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ORIGINAL ARTICLE

What is actually happening inside the "cone of economy": compensatory mechanisms during a dynamic balance test

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Abstract

Study design A nonrandomized, prospective, concurrent control cohort study.

Objective To further develop cone of economy (CoE) measurements by identifying compensatory mechanisms at the extremes of the CoE and comparing balance control strategies in a group of adult degenerative scoliosis (ADS) patients with non-scoliotic controls.

Summary of background data The CoE concept was first proposed by Dubousset and is frequently referred to when assessing balance in spinal deformity patients. Recently, a method that quantifies the CoE of individual patients through 3D video kinematic and electromyography data was developed. However, this method lacks measurements that describe the motor control strategies utilized by spinal disorder patients to maintain balance.

Patient sample Twenty ADS patients and 15 non-scoliotic controls.

Methods All test subjects were fitted with a full body marker set. Each subject performed a series of functional balance tests (Romberg's with eyes opened) while being recorded in a human motion capture system. Three-dimensional CoE dimensions, range of sway (RoS), overall sway and lower extremity and trunk range of motion (RoM) were measured and analyzed.

Results Patients with ADS demonstrated greater overall sway and RoS in the sagittal and coronal planes compared to controls. Moreover, ADS patients presented with more hip flexion and trunk flexion at maximal points of sway and more ankle, knee, hip and trunk RoM when swaying in comparison with controls.

Conclusions ADS patients have larger CoE dimensions and increased sway when compared to non-scoliotic controls. ADS patients rely on a hip balance control "strategy" and lower extremity RoM to maintain balance, which differed from control subjects. Unlike prior attempts to define compensatory mechanisms in ADS patients, the described technique utilizes dynamic, three-dimensional measurements to define what is occurring within the CoE. By expanding on prior CoE measurements, we were able to define a unique dynamic balance control strategy for each patient.

Keywords Cone of economy · Balance control strategies · Adult degenerative scoliosis · Romberg's test · Sway · Range of motion

Key points

1. The previously described cone of economy (CoE) measurement method does not fully account for motor control strategies that patients use to maintain balance; what is actually happening inside the CoE.
2. With this study, we were able to define a unique balance control strategy for each patient.
3. Adult degenerative scoliosis patients have larger CoE dimensions and increased sway while utilizing a hip balance control "strategy" and lower extremity RoM in comparison with the non-scoliotic controls to maintain balance.
4. Adult degenerative scoliosis patients had greater hip and trunk motion than controls, which is associated with higher energy consumption and greater utilization of pelvic and lumbar spine musculature.

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Introduction

The cone of economy (CoE) concept was first proposed by Prof. Dubousset [1] and is frequently referred to when assessing balance in spinal deformity patients (Fig. 1) [2–4]. The CoE refers to a stable region of standing posture. Dubousset noted that with minimal use of muscle action, the "orthogonal gravity line passes through center of the polygon of sustentation," while greater muscle activation would be required if body-segment relative motions were required to maintain balance (Fig. 1) [1, 4, 5]. The ability of the human body to maintain the center of mass (CoM) within the CoE with minimal energy expenditure results from a complex interaction between supra- and infra-pelvic alignment parameters [6–8]. These parameters are influenced by the flexibility of the spine and joints of the lower extremities, neuromuscular control, muscle strength, muscle endurance and body habitus [9].

Diebo et al. [7] investigated the sagittal compensatory mechanisms during static, standing posture in adult deformity patients using full-standing axis stereoradiography (EOS imaging). They concluded that spinopelvic mismatch triggers a chain of compensatory mechanisms to counteract global malalignment. As spinopelvic mismatch increases, there is a steady transfer of compensation from the thoracic spine and pelvis toward the lower limbs [7]. This work and prior studies [10, 11] have described the compensatory mechanisms utilized by patients in the setting of sagittal plane malalignment and spinopelvic mismatch. While helpful in defining the mechanisms utilized to maintain erect posture and horizontal gaze, their assessments are based on measurements and observations from static, standing lateral images. As a result, they do not provide information on dynamic motion and the compensatory strategy utilized by spinal deformity patients after they encounter maximal displacement (borders of CoE) in all three planes.

Recently, a method that quantifies an individual's CoE using 3D video kinematic and electromyography (EMG) data was developed [4]. This method quantifies CoE dimensions by measuring the range of sway (RoS) and balance effort for each patient [4, 12]. This dynamic method has now been used to explore balance in adult degenerative scoliosis (ADS) [3, 4],

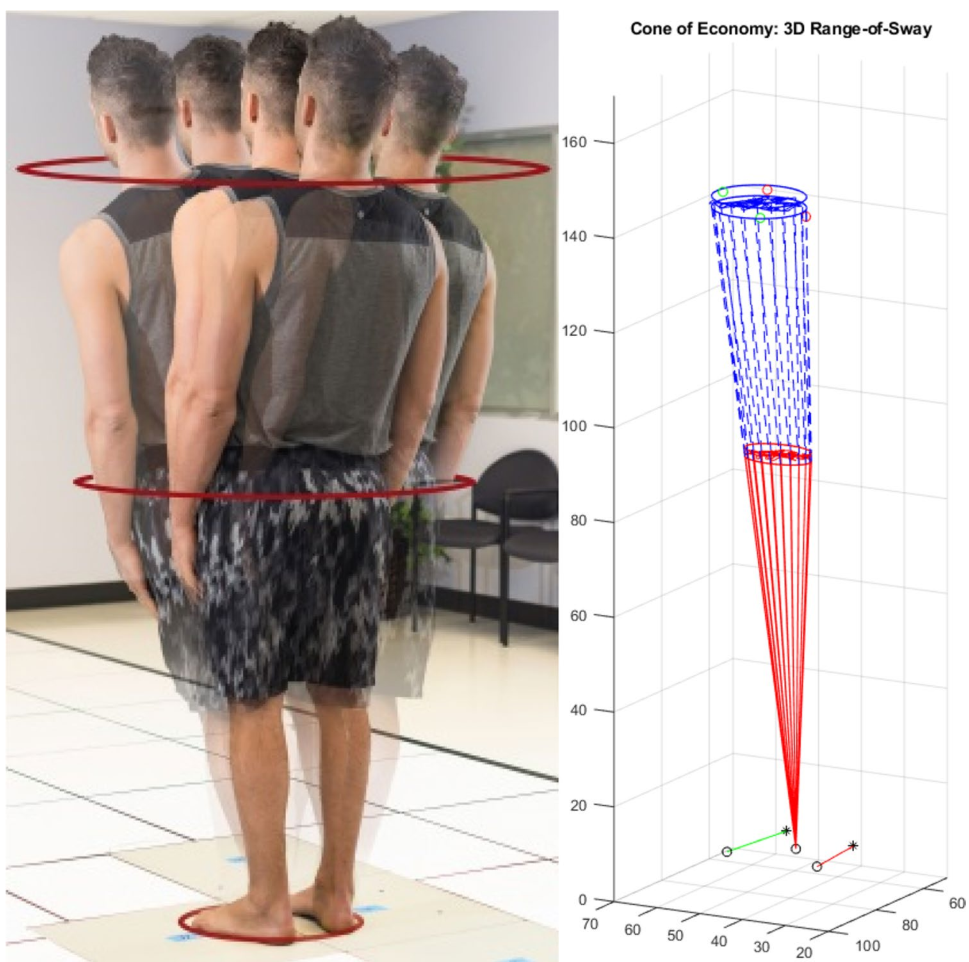

Fig. 1 Cone of economy

cervical spondylotic myelopathy (CSM) [2] and degenerative lumbar spondylolisthesis (DLS) [13] patients. These studies all described an increase in both the sagittal and coronal RoS and a greater amount of sway over time when compared to the controls [4]. Furthermore, ADS and CSM patients were shown to expend more energy during a simple standing task in an effort to maintain balance within their cone of economy when compared to healthy controls [2–4]. This same method was also used to investigate the effect of surgical intervention on ADS, CSM, DLS, and SID patients. In these studies, spinal surgery was found to increase stability, reduce the amount of sway, reduce CoE dimensions and reduce balance effort as seen by smaller spine and lower extremity energy expenditure [3, 4].

To maintain dynamic postural control, the body uses distinct balance control strategies: ankle-, knee- (suspensory) and hip-based strategies [14–16]. “Ankle strategy” involves postural sway control from the ankles and feet. Mechanically, the ankle strategy consists of a rotation of the body about the ankle joint with minimal movement through superior joints [17]. This allows the body to act as a single-segment inverted pendulum controlled by ankle joint torque [15, 16, 18]. “Hip strategy” involves postural sway control from the pelvis and trunk along with delayed activation of the trunk and thigh muscles. With “hip strategy”, the upper body rotates forward and downward which imposes a backward rotation on the lower body while also decreasing the moment of inertia about the ankle. The decreased ankle moment of inertia allows a given ankle torque to effect a higher angular acceleration of the body [17, 18]. The “knee strategy” involves an adjustment of the CoM toward the base of support by bilateral lower-extremity flexion or a slight squatting motion [17, 18].

These balance control strategies can be described as emergent neural control processes and are best differentiated by what the central nervous system (CNS) is attempting to control [16]. Although ankle and hip strategies in standing balance have been identified, some studies have described how one strategy or a combination of strategies may be preferred over another in different situations. The preferred strategy in ADS patients is unclear. Therefore, the purpose of the present study is to further develop CoE measurement methods to include evaluation of balance effort and the dynamic compensatory strategy or strategies utilized by ADS to maintain balance at the extremes of sway. Once obtained, this information will shed light on what is actually happening inside the CoE.

Methods

After receiving institutional review board approval and informed consent from each participant, we prospectively recruited patients with spinal pathology who presented to our offices and were deemed surgical candidates. We also recruited normal volunteers to undergo balance analysis to serve as normal controls to which the surgical patients will be compared.

Subjects

Data were collected from 20 ADS patients (Cobb angle: 43.06° ± 12.2°) and 15 non-scoliotic controls (C; Table 1). Patients were included in the study if they were between the ages of 45 and 75 years with clinically diagnosed thoracolumbar and/or lumbo-sacro-pelvic deformity, with a coronal Cobb angle of 25° or greater, were deemed symptomatic enough to undergo surgical intervention and were able to ambulate without assistance. Patients were excluded if they had a history of prior spine or major lower extremity surgery or previous injury that may affect standing, had a BMI higher than 35, had a primary neurological disorder, had a diabetic neuropathy or other disease that impairs the patient’s ability to ambulate or stand without assistance and were pregnant. Non-scoliotic volunteers were recruited from the general population. These volunteers were between the ages of 30 and 70 years and had no history of spinal deformity or spinal surgery.

Preparatory procedures

All test subjects were fitted with a full body marker set with 41 external reflective markers [4]. These markers were placed on the skin overlying strategic anatomic points as described in Fig. 2. These markers were placed on the skin overlying the C7 and T12 spinous processes, jugular notch, xiphoid process, middle of the right scapula, four markers on the head and bilaterally on the skin overlying the acromion process, mid-upper arm, lateral radial head, mid-forearm, ulnar and radial styloid, third metacarpal head, anterior superior iliac spine, posterior superior iliac spine, top part of the iliac-crest, lateral mid-segment of the thigh, lateral femoral epicondyle, lateral mid-leg at its largest circumference, lateral malleolus, heel and second metatarsal head. Anthropometric measurements (i.e., height, weight, pelvic

Table 1 Anthropometric data for adult degenerative scoliosis patients and healthy control ($M \pm SD$)

	ADS ($N=20$)	Control ($N=15$)	p value
Gender (*F/M*)	15/5	9/6	$p>0.050$
Age (years)	55.6 ± 13.7	50.7 ± 6.9	$p>0.050$
Height (m)	1.59 ± 0.1	1.70 ± 0.1	$p>0.050$
Weight (kg)	64.81 ± 14.4	68.38 ± 13.1	$p>0.050$
BMI	25.52 ± 5.4	24.67 ± 3.2	$p>0.050$

*Indicates significance of $p<0.050$

Fig. 2 Full body marker set with surface electromyography

width, extremity lengths and major joint width) were taken before the test.

Testing procedures

Each subject performed a series of functional balance tests a week before surgery for the ADS group and at the subject's convenience for the control group. The functional balance test was similar to a Romberg's test [19] in which the patients are required to stand erect with feet together and eyes opened in their self-perceived balanced and natural position for a full minute. Each patient performed the test three times. The average of the three tests was used for further analysis.

Data acquisition

Three-dimensional (3D) kinematic data were recorded at 100 Hz using a 10 camera Vicon Video system (Vicon Vantage 16 Megapixels, Englewood, CO). The kinematic data were low-pass filtered with a fourth-order Butterworth filter with a lower cutoff at 4 Hz.

Cone of economy dimensions and balance effort

Range of sway and total sway calculation was based on our previously published balance work (Fig. 3, right) [4]. A custom algorithm (Vicon Nexus 2.7 Inc., Englewood, CO; MATLAB R2018b) was used to calculate head and CoM sway and displacement. To establish the CoE boundaries in three dimensions, we calculated stance width and used that to set the tip of the cone (lower CoE ring). We then measured CoM RoS (middle CoE ring) and mid-head RoS (top CoE ring) in the sagittal, coronal and axial planes during the functional balance test using a custom algorithm (MATLAB R2018b, Fig. 3). Those values were used to determine the boundaries of the CoE and sagittal, coronal and axial RoS. This was followed by plotting and calculating the CoM and head total sway in the sagittal, coronal and axial directions (Fig. 3, right) [4].

Balance strategy—kinematics calculation

To evaluate balance control strategy, we utilized a series of measurements during the one-minute functional balance test. First, we plotted the head RoS for both sagittal and coronal planes (Fig. 4, top). Then, we defined a baseline posture based on the average head position at the beginning and end of the trial (Fig. 4, top). Four peak sways were identified: maximal anterior (1) and posterior (2) sway (sagittal) and maximal right (3) and left (4) sway (coronal). Trunk and lower extremity joint angles were plotted for the sagittal plane (Fig. 4, bottom). As a result, we were able to determine which joint (trunk or lower extremity) was more dominant during sway. Joint angle for each joint was calculated for the four peak sways. Then, each patient's posture was plotted at the peak sway points based the measured joint angles. This method determines patient posture at the peak points of sway and helps determine the control strategy. Range of motion (RoM) was calculated for each joint at baseline to peak and peak return to baseline in the sagittal and coronal planes. These data were used to categorize the balance control strategy for each patient.

Outcome measurements

Cone of economy CoM and head RoS in the sagittal, coronal and axial planes, CoM and head total sway amount. *Balance strategy* Trunk and lower extremity joint angles at the peak head sway points in the sagittal and coronal planes. Lower extremity and trunk RoM from baseline to peak sway and return to baseline.

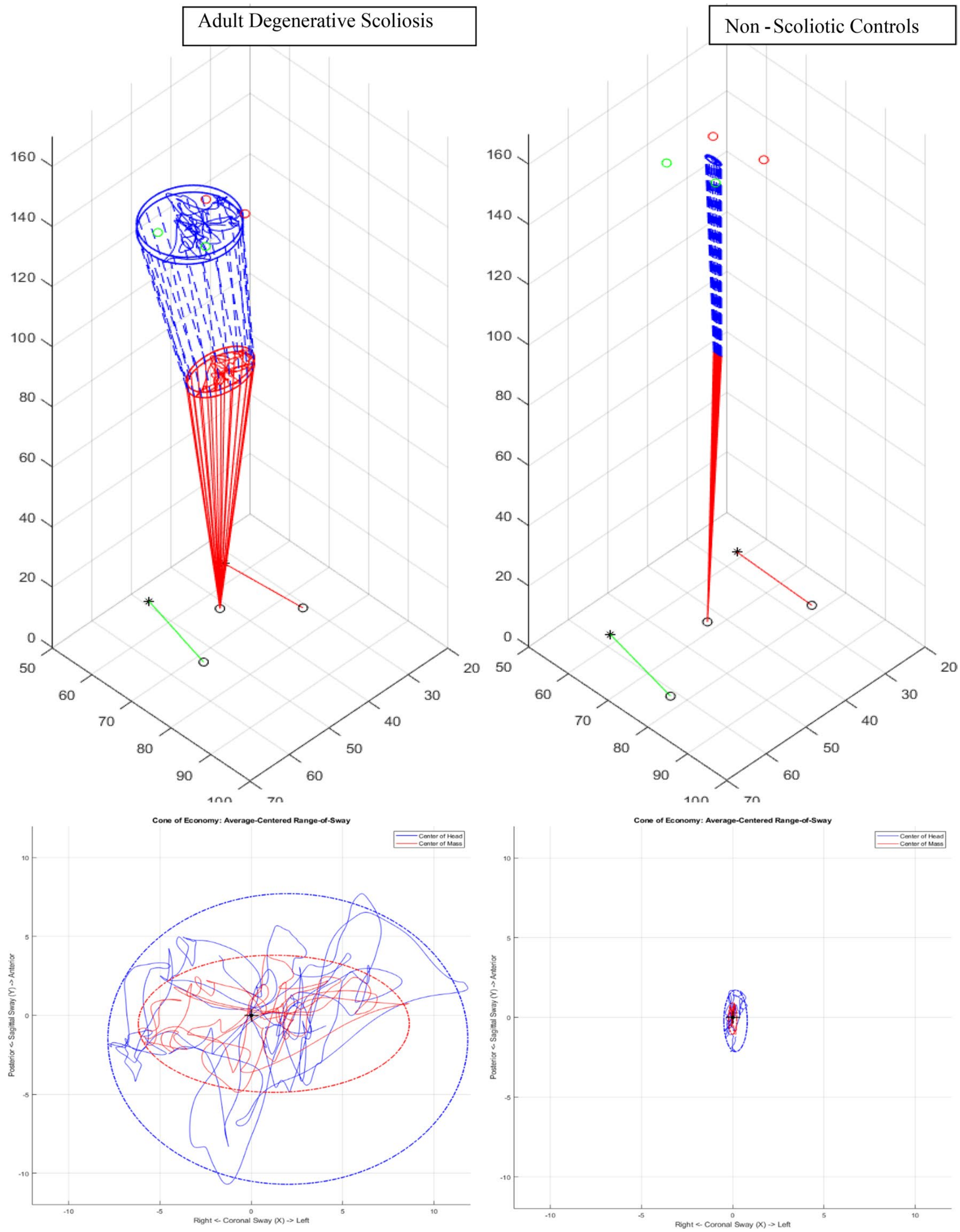

Fig. 3 Representative comparisons of 3—(top) and 2—(bottom) dimensional cone of economy and range of sway of adult degenerative scoliosis (left) and non-scoliotic controls (right)

Statistical analysis

One-way ANOVA was used to determine differences in the CoE parameters and balance control strategy between the ADS patients before surgical intervention and to non-scoliotic controls. Critical alpha level was set to 0.05. Statistical analyses were conducted using SPSS, Version 23.0 (IBM, Inc., Chicago, IL).

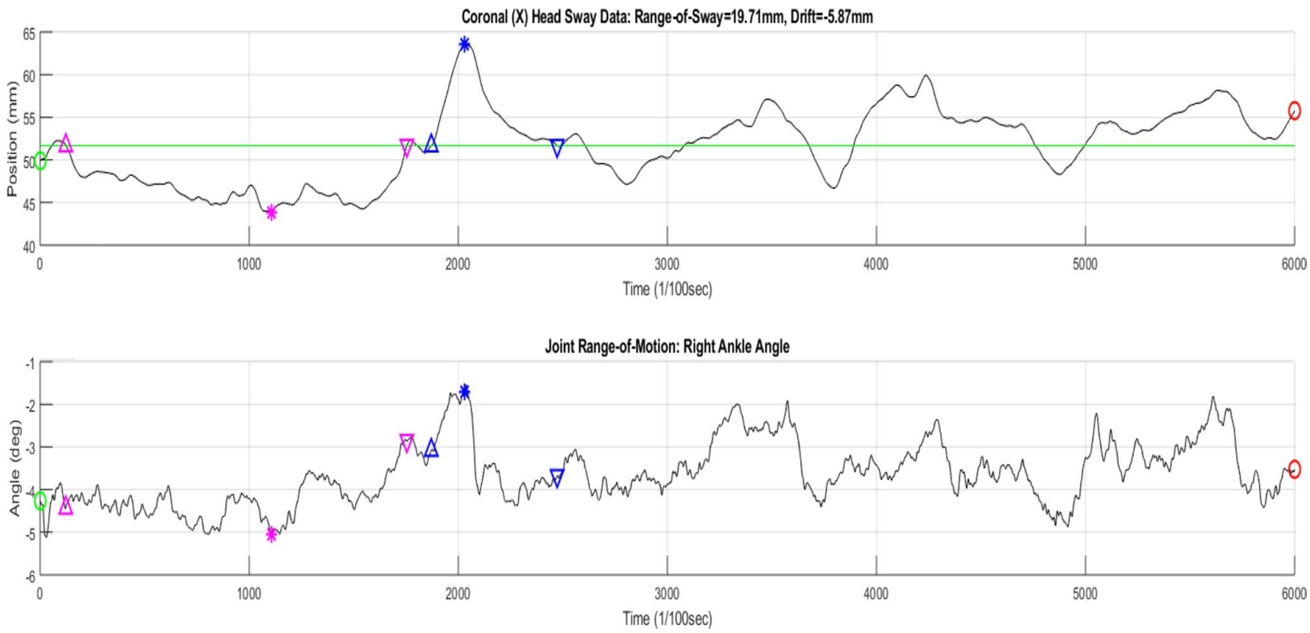

Fig. 4 Representative of head range of sway (top) and ankle joint angle (bottom) at peak sway (*) and beginning (Δ) and end (Δ) of maximum sway

Results

There were no statistically significant differences between the ADS patients and non-scoliotic controls with regard to age, height, weight and BMI (Table 1).

Cone of economy dimensions and balance effort

Patients with ADS demonstrated greater CoM (ADS: 36.18 vs. C: 21.68 cm, $p=0.006$) and head (ADS: 61.83 vs. C: 44.33 cm, $p=0.022$) total sway during the Romberg's test than asymptomatic controls (Table 2, Fig. 3). These patients also exhibited larger CoM and head RoS in the sagittal and coronal planes compared to controls. However, axial RoS differences were observed between the groups only for head RoS (Table 2, Fig. 3).

Dynamic compensatory strategy

When comparing trunk and lower extremity joint angle at the peak point of sway, ADS patients presented with more hip flexion in comparison with the non-scoliotic controls (ADS: 4.48 vs. C: 0.79°, $p=0.037$, Table 3). Ankle, knee and trunk joint angle measurements did not reveal a significant difference. However, greater trunk flexion was observed in ADS patients in comparison with the non-scoliotic controls.

As expected with larger dimensions of the CoE, ADS patients demonstrated a greater trunk and lower extremity RoM in comparison with the non-scoliotic controls (Table 4). For the sagittal sway, ADS patients presented with more ankle (ADS: 5.81 vs. C: 2.19°, $p=0.046$), knee (ADS: 9.38 vs. C: 5.01°, $p=0.044$), hip (ADS: 11.95 vs. C: 5..36°, $p=0.046$) and trunk (ADS: 9.40 vs. C: 2.90°, $p=0.039$) RoM when swaying forward and more ankle

Table 2 Representative balance data of 20 adult degenerative scoliosis patients and 15 controls during eye open Romberg's test (cm; $M \pm SD$)

	Adult degenerative scoliosis		Non-scoliotic controls		*p* value
	Mean	Standard deviation	Mean	Standard deviation	
Base of support					
Base width	0.27	0.05	0.29	0.06	0.468
Base length	0.24	0.01	0.26	0.01	0.493
CoM					
RoS sagittal	3.50	1.18	2.39	0.53	0.005*
RoS coronal	2.11	1.37	0.79	0.33	0.003*
RoS axial	0.87	0.79	0.52	0.22	0.158
Total sway	36.18	16.22	21.68	5.56	0.006*
Head					
RoS sagittal	6.77	1.94	4.38	0.98	0.001*
RoS coronal	3.22	2.00	1.76	0.56	0.020*
RoS axial	1.48	1.00	0.58	0.41	0.007*
Total sway	61.83	23.45	44.33	10.32	0.022*

CoM center of mass, *RoS* range of sways

*Indicates significance of $p<0.050$

Table 3 Representative data of the CoE measurement method—sagittal joint angle at peak sway (°) during 1-min Romberg's test

	Adult degenerative scoliosis		Non-scoliotic controls		*p* value	Adult degenerative scoliosis		Non-scoliotic controls		*p* value
	Mean	Standard deviation	Mean	Standard deviation		Mean	Standard deviation	Mean	Standard deviation	
Sagittal plane sway										
	Peak anterior sway					Peak posterior sway				
Ankle	1.89	2.93	0.87	6.77	0.627	3.37	7.78	0.48	3.33	0.328
Knee	3.48	6.78	3.15	4.24	0.232	5.93	6.52	2.84	4.04	0.153
Hip	4.48	7.74	0.79	2.75	0.037*	5.29	16.09	0.71	7.63	0.366
Trunk	8.53	6.10	4.07	5.80	0.478	6.63	10.18	0.50	3.49	0.193
Coronal plane sway										
	Peak right sway					Peak left sway				
Ankle	1.10	6.77	1.41	3.00	0.482	0.97	7.65	1.00	2.83	0.202
Knee	3.17	6.76	3.12	4.14	0.185	5.81	3.57	3.73	4.14	0.204
Hip	4.04	8.37	1.34	6.37	0.169	4.95	5.22	0.04	7.28	0.326
Trunk	9.20	10.58	4.69	7.93	0.486	7.94	8.38	4.14	5.64	0.587

Table 4 Representative data of the CoE measurement method—sagittal joint RoM (°) during 1-min Romberg's test

	Adult degenerative scoliosis		Non-scoliotic controls		*p* value	Adult degenerative scoliosis		Non-scoliotic controls		*p* value
	Mean	Standard deviation	Mean	Standard deviation		Mean	Standard deviation	Mean	Standard deviation	
Sagittal plane sway										
	Baseline to peak anterior sway					Peak anterior sway to baseline				
Ankle	5.81	5.85	2.19	1.49	0.046*	5.92	5.90	2.27	2.10	0.049*
Knee	9.38	6.82	5.01	2.77	0.044*	9.90	6.55	5.53	3.61	0.044*
Hip	11.95	10.35	5.36	4.34	0.046*	12.08	10.78	3.62	2.48	0.013*
Trunk	9.40	10.24	2.90	2.10	0.039*	7.15	5.36	3.26	2.54	0.026*
	Baseline to peak posterior sway					Peak posterior sway to baseline				
Ankle	6.15	5.98	2.08	1.45	0.029*	5.91	5.83	2.25	1.73	0.044*
Knee	9.54	6.62	5.38	2.97	0.051	9.34	6.78	5.08	3.61	0.055
Hip	11.83	10.21	5.67	4.90	0.062	11.91	10.38	5.16	3.80	0.040*
Trunk	8.82	9.02	3.78	2.78	0.072	9.42	10.05	2.73	1.75	0.031*
Coronal plane sway										
	Baseline to peak right sway					Peak anterior right to baseline				
Ankle	7.09	7.57	2.85	2.44	0.072	6.91	7.30	2.77	2.15	0.067
Knee	8.66	6.39	2.54	2.29	0.004*	8.70	6.42	2.64	2.27	0.004*
Hip	3.78	2.59	1.77	1.39	0.075	3.73	3.55	1.55	1.33	0.052
Trunk	5.59	6.61	1.49	0.79	0.042*	5.69	7.19	1.40	0.71	0.050*
	Baseline to peak left sway					Peak left sway to baseline				
Ankle	6.94	7.07	2.56	1.90	0.045*	7.12	7.46	2.54	1.85	0.047*
Knee	8.58	6.40	2.49	2.25	0.004*	8.61	6.48	2.67	2.24	0.005*
Hip	3.62	3.38	1.60	1.42	0.060	3.70	3.64	1.86	1.64	0.111
Trunk	5.57	6.54	1.46	0.84	0.040*	5.33	6.19	1.11	0.75	0.027*

RoM (ADS: 6.15 vs. C: 2.08°, $p=0.029$) when swaying backward in comparison with controls (Table 4). During coronal sway, ADS patients presented with more ankle (ADS: 6.94 vs. C: 2.56°, $p=0.045$), knee (ADS: 8.58 vs. C: 2.49°, $p=0.004$) and trunk (ADS: 5.57 vs. C: 1.46°,

$p=0.040$) RoM in comparison with asymptomatic controls (Table 4).

Discussion

This study is the first attempt to describe the dynamic balance control strategy of ADS patients and detail what is occurring within the CoE. Adult degenerative scoliosis patients presented with larger CoE dimensions and increased total sway compared to the non-scoliotic controls. Previous literature on the CoE referred to it as a stable region of standing posture [1, 4, 12, 20, 21]. However, the result of this paper defines the compensatory mechanisms by which ADS patients compensate to maintain their balance during dynamic testing. ADS patients exhibited increased motion in the trunk, hip, knee and ankle joints inside the CoE and relied on a hip balance control strategy to maintain their balance. The methods described in this paper can be used to describe the balance control strategy for individual patients.

ADS patients exhibited greater hip and trunk motion which results in higher energy consumption and greater utilization of pelvic and lumbar spine musculature. Hip-based compensatory mechanisms involve the upper body rotating forward and downward, imposing a backward rotation on the lower body while also decreasing the moment of inertia about the ankle and allowing a given ankle torque to effect a higher angular acceleration of the body [17, 18]. Hip "strategy" involves postural sway control from the pelvis and trunk along with delayed activation of the trunk and thigh muscles [22, 23]. Although this was not statistically significant, ADS patients presented with higher joint angle values for the trunk, knee, and ankle. Furthermore, these patients presented with significantly greater trunk and lower extremity RoM during sway in comparison with controls. This was expected due to larger CoE dimensions. Healthy controls did not reveal any specific control strategy but did show smaller joint angle values in all trunk and lower extremity joints and relatively less RoM during the dynamic balance test in comparison with the ADS patients. Literature shows that healthy control tends to sway using ankle "strategy" [17, 18]. This was not the case in our study and can potentially be due to a small sample size.

The ankle "strategy" is expected to be employed for unperturbed stance and for slow and low amplitude perturbations, whereas the hip strategy is expected to be employed for fast or large amplitude perturbations or when the support surface is narrow and little ankle torque can be applied [14, 17, 18]. Regardless of which strategy is employed, motion and torque about both the ankle and hip are unavoidable, as accelerations of one segment will result in accelerations on other segments that must be either resisted or assisted by the appropriate muscle group [17, 18, 23–25]. Ultimately, an attempt at an ankle strategy will require compensatory hip torque acting in the same direction as ankle torque to resist the load imposed on it by the acceleration of the legs. Conversely, an attempt at a hip strategy will require complementary ankle torque acting in the opposite direction to hip torque to achieve the required anti-phase rotation of the upper and lower body [18]. The way an individual patient compensates for trunk imbalance may be variable and may depend on other constitutional factors such as age, neuromuscular condition and BMI. In general though, the brain, through the righting reflex, will sacrifice focal alignment to optimize global balance within the CoE [4].

Prior studies have elucidated the compensatory mechanisms to maintain erect posture and horizontal gaze in patients with sagittal malalignment and spinopelvic mismatch [7, 10, 11]. These studies have defined a unique sequence of compensatory mechanisms based on standing, full-length head-to-toe radiographic images. In contrast, the present study offers insight into the mechanisms employed by ADS patients at the extremes of motion within the CoE. Through dynamic, three-dimensional measurements, we are able to identify the compensation "strategy" employed by ADS patients and compare them with normal controls. At the peaks of sway, ADS patients utilized hip flexion to stay within the CoE. In contrast, the aforementioned studies based on static images in the setting of sagittal deformity have demonstrated pelvic retroversion (and thus hip extension) and knee flexion ("knee strategy) as components of the compensation cascade [7]. While the knee joint plays an important role in detecting balance perturbations and aiding in compensatory postural strategies [7, 26], the perspective is entirely different when viewing a dynamic balance test. Patients utilize different strategies when attempting to stay balanced within the CoE compared with maintaining an erect posture at single point in time while in the standing position. This is consistent with prior research that showed pelvic parameters (compensatory mechanism) change during a dynamic test and that static measurements may underestimate global malalignment when compared with dynamic methods [27].

This study does have inherent limitations. Human motion video capture and associated kinematic modeling are susceptible to skin movement, system tracking issues and data smoothing errors. Furthermore, human function analysis is subject to large inter-subject variability and therefore three trials were collected and averaged. The current method does not provide insight into the nature of any impairments or age-related changes to ocular (visual), vestibular and proprioception (tactile and joint position sense) systems. Furthermore, age is known to play a role in trunk posture and subsequent lower extremity compensatory changes [5, 7]. Future studies will aim to explore the impact of age-related changes on the CoE and dynamic balance control strategies. Diebo et al. [7] demonstrated that compensatory mechanisms are transferred to the lower extremities, particularly through knee flexion ("knee" strategy), as spinopelvic mismatch increases, and other compensatory mechanisms are exhausted. We did not specifically evaluate the impact of spinopelvic mismatch and sagittal balance on CoE and balance measurements. ADS encompasses a heterogeneous group of deformities, and thus different subgroups may employ different balance strategies. Further work will explore balance strategies within specific subgroups of ADS patients.

Nonetheless, this method provides a more quantitative model for balance than clinician observation alone. Although ADS patients sway more and use more hip control strategy based on a group statistical analysis, a substantial variation between patients was found. Therefore, it may be more beneficial to use this method in a repeated-measurement design fashion (i.e., before and after surgical treatment). Regardless, this method can be used when assessing the severity of a patient's balance and recording the changes following surgical intervention. Moreover, this method can provide more detailed information to spine care practitioners on their patient's balance pattern and posture. We encourage spine care providers, who have access to a human motion laboratory, to consider this method as part of their evaluation in order to evaluate the effect of surgical or non-surgical intervention on their patient's balance effort and compensatory mechanisms.

Conclusions

This study is the first attempt to describe the balance control "strategy" employed by ADS patients during a dynamic evaluation. Unlike prior attempts to define compensatory mechanisms in ADS patients, the described technique utilizes dynamic, three-dimensional measurements to define what is occurring within the CoE. ADS patients have larger CoE dimensions and increased sway than non-scoliotic controls. Furthermore, they rely on a hip balance control "strategy" and lower extremity ROM, which differed in comparison with the non-scoliotic controls. Through the described methods, we were able to define the unique balance control strategy employed by each patient. This method can be used when assessing the severity of a patient's balance and recording the changes following surgical intervention. Furthermore, this method can provide more detailed information to spine care practitioners on their patient's balance pattern and dynamic posture.

Compliance with ethical standards

Conflict of interest The authors states that there is no conflict of interest.

IRB approval The study was approved by the Western Institutional Review Board (IRB#: 20151780).

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