Correlations Among Measured Parameters

Building upon previously articulated hypotheses, correlation analysis of recorded data was conducted, presented in Table 4.

Table 4. Correlation coefficient values

Variables	**BMI**	**SCOP**	**DCOP**	**WA**	**HA**	**S/D**	**W/H**	**U S/H**	**U Th**	**U L**	**F S/H**	**F Th**	**F L**
H	-0.09	0.64	0.63	0.57	0.79	0.71	0.39	-0.50	0.17	0.53	0.21	-0.11	-0.70
W	0.95	0.42	0.63	0.52	0.35	0.29	0.54	0.05	0.28	0.16	0.19	0.20	-0.24
BMI	1.00	0.20	0.42	0.32	0.10	0.06	0.42	0.22	0.24	-0.01	0.07	0.21	0.01
SCOP		1.00	0.87	0.97	0.81	0.97	0.80	-0.07	0.57	0.06	0.25	-0.10	-0.46
DCOP			1.00	0.89	0.79	0.79	0.77	-0.11	0.59	0.15	0.38	-0.09	-0.54
WA				1.00	0.70	0.89	0.90	-0.10	0.55	0.10	0.31	-0.06	-0.50
HA					1.00	0.86	0.39	-0.22	0.47	0.23	0.26	-0.16	-0.53
S/D						1.00	0.70	-0.08	0.59	0.04	0.07	-0.17	-0.39
W/H							1.00	-0.03	0.52	0.03	0.15	-0.01	-0.36
U S/H								1.00	0.04	-0.90	-0.28	0.28	0.72
U Th									1.00	-0.28	-0.18	-0.60	0.13
U L										1.00	0.33	0.05	-0.81
F S/H											1.00	0.35	-0.67
F Th												1.00	-0.17
F L													1.00

* **Legend**: H- Height, W- Weight, BMI= body mass index, SCOP- CoP Surface (mm²),DSCOP- Total Displacement [mm], WA- Width Amplitude [mm], HA- Height Amplitude [mm], S/D- COP Surface/Displacement [mm²/mm], W/H- COP Width/Height [mm/mm],U S/H- standing upright Sac/Hip, U Th- standing upright ThSp fixed at Th12, U L - standing upright LSp fixed at Th12.

Analysis demonstrates robust correlation between CoP displacement magnitude and the surface area across which displacement occurs.

To verify these correlations were non-random, Pearson-type T-test analysis was implemented, illustrated in the table below, confirming statistically significant correlations among multiple parameter sets.

Table 5. Synthesis of p-parameter values from t-test conducted for Pearson-type correlations*

Variables	BMI	WA	S/D	W/H	UL
W	0.0000006760				
SCOP		0.0000000423	0.0000000423		
WA				0.0000277000	
US/H					0.0000277000

Significance threshold established at α=0.05. All p-parameter values registered below significance threshold

Based on collected data, relationship analysis among various parameters proceeded as follows:

a. Associations Between Anthropometric Variables and Stability Parameters

BMI and Weight: Exceptionally robust correlation (r = 0.95), clinically anticipated given BMI's direct derivation from weight and height measurements.

BMI and postural parameters: Correlations ranged from weak to moderate levels (r = 0.07 - 0.42), indicating BMI exerts minimal significant influence upon static stability parameters (CoP Surface, Total Displacement, etc.).

BMI's limited influence on stability suggests postural instability risk determination extends beyond weight status alone, primarily involving body mass distribution patterns and neuromuscular control mechanisms.

Moderate correlations between weight/BMI and postural parameters indicate subjects presenting increased weight or elevated BMI may exhibit greater postural oscillations, potentially elevating imbalance and fall risk. Evaluating these correlations enables identification of high-risk subjects who may derive benefit from preventive interventions (balance exercises, environmental modifications).

b. Associations Between Postural Parameters and Segmental Movements

Standing upright Sac/Hip and standing upright LSp fixed at Th12: Exceptionally robust negative correlation (r = -0.90), clinically suggesting sacroiliac mobility demonstrates inverse proportionality with lumbar stability during vertical positioning. Negative relationships between hip-level mobility and lumbar stability may indicate biomechanical compensations, specifically that when one segment achieves increased mobility, another tends toward stabilization to maintain global equilibrium.

c. Analysis of Connections Between Kyphotic Curvature and Vertebral Column Mobility

Kyphotic curvature receives clinical reflection through parameters including "standing upright ThSp fixed at Th12" (vertical positioning, thorax fixed at T12) and "standing flexion ThSp fixed at Th12" (flexion, thorax fixed at T12).

Vertebral column mobility assessment occurred through correlations with lumbar and hip segments (examples: "standing upright LSp fixed at Th12", "standing flexion LSp fixed at Th12", "standing upright Sac/Hip").

Identified relevant correlations targeted:

- Correlation between "standing upright ThSp fixed at Th12" and "standing upright LSp fixed at Th12" demonstrates negative values (r = -0.28), suggesting increased thoracic mobility may associate with decreased lumbar mobility during orthostatic stance.

- Correlation between "standing upright ThSp fixed at Th12" and "standing flexion ThSp fixed at Th12" shows negative values (r = -0.60), indicating accentuated kyphosis during orthostatic positioning may limit thoracic segment flexion mobility.

- Correlations between "standing upright ThSp fixed at Th12" and amplitude parameters (Width/Height Amplitude) range from moderate to weak (r = 0.55 and r = 0.47 respectively), suggesting connections between kyphotic curvature and postural oscillations.

- Clinical consequences indicate that accentuated kyphosis (increased thoracic curvature) may restrict thoracic segment mobility, reflected through negative correlations with lumbar mobility and flexion movement amplitude, potentially triggering compensations at lumbar or sacroiliac levels, elevating overload risk or functional imbalance.

- Implementing this evaluation type and identified correlations permits recognition of patients presenting thoracic rigidity, who may require specific interventions for mobility enhancement and postural complication prevention.

3.4. Relationship between parameters using the statistical data analysis additionally incorporated clustering analysis (k-means) on stability variables to identify subject cohorts (reduced vs. elevated stability) linked to postural parameter values characterizing vertebral column statics.

Included variables (numerically comparable, pre-analysis standardization) (all standardized via z-score): COP Surface, Total Displacement, Width Amplit, Height Amplit, COP Surface/Displ, COP Width/Height, SacHip, ThSp, LSp. Clustering quality evaluation utilized algorithms such as K-Means, enabling cluster characterization. We made multiple tests for stability and spinal deviation, and the data have been integrated in a model that share the subjects in clusters. Validation of the clusters included Silhouette score for statistic confirmation and clinical difference for medical confirmation. By this way we obtained 2 clusters.

k-means for k=2..5, with k selection based on silhouette score. Silhouette scores (incorporating thoracic, lumbar, hip angles) represent a metric employed for clustering algorithm quality evaluation (such as k-means). It quantifies cluster separation effectiveness and intra-cluster point coherence. Orientative thresholds: *0.5 → satisfactory cluster separation. 0.25 – 0.5 → moderate separation. < 0.25 → weak separation (cluster overlap).*

1. Two clusters emerged (k-means, k=2) Cluster 0 (69.23% of cohort) Cluster 1 (23.07% of cohort)

Within clusters, centroids-representing the central point of a cluster, calculated as arithmetic mean of all contained points-were as follows Table 6, while statistical analysis and effect magnitude underwent assessment through non-parametric Mann-Whitney testing. Test: Mann-Whitney U (non-parametric, two-tailed) on each variable between Cluster 0 and Cluster 1.

Effect magnitude: Cliff's delta (∈ [-1, 1]); values ∣δ∣≈1 indicate exceptionally powerful effect.

Reporting: cluster-based medians, U statistics and p-values, Cliff's delta.

Findings are documented in Table 6, while graphical representations of variables for each cluster appear in Figures 9, 10, 11, 12, 13.

Table 6. Centroids (original units)

Variable	Cluster 0	Cluster 1
CoP Surface	86.84	312.86
Total Displacement	93.08	145.11
Width Amplit	8.39	15.69
Height Amplit	11.67	20.89
COP Surface/Displ	0.93	2.16
COP Width/Height	0.73	0.78
SacHip	2.56	-5.00
ThSp	35.56	44.00
LSp	-10.67	-2.33

Table 7. Statistical cluster comparison (Mann–Whitney + Cliff's δ)

Variable	Median C0	Median C1	U	p	Cliff's δ
CoP Surface	92.55	229.65	0.0	0.009	-1.000
Total Displacement	85.26	143.85	0.0	0.009	-1.000
Height Amplit	11.60	21.06	0.0	0.009	-1.000
COP Surface/Displ	1.02	1.54	0.0	0.009	-1.000
Width Amplit	9.33	17.24	1.0	0.018	-0.926
ThSp	35.00	48.00	6.5	0.228	-0.519
SacHip	3.00	-9.00	20.0	0.282	0.481
LSp	-15.00	-1.00	7.5	0.308	-0.444
COP Width/Height	0.72	0.71	12.0	0.853	-0.111

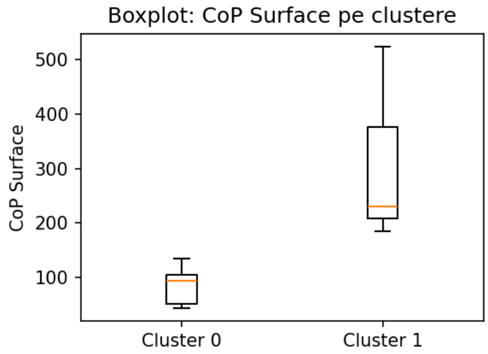

Figure 9. CoP clusters

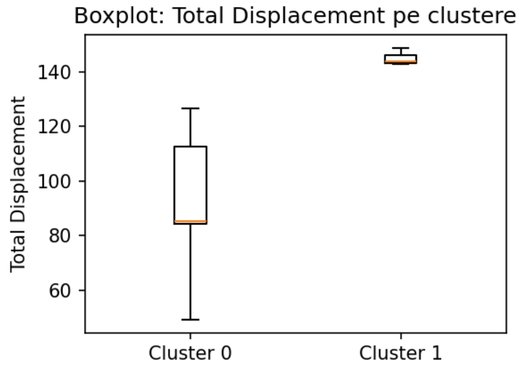

Figure 10. DSCOP clusters

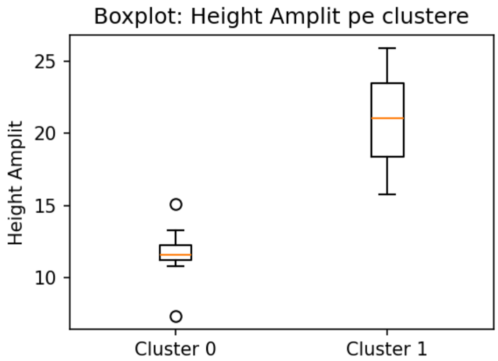

Figure 11. Y-axis displacement clusters

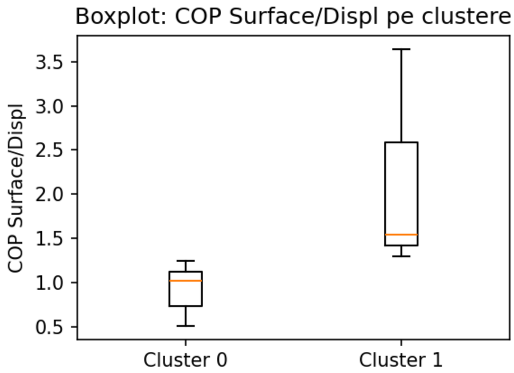

Figure 12. SCOP/DSCOP ratio clusters

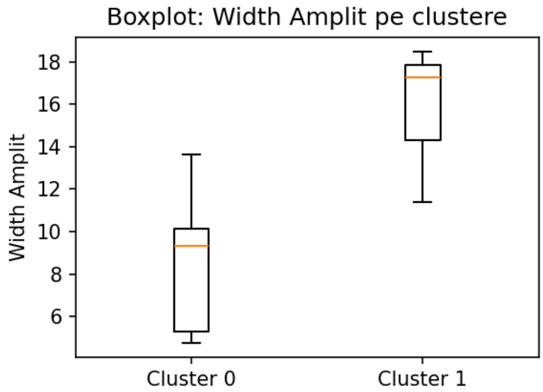

Figure 13. DSCOP X-axis clusters

Results examination reveals that Cluster 0 (relatively superior stability) demonstrates: reduced CoP parameters, sacrum/hip positioning slightly toward flexion/anteversion (+), ThSp approximating 35°, LSp presenting more negative values (lordosis/retroversion).

Cluster 1 (relatively elevated instability) exhibits: amplified CoP parameters (CoP Surface, amplitudes, displacement), Sac/Hip trending toward negative values (posteriorization), ThSp elevation (~44°), LSp approaching zero proximity (diminished negativity).

Statistical comparison between both clusters (k-means) utilizing Mann-Whitney U (two-tailed) for each variable, complemented by Cliff's delta as effect magnitude measurement, incorporates postural angles (Sac/Hip, ThSp, LSp), Table 9.

Table 8. Statistical comparison outcomes between both clusters (ranked by p-value)

Variable	Median C0	Median C1	U	p-value	Cliff's δ	Interpretation
CoP Surface	92.55	229.65	0	0.0091	-1	Diferență semnificativă, efect extrem (C1 > C0)
Total Displacement	85.26	143.85	0	0.0091	-1	Semnificativ, efect extrem (C1 > C0)
Height Amplit	11.6	21.06	0	0.0091	-1	Semnificativ, efect extrem (C1 > C0)
COP Surface/Displ	1.02	1.54	0	0.0091	-1	Semnificativ, efect extrem (C1 > C0)
Width Amplit	9.33	17.24	1	0.0182	-0.926	Semnificativ, efect foarte mare (C1 > C0)
ThSp	35	48	7	0.2278	-0.519	Nesemnificativ, efect moderat (C1 > C0)
SacHip	3	-9	20	0.2818	0.481	Nesemnificativ, efect moderat (C0 > C1) (valori mai pozitive în C0)
LSp	-15	-1	8	0.3075	-0.444	Nesemnificativ, efect moderat (C1 > C0; mai puțin negativ în C1)
COP Width/Height	0.72	0.71	12	0.8531	-0.111	Nesemnificativ, efect mic

* Significance threshold: $\alpha = 0.05$

Results examination demonstrates CoP parameters (CoP Surface, Total Displacement, Width/Height Amplit, Surface/Displ) register significantly elevated values within Cluster 1, indicating relatively amplified postural instability, with extreme effects (Cliff's δ ≈ -1 for 4 variables, ≈ -0.93 for Width Amplit). COP Width/Height fails to differentiate clusters (p ≈ 0.85, minimal effect).

Regarding postural angular measurements: ThSp (thoracic) demonstrates elevation in Cluster 1 (median 48° vs 35°), though lacking statistical significance within this sample (small n). Sac/Hip: increased positivity in Cluster 0 (median +3 vs -9), yet non-significant. LSp: reduced negativity in Cluster 1 (median -1 vs -15), non-significant.

Clinical interpretation indicates Cluster 0 presents a characteristic profile: relatively satisfactory stability, moderate CoP parameters, balanced postural angles, necessitating periodic monitoring protocols. Cluster 1 demonstrates accentuated instability, elevated CoP parameters, postural compensations (thoracic flexion, pelvic retroversion, lordosis reduction), requiring stabilization exercises, postural correction interventions, supplementary clinical evaluation.

Cluster-type analysis was additionally conducted regarding data obtained through Spinal Mouse equipment, generating 2 clusters: Cluster 1 (46% cohort) encompassed children presenting moderately severe thoracic kyphosis with elevated progression risk, whereas Cluster 2 (53% cohort) included children demonstrating favorable reference parameters, exhibiting superior intrinsic stability at dorsolumbar vertebral column level Table 10.

Table 9. Cluster distribution according to kyphotic degree

Parameter	Cluster 1	Cluster 2	Difference
Toracic (cifoza)	47.33°	31.29°	+16° (exagerată!)
Lombar (lordoza)	-11.67°	-5.57°	+6°

Normal thoracic reference values establish 20-35° range. Cluster 1 exhibits excessive kyphotic presentation (47° > 35°).

Behavioral analysis of parameters measured utilizing Kinvent platforms across both clusters appears in Table 11.

Table 10. CoP parameter relationships with vertebral clusters

Parameter	Cluster 1 (Risc)	Cluster 2 (Bun)	Difference
CoP Surface	362.64 mm²	86.37 mm²	×4.2 mai mare
Displacement	142.59 mm	92.59 mm	54%
Width Amplitude	20.59 mm	7.47 mm	×2.8
Height Amplitude	16.85 mm	13.13 mm	28%

Cluster 1 demonstrated substantially greater postural instability.

4. Discussion

Our investigation into the complex somatofunctional behavior of children presenting with kyphosis can be compared to research conducted by Gao and colleagues [31], whose findings, though focused on scoliosis cases, demonstrate parallel patterns. Their work revealed that individuals with severe scoliotic curves exhibited reduced body weight and body mass index values when compared to those with mild to moderate curvature severity. This observation suggests that pronounced scoliosis may impact somatic development patterns and influence how body load distributes across the plantar surface in adolescent populations. Notably, they found no strong correlation between weight and BMI parameters - a pattern we similarly identified in our kyphotic pediatric cohort. This finding indicates that vertebral static disorders do not consistently correlate with weight or BMI measurements.

Further support for this concept comes from additional work by Gao and colleagues [14], where they documented a decreasing trend in body mass index, derived from anthropometric measurements, as scoliotic severity intensified. This finding points toward a potential association between musculoskeletal abnormalities and progression severity, aligning with their earlier research [31] that documented significant BMI reduction in adolescent idiopathic scoliosis (AIS) cases.

Our observational study findings demonstrated moderate correlations between weight/BMI parameters and postural measurements. This suggests that pediatric subjects with elevated weight or increased BMI values may exhibit greater postural oscillations, potentially elevating fall and balance loss risk. However, postural instability risk appears determined not solely by weight status but rather through the interplay of body mass distribution and neuromuscular control mechanisms.

In their scoping review, Scaturro and colleagues [32] highlighted that certain authors propose above-normal body weight might confer protective effects. Nevertheless, the biological mechanism underlying this association remains unclear. Some researchers have characterized low BMI as an organic consequence of scoliotic conditions [33], while others have identified it as a risk factor [34].

Literature analysis reveals considerable variability regarding the connection between body mass index and scoliotic conditions, preventing definitive conclusions. Most investigations support an association between low BMI values and scoliosis development. Concurrently, a smaller number of studies either identify no association or demonstrate inverse relationships.

Our findings regarding COP parameter modifications between normal subjects and those with AIS, as well as among AIS children with varying severity grades, indicate that loading patterns and load magnitudes accepted by segments within the kinematic chain tend to shift due to vertebral static disorder presence. These loading patterns appear influenced by disorder severity. Our cluster analysis results, which examined distribution according to COP and vertebral parameters, similarly demonstrated that Cluster 0, characterized by smaller COP parameters, sacrum/hip slightly in flexion/anteversion (+), ThSp around 35°, and more negative LSp (lordosis/retroversion), exhibited greater stability.

Considering these results and statistical evidence [35,36] showing kyphosis onset in girls begins at ages 11-12 years, the critical issue concerns early detection and comprehensive evaluation - not merely from clinical perspectives but regarding the complexity of complications and associated disorders that thoracic kyphosis can generate. In this context, our study and results demonstrate the possibility of kyphosis development associated with balance disturbances, clinically undetectable at age 11 but becoming evident as kyphosis progresses.

These aspects have been explained in idiopathic scoliosis cases, with explanations equally pertinent for kyphotic conditions. Wen and colleagues [26], citing Beaulieu et al [37], highlighted sensory deficiencies in adolescents diagnosed with idiopathic scoliosis [38], demonstrating inability to correctly perceive center of pressure positioning relative to body mass center and this could be a start for develop virtual model that contains many elements, so it can be used as an environment for the simulations of real situations (normal, pathological) in the future analysis of balance in spine static disorders [39]. This perceptual problem may represent one cause of trunk instability observed in children with vertebral static disorders, with potential for progression.

Building on these scoliosis-related observations, Beaulieu and team demonstrated this type of sensory dysfunction while proposing a hypothesis whereby spinal deformity progression unfolds in two distinct phases. Initially, vertebral static disorder would be determined by neuromuscular and sensorimotor system abnormalities, while in the second phase, pathological curve aggravation and neurological problems would interfere with the organism's capacity to recalibrate center of pressure position relative to mass center or maintain postural equilibrium [40].

It is essential to emphasize screening importance in young subjects and adolescents, since early diagnosis represents the premise for more effective therapeutic approaches - both for subjects with low BMI and obese individuals, where diagnosis is frequently delayed. Therefore, despite results obtained thus far, definitive conclusions cannot be formulated, necessitating large-scale epidemiological studies across diverse ethnic groups accompanied by in-depth biomarker investigation to better clarify the correlation between body mass index and scoliotic conditions.

The relatively limited studies regarding thoracic kyphosis onset in girls under 12 years led us to analyze research examining how COP behavior is influenced by vertebral static disorders. We found our results regarding increased COP oscillation surface area in girls with kyphosis is also observed in scoliosis and has been utilized as a monitoring method. Khorramroo and colleagues [41] observed that increased CP oscillation area and asymmetry in progression configurations indicate compromised balance and stability in scoliotic patients. The mediolateral displacement of COP trajectory, which we also identified in thoracic kyphosis cases, corresponds with modified load distribution caused by vertebral deformation.

The presence of balance disorders in kyphotic cases was also presented by Eum and colleagues [42], who conducted a review mentioning study results suggesting balance disturbances in kyphotic conditions occur more frequently in females than males. Additionally, they note that sample sizes studied are generally small.

From a biomechanical perspective, our results revealed that clinically, pronounced kyphosis (increased thoracic curvature) can limit thoracic segment mobility, reflected in negative correlations with lumbar mobility and flexion movement amplitude. This can lead to lumbar or sacroiliac compensations, increasing overload risk or functional imbalance. Yang and colleagues [43] reached similar conclusions in their narrative review, stating that vertebral alignment abnormalities can lead to biomechanical stress on the thoracic spine with implications for neuromuscular, musculoskeletal, and sensory balance. Malalignment progression leads to reduced range of motion - an aspect we found not only at lumbar level but also thoracically and at hip level. Additionally, the effect on center of pressure favors pelvic retroversion, demonstrated by our results [44].

Using the same equipment as ours, Mete and colleagues [45] analyzed thoracic kyphosis and lumbar lordosis in a group of children with chest deformities (pectus carinatum and pectus excavatum) and healthy children. They observed that thoracic kyphosis and lumbar lordosis are more pronounced in children with chest malformations than in healthy peers, with both vertebral segments displaying much larger angles. Furthermore, hip mobility relative to the sacrum in the sagittal plane showed lower values in the same category of children compared to healthy ones - an aspect we also identified, with the correlation between thoracic curvature and sacral-hip angle being strong but negative (r=-0.902).

The authors note that in these subjects with chest malformations, spinal mobility significantly reduces, as also remarked by Bayartai and colleagues [46].

5. Conclusions

Conducting this type of evaluation and the identified correlations enable identification of patients with thoracic rigidity who may require specific interventions for mobility improvement and postural complication prevention.

Data examination indicates predominance of moderate thoracic kyphotic presentation alongside lumbar curvature effacement, likely representing compensatory adaptation.Instability quantification through COP Surface measurement appears primarily governed by transverse component characteristics (Width).

Analysis demonstrates robust correlation between COP displacement magnitude and the surface area across which displacement occurs.

Moderate correlations between weight/BMI and postural parameters indicate subjects presenting increased weight or elevated BMI may exhibit greater postural oscillations, potentially elevating imbalance and fall risk

Negative relationships between hip-level mobility and lumbar stability may indicate biomechanical compensations, specifically that when one segment achieves increased mobility, another tends toward stabilization to maintain global equilibrium.

Clinical consequences indicate that accentuated kyphosis (increased thoracic curvature) may restrict thoracic segment mobility, reflected through negative correlations with lumbar mobility and flexion movement amplitude, potentially triggering compensations at lumbar or sacroiliac levels, elevating overload risk or functional imbalance.

Based on data resulting from cluster organization and correlations obtained between parameters, an inverse relationship was observed between kyphotic curvature and spinal mobility, particularly at lumbar and thoracic levels. This relationship holds important clinical implications for evaluation and management of patients with postural modifications or back pain.

6. Research Limitations

The relatively small number of study participants necessitates longitudinal evaluation to better quantify the relationship between evolution of parameters characterizing sagittal plane spinal curves and COP behavior. These aspects should be associated with supplementary data regarding daily or weekly physical activity.Further contributions will include a large number of participants, make the evaluation also by eyes-closed and also during gait.

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