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Clinical Study

Comparison of whole body sagittal alignment during directed vs natural, relaxed standing postures in young, healthy adults

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Abstract

BACKGROUND CONTEXT: Imaging for adult spinal deformity is conventionally performed in a directed manner to assess the most upright standing posture one can assume. However, this method does not reflect an individual's natural, relaxed posture, which is the posture a patient likely reverts to postoperatively, and also the posture likely to explain spinal pathologies.

PURPOSE: To identify radiographic differences between directed and natural, relaxed standing postures in young healthy subjects.

STUDY DESIGN: A randomized, prospective, radiographic study.

PATIENT SAMPLE: Sixty healthy 21-year-old subjects (48 male, 12 female).

OUTCOME MEASURES: Radiographic parameters including sagittal vertical axis (SVA), C2 SVA, C2−7 SVA global cervical angle, T1-slope, global thoracic angle (GTA), thoracolumbar angle (TLA), global lumbar angle (GLA), sacral slope, pelvic tilt (PT), pelvic incidence, femoral alignment angle (FAA), and knee alignment angle (KAA).

METHODS: The EOS whole body radiographs of patients in directed and natural, relaxed standing postures were obtained, with subsequent comparison of radiographic parameters. Differences in Roussouly curve types, sagittal curve apices, and end vertebrae were also evaluated. Univariate analyses using Wilcoxon sign-rank, paired *t* tests, and paired chi-square tests were performed.

RESULTS: Compared with directed standing, natural, relaxed standing results in a more kyphotic spinal profile marked by a significantly less lordotic GLA, larger GTA, TLA, and T1-slope. The PT+FAA demonstrated true hip movement during sagittal balancing. Lower thoracic and lumbar apices, lower thoracolumbar end vertebrae, and lower Roussouly curve types were observed during natural, relaxed standing.

CONCLUSIONS: Our study found significant differences in sagittal radiographic parameters between directed standing and the natural, relaxed standing posture, with the latter demonstrating a more kyphotic spinal profile in terms of magnitude and span, as well as complementary changes in cervical and spinopelvic alignment. The natural, relaxed standing posture, a marker for energy conservation principles in standing, may infer value in less aggressive lordotic restoration, as well as concentration of lordosis in the lower lumbar spine.

FDA device/drug status: Not applicable.

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Introduction

Over the past two decades, several concepts have revolutionized adult spinal deformity (ASD) surgery. Dubousset first propagated the concept of energy conservation, describing a "cone of economy," where an individual keeping within the said cone could achieve balance with minimal effort [1,2]. Next, the importance of spinopelvic parameters was uncovered with pelvic incidence (PI) as a unique constant used to determine the magnitude of lordotic correction, with increased pelvic tilt (PT) reflecting sagittal compensation achieved via pelvic retroversion [3−5]. Subsequently, the importance of sagittal balance over coronal balance in ASD was recognized [6], with establishment of key sagittal parameters used to guide deformity correction. Specifically, according to the Scoliosis Research Society (SRS)-Schwab classification, surgery should achieve sagittal vertical axis (SVA) <4 cm, a PI-lumbar lordosis discrepancy <10° and a PT of <20° [7] in order to improve patient-reported outcome scores [4,6,8].

To ascertain the need for surgery and determine these deformity correction targets, radiographs are conventionally performed with the patient being instructed to stand straight [9,10] as this allows assessment of the patient's capacity to achieve the most upright standing posture. Consequently, there has been a lack of understanding on the natural, relaxed postures commonly assumed in daily life, which may be more likely to explain existing spinal pathologies [11] as well as predict postoperative complications such as proximal junctional failure (PJF) and rod breakages [12−15]. Therefore, this novel study compares radiographs of the directed standing posture with those of the natural, relaxed standing posture, in order to obtain additional information beyond what is already known of the former. The null hypothesis states that there is no difference in the sagittal radiographic parameters between the natural, relaxed standing posture and the directed standing posture.

Materials and methods

Study design

This study compared whole body radiographs of subjects in both natural, relaxed standing (hence assuming greater energy conservation), and directed standing postures. It was conducted prospectively over 6 months at a single tertiary health-care center. Local ethics board approval was obtained before commencement.

To study normal postural behavior in the healthy spine, 21-year-old subjects were recruited between January to June 2017. Such subjects were selected over adult deformity patients due to greater spine flexibility and likelihood of more pronounced magnitudes of angular change, enabling the study of a physiological phenomenon (proof-of-concept). Before recruitment, all subjects underwent a thorough clinical assessment to screen for pre-existing spinal problems. Exclusion criteria comprised:

1. Any history of significant back or leg pain (either >1 episode, VAS >3, or pain for >6 weeks);
2. Any previous spinal conditions or spine surgery;
3. Any red flag symptoms including constant pain, night pain, fever, loss of weight, loss of appetite;
4. Any significant previous or recent trauma to the spine;
5. Any significant personal or family history of malignancy;
6. Any contraindication to radiation exposure (eg, pregnancy);
7. Any presence of spinal deformity upon Adam forward bending test.

Radiographic examination

All eligible subjects underwent two sets of whole body radiographs using EOS technology, a modality advantageous for taking true-to-proportion and true-to-axis whole body images [16,17]. The sequence of postures was computer randomized using blocks of the two postures (relaxed followed by directed posture or directed followed by relaxed posture). This ensured equal distribution of both postures.

To promote standardization, pictorial charts demonstrating how to stand straight for the directed standing posture were displayed by the EOS machine. Uniformity of this posture was further reinforced through standardized verbal instructions given by the radiographer as follows: "stand as straight as possible without leaning forwards or backwards, and touch your collarbones with your fingers." The natural, relaxed standing posture was not guided so as to allow the subject to stand in his/her normal, relaxed way. Subjects were simply asked to "stand in a natural, relaxed way," and once this posture had been assumed, they were then told to maintain it with the instructions, "hold on to your current posture and bring your fingers to touch your collarbones." Although assuming the fingers-on-clavicles may be arguably unnatural, the authors mitigated this through a stepwise process of assuming this posture, first to ensure the subject stands in the natural, relaxed manner and then placing their upper limbs in forward flexion and fingers on clavicles without altering this posture. All images were performed by trained radiographers with over 3 years of experience in EOS technology.

Radiographic measurements

Radiographic measurements were performed by two blinded orthopedic surgeons, and an average of their readings was recorded. Measurements performed included the SVA, C2 SVA, C2−7 SVA, global cervical angle (GCA), T1-slope, global thoracic angle (GTA), thoracolumbar angle, global lumbar angle (GLA), PI, PT, sacral slope (SS), femoral alignment angle (FAA), and knee alignment angle (KAA).

All angular measurements were performed using the Cobb method. The GCA was measured between the inferior end plate of C2 to inferior end plate of C7, GTA was measured between the superior end plate of T1 and the superior end plate of T12. Thoracolumbar angle was measured between the superior end plate of T11 and the inferior end plate of L2. The GLA was measured between the superior end plate of T12 and the superior end plate of S1.

The SVA, C2 SVA, and C2−7 SVA, as well as the spinopelvic parameters PI, PT, and SS were measured as per convention in the literature [7,18]. The FAA was taken as the acute angle subtended by the femoral axis (midpoint of bicoxafemoral hip center to midpoint of both mid-Blumensaat lines) and the vertical axis. Knee alignment angle was taken as the acute angle between the femoral axis and the tibial axis (midpoint of both midtibial plateaus to the midpoint of both midtibial plafonds). The inflection vertebra is defined as the most tilted vertebra on the lateral EOS image that marks the distal end of kyphosis and proximal end of lordosis at the thoracolumbar junction.

The sagittal spinal curve morphology for both postures was also described using apical and inflection vertebrae, which were taken as the most horizontally displaced and most tilted vertebra on the sagittal profile of the spine, respectively. Spinal curve types were described using Roussouly classification [19] primarily based on sacral slope. Types 1 and 2 curves were further differentiated based on curve morphology described by Roussouly et al. [19].

Statistical calculations

A power analysis was performed by using pilot study data of 10 subjects, and by referring to similar studies which compared other postures [11,20]. These preliminary subjects were not included in the actual study. With α=0.05 and β=80, it was estimated that a sample size of 60 subjects will be sufficient to detect a statistical in SVA, GLA, and PT when using paired t tests. These parameters were used as they are arguably the key radiographic parameters used in sagittal spinal alignment assessment, and are expected to undergo substantial changes when subjects assume a more relaxed standing posture [20]. SVA had the largest standard deviation in the pilot data and was the determinant of sample size. An arbitrary clinical difference in SVA of 4 cm, GLA of 5°, and PT of 5° between directed and natural, relaxed standing postures were also expected.

All statistical analysis was conducted using IBM SPSS Statistics v23.0 (Armonk, NY, USA), with statistical significance set at p<.05 throughout. Wilcoxon rank-sum tests, paired t tests, and paired chi-square tests were used for univariate analysis to compare radiographic parameters across postures.

Results

Sixty young healthy subjects (48 males and 12 females) comprising 42 Chinese, 10 Malays, and 8 Indians were recruited for this study. Multiple significant radiographic differences were found between their directed and natural, relaxed standing postures (Table 1). Mean SVA and C2 SVA became positive during natural, relaxed standing, signifying forward shift of the upper trunk relative to the sacrum (p=.034 and p=.041, respectively). Natural, relaxed

Table 1
Sagittal spinal, spinopelvic, and lower limb alignment parameters in the directed and natural standing postures

	Directed standing (mean±SD)	Natural standing (mean±SD)	p value
	Sagittal balance		
Sagittal vertical axis (SVA) (cm)	−0.3±24.2	9.6±35.3	.034*
C2 SVA (cm)	0.3±25.6	12.6±45.3	.041*
C2−7 SVA (cm)	0.5±9.9	3.0±24.4	.341
	Spinal curvature		
Global cervical angle (GCA) (°)	3.4±11.9	-7.4±15.2	<.001*
T1-slope (°)	15.2±7.4	30.1±9.0	<.001*
Global thoracic angle (GTA) (°)	26.1±11.4	44.4±11.5	<.001*
Thoracolumbar angle (TLA) (°)	2.2±8.0	12.1±8.7	<.001*
Global lumbar angle (GLA) (°)	-50.6±11.6	-44.8±13.0	<.001*
	Spinopelvic and lower limb compensation parameters		
Pelvic tilt (PT) (°)	8.4±6.7	16.4±8.1	<.001*
Pelvic incidence (PI) (°)	48.8±9.7	48.9±9.3	.921
Femoral alignment angle (FAA) (°)	4.9±2.4	3.3±3.1	<.001*
Pelvic tilt+femoral alignment angle (PT+FAA) (°)	13.3±7.1	19.7±8.7	<.001*
Knee alignment angle (KAA) (°)	4.0±3.2	4.3±3.3	.624

SD, standard deviation.

Positive values signify an anterior position of the vertical plumb line with respect to the caudal landmark for translation measurements, and kyphosis for angular measurements. FAA is positive when the hip is extended relative to vertical axis and KAA is positive when knee is extended relative to the femoral axis.

* Significant.

standing also showed less lordotic GLA than directed standing ($p \leq .001$). This was associated with further kyphosis of the thoracic spine both in terms of magnitude ($p<.001$) and span (number of involved vertebral levels). The latter was substantiated by a concomitant increase in thoracolumbar kyphosis ($p<.001$), a higher T1-slope ($p<.001$), and a caudal shift in the median inflection vertebra (Table 2, $p<.001$). Mean GCA became more lordotic during natural, relaxed standing ($p \leq .001$).

Spinopelvic and lower limb parameters change in compensation for the aforementioned findings (Table 1). When transitioning from directed to natural, relaxed standing, there was an increase in PT ($p<.001$). Although a slight decrease in FAA occurred in natural, relaxed standing ($p<.001$), a larger PT+FAA ($p<.001$) was still observed ($p<.016$).

In terms of curve morphology, significant changes occur such that the apices of both the thoracic and lumbar curve, as well as the inflection vertebra at the thoracolumbar junction shifted caudally during natural, relaxed standing (Table 2). The thoracic apex shifted from a median of T5 to T7 ($p<.001$), the lumbar apex from L3/4 to L4 ($p<.001$) and the inflection vertebra from T12 to L1 ($p<.001$). When applying Roussouly's classification [19] to our study cohort, it was found that every subject assumed a lower SS ($p<.001$) and had a corresponding change in thoracic and lumbar sagittal curve profile, rendering them an average of one curve type lower ($p<.001$) during natural, relaxed standing. In our cohort, 20 subjects maintained their curve type, 23 decreased by one curve type, 13 decreased by two curve types, and 4 decreased by three curve types.

Table 2
Differences in sacral slope and Roussouly curve types, as well as corresponding differences in sagittal curve apices and end vertebrae between the directed and natural standing postures

	Directed standing	Natural standing	p value
Sacral slope (SS) (°)†	40.8±7.7	32.4±7.4	<.001*
	Roussouly curves		
Mean curve type†	3.0±0.8	2.0±0.9	<.001*
Type 1‡	3 (5.0%)	23 (38.3%)	
Type 2‡	12 (20.0%)	19 (31.6%)	<.001*
Type 3‡	30 (50.0%)	17 (28.3%)	
Type 4‡	15 (25.0%)	1 (1.6%)	
	Thoracic alignment		
Proximal end vertebra§	T1 (T1−T3)	T1 (T1−T2)	.224
Apical vertebra§	T5 (T3−T10)	T7 (T5−T12)	<.001*
	Thoracolumbar junction alignment		
Inflection vertebra§	T12 (T8−L2)	L1 (T10−L4)	<.001*
	Lumbar alignment		
Apical vertebra§	L3/4 (L2−L5)	L4 (L3−L5)	<.001*
Distal end vertebra§	S1 (L5−S1)	S1 (L5−S1)	.321

* Significant.
† Values are reported as means±1 standard deviation.
‡ Values are reported as frequencies.
§ Values are reported as median vertebra with ranges.

Discussion

Lordotic realignment of the lumbar spine has been shown to yield good patient-reported outcome scores [6,8], with overcorrection likely giving a larger benefit [21]. However, the parallel rise in postoperative complications such as PJF [12−14] and rod breakage [15] suggests unresolved biomechanical issues following realignment surgery. A common method of obtaining whole body radiographs to evaluate ASD requires patients to stand straight in a directed manner [9,10]. Although advantageous in assessing the spine's capacity to assume the most upright posture, this method may be less useful for understanding postural tendencies or predicting pathologies [11]. Therefore, we postulate that a combination of the directed and relaxed standing postures for spinal imaging may help improve spinal realignment strategies.

Differences between both postures demonstrate the role of key ligaments during natural, relaxed standing. A similar concept was introduced in a previous study on natural sitting postures, where the whole spine was described to assume an almost full C-shape, placing the posterior ligamentous complex in tension [22]. In this study, the body in standing maintains global balance by continuously adapting via an interplay of dynamic muscle counterbalancing and static ligamentous support. This ligamentous-muscular counterbalancing works in concert with maintenance of the body in its "cone of economy" to maximize energy conservation (Fig. 1). An increase in thoracic kyphosis (GTA), an extension of the kyphotic span into the thoracolumbar junction, and a less lordotic GLA demonstrated that natural, relaxed standing stresses the entire spine into kyphosis. Akin to the aforementioned natural sitting study, these findings reflect the body's subconscious efforts in conserving energy such that the entire spine, though standing, resembles more of a "sitting" posture, with the use of the posterior ligamentous complex for tension band effect [22]. In contrast with natural sitting, natural, relaxed standing leads to additional pelvic retroversion (increased PT), which recruits anterior hip ligaments during hip extension. This mechanism helps to further conserve energy during natural, relaxed standing (Fig. 2) [23].

In this study, we measured FAA, a parameter that assesses femoral axis inclination relative to the vertical axis during standing. Both pelvic retroversion and backward femoral inclination are rotational actions about the hip center. Their combined behavior determines true spinopelvic movement at the hip joint (Fig. 3). Understanding this concept is paramount as it determines how we interpret hip compensation during forward spinal imbalance. Upon maximum hip compensation, knee flexion follows to achieve full body sagittal balance. Although it may be arguable that the changes in magnitude of FAA may appear much less than PT in this study, its role in an anteriorly shifted pelvis, either as a result of natural, relaxed standing or sagittal balancing in a kyphosed spine, is not fully understood. Moreover, different conditions (eg,

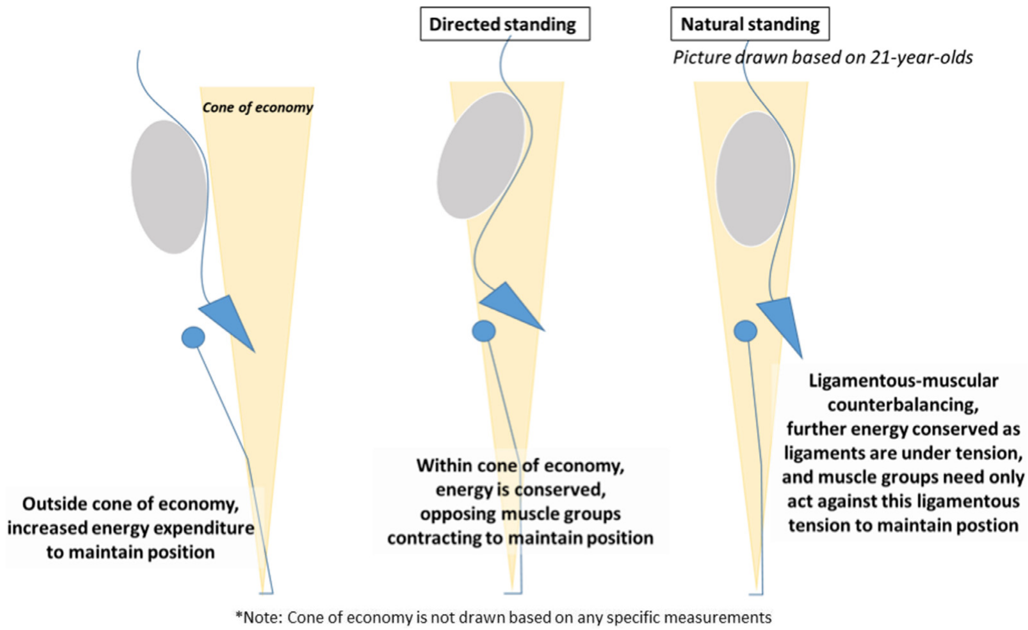

Fig. 1. Energy conservation is achieved by staying within one's cone of economy; further energy conservation is achieved by employing "ligamentous-muscular counterbalancing."

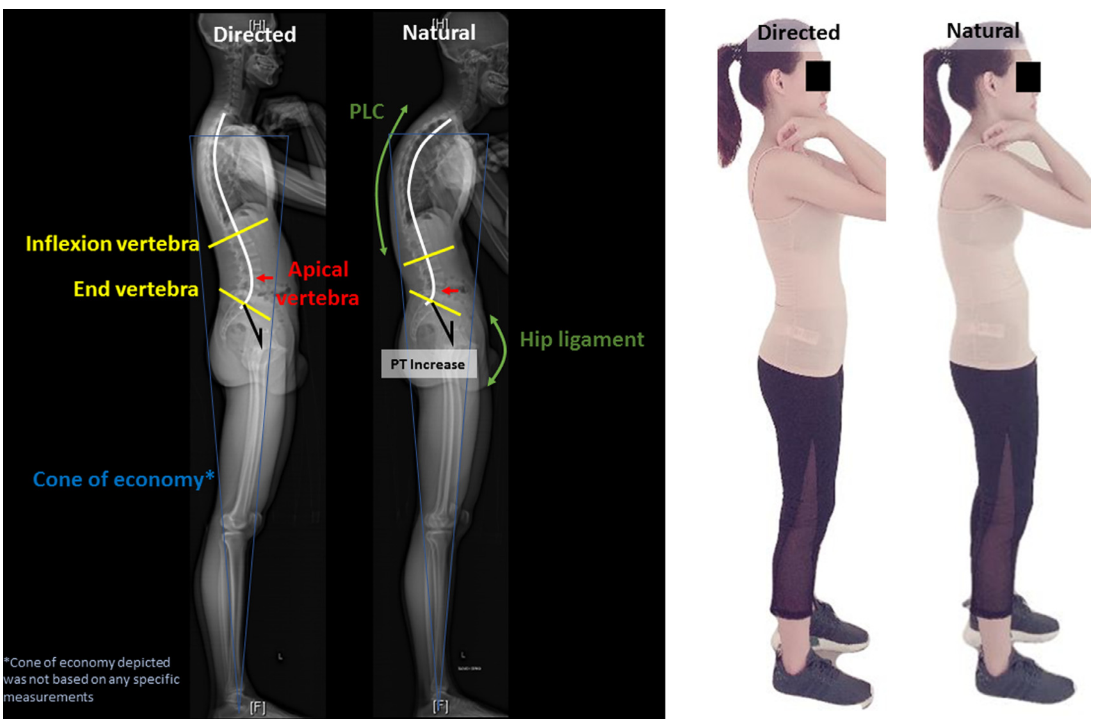

Fig. 2. Radiographic and real-life representation of changes when transitioning from a directed to a natural/relaxed standing posture. PLC, posterior ligamentous complex.

arthritic hip conditions or patients with ligamentous laxity) may also display different hip movements. The role of PT +FAA, which has already been shown in this study to vary between standing postures, should thus be further analyzed in future studies on ASD patients.

Whole body balance relies on having adequate lordosis to balance kyphosis, and vice versa [24], in the process maintaining horizontal gaze. During natural, relaxed standing, increased kyphosis at both the thoracic region and thoracolumbar junction necessitate greater concentration of lordosis caudally, as evidenced by the shorter lordotic span and lower lumbar apical vertebrae, as well as increased lordosis cranially in the cervical spine. This explains why concentrating restoration of lordosis in the lower lumbar

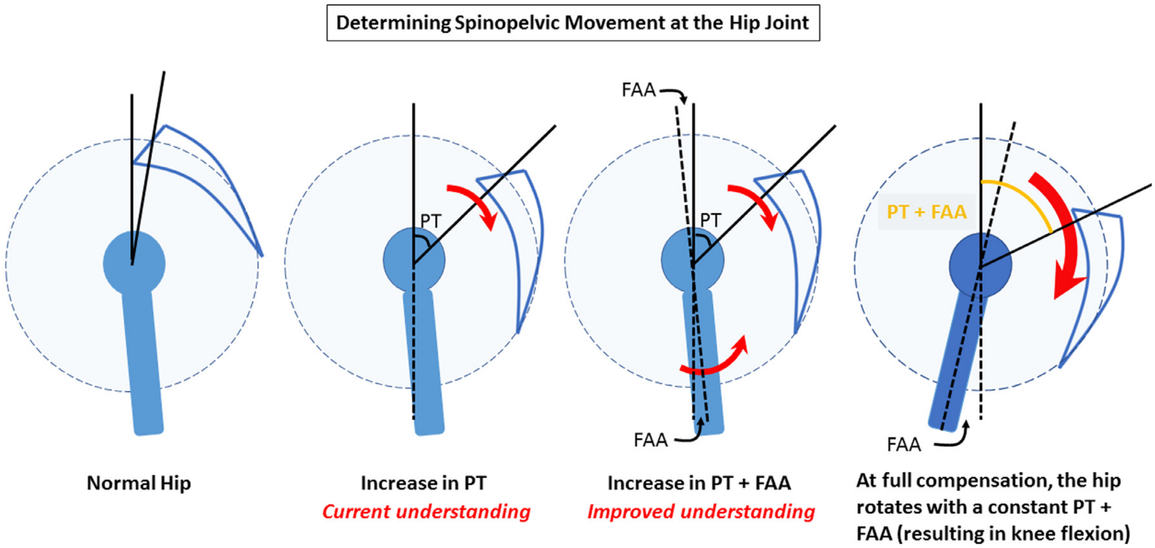

Fig. 3. Spinopelvic movement and compensation.

segments may present a more physiological strategy in spinal realignment surgeries. These hypotheses correspond with current literature that associates undercorrection with reduced proximal junctional kyphosis (PJK) rates [25]. The value of concentrating lordosis at the lower lumbar spine, in addition to undercorrection, should be further explored in future studies.

The conventional fixed anatomical definition of lumbar lordosis fails to consider that the inflection vertebra varies both across [19] and within individuals [11]. Although the Roussouly classification of sagittal spinal profiles has already described differences *across individuals*, our findings of a kyphosing thoracolumbar junction and descending inflection vertebra during transition from directed to natural, relaxed standing add to the growing evidence proposing variations *within individuals* [11,22,26−28]. These findings also imply that Roussouly curve types may vary with change in standing postures and should be interpreted with caution. Although not all subjects assumed a lower Roussouly curve type, all subjects assumed a different spine profile, which is akin to a lower curve type. This is the result of (1) a kyphosing spine, (2) reduction in GLA, (3) shortening of lordotic span, (4) an increase in PT with concomitant decrease in SS, and (5) an overall change in the whole body lordotic profile to incorporate the hip movement. These findings contest the current understanding that Roussouly's classification of sagittal spinal profiles is individual-specific and changes only with pathology, thus prompting the need for clear imaging instructions to study directed and natural, relaxed standing postures, so as to promote reproducibility and enable accurate assessment of sagittal alignment.

It has been commonly accepted that life is a kyphosing event. This study relates this concept by showing that the natural, relaxed standing posture produces radiographic parameter changes identical to an aged spine, therefore suggesting that the changes with age is likely produced by relaxed postural tendencies, the latter happening before the former. In terms of ASD surgery, although age-adjusted strategy is increasingly being recognized to minimize mechanical complications such as PJK/PJF, occurrence of such complications even in younger patients following deformity correction warns us of a constantly ongoing mechanical problem (ie, postural tendencies) that affects all, even though the elderly may be more at risk due to a weaker and more evolved physiology. Therefore, we feel strongly that natural, relaxed standing postures should be given equal emphasis as age-adjusted deformity correction strategies.

This study included a predominantly male population, which could be a source of selection bias. Although gender may not have not been clearly shown to influence sagittal balancing either in terms of type of deformity it produces or by the compensatory mechanisms it involves, pelvic morphology is known to be different between sexes. Because lumbar morphology is largely accepted to be determined by pelvic morphology, interpretation and application of our study results should still consider this potential bias. Future results with larger series of female gender can be performed to further investigate this topic. The small number of Malays and Indians also prohibited comparison between ethnic groups. Nevertheless, its spectrum may allow generalization and clinical application of our findings. In addition, because the design of this study includes subjects crossing over to receive different interventions, there are potential biases of "order" and "carry-over." The effects of assuming a natural, relaxed posture immediately after a directed posture may not be identical to one performed before, and vice versa. However, as we do not truly know the effects of postural sequences on their radiographic outcomes, this was allowed in the current study. Future studies can analyze this effect by implementing a washout period between EOS imaging of both postures.

This study uses the standard finger-on-clavicle method to achieve a reproducible upper limb forward flexed position [29−31], albeit with interindividual variations due to body morphological differences. Although there are several other methods in terms of upper limb positioning when performing whole body imaging [32−34], this method is common in many centers and allows for cross-interpretation. The basis of upper limb positioning hinges on two main issues: (1) not having them in a position (ie, by the side) that would block visualization of the spine on the lateral view, and (2) not having them placed in a position such that they would substantially influence whole body balance (ie, not too flexed at the shoulder to create a larger anterior gravitational lever arm, or placing the hand on an anterior support to allow load sharing). The natural, relaxed standing posture in this study results in the upper limbs appearing less forward flexed which is likely caused by shoulder protraction and thoracic spine kyphosis. As it is more important to ensure naturality than directing specific orthogonal angles during body positioning, finger-on-clavicle position is preferred over fixing flexed upper limbs at 30°, which has been suggested by some authors.

Natural, relaxed standing posture, a marker for energy conserved standing, can be explained by ligamentous-muscular counterbalancing. Although distinctively different from the directed standing posture, both are equally important and should be studied. The constellation of findings regarding the natural, relaxed standing posture supplements the existing literature to infer potential value in undercorrection of lordosis, as well as potential value in concentrating lordosis in the lower lumbar spine. Application of the aforementioned forms a spine resembling a lower Roussouly curve type, and may potentially reduce biomechanical complications. This current study demonstrates proof-of-concept in young, healthy patients and its findings cannot be directly applied to adult patients with spinal deformity. Its use in patients with ASD remains theoretical at this point until a further study showing the reproducibility of these concepts in ASD patients can be produced.

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