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Research Article

Segmental Spine Dynamic Theory (SSD Theory): A New Concept for Spine Dynamics

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Abstract

Background/Objectives: The biomechanics of spinal loading remain complex and incompletely understood. During spinal loading, and at different spine positions, there are changes of angles between each part of the spine to keep the normal spine curvature and function. The aim is to understand these changes which may help in clinical and surgical ways

Methods: A prospective analysis study of 80 patients admitted to our hospital for reasons other than lower back pain, who underwent routine spine screening with whole–body imaging. The spine was conducted looking at: the relations of the vertebral body-pedicle long axis to the long axis of the facet joint, and long axis of pars interarticularis, Aso the ties of the disc space height long axis to the long axis of the facet joint, and long axis of the pars interarticularis, using CT spine (mainly sagittal view cuts) while supine position. The height of the disc space at different levels is also measured and compared to these angles to find the normal variations between them.

Results: Our results show that the normal variant between each angle measured at each spinal segment and at different levels is different in the supine position, so we suggested that during spinal loading, and at different spine positions, these angles will be changed to keep the normal spine curvature and function. The Clinical implications of these measures may help to understand the normal angles and direction of screw placement during spinal fixation to preserve the normal curvature and dynamic.

Conclusion: This study proposes the "Segmental Pressure Distribution Theory," which offers a new model to explain how mechanical forces are transmitted and distributed across each spinal segment during various physiological movements. And proposing that the whole spine's dynamic motion and alignment depend on the dynamic relationships among each spinal segment. This Theory offers a novel framework to understand spine biomechanics by quantifying it as a segmental angular relationship. It holds promises for enhancing diagnostic precision and surgical planning, especially during spinal fixation.

Keywords: Spine biomechanics, Spine angulation, Segmental spine dynamics, Spine theory

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Abbreviations: SSD Theory=Segmental Spine Dynamic Theory, MRI=Magnetic Resonance Imaging, CT= Computed Tomography, PACS=Picture Archiving and Communication System. IVD= Intervertebral discs

Introduction

Dynamic and functional anatomy is the field of anatomy that considers topographic, stereometric, and functional interactions of anatomical objects in various physiological movements and processes. Measurement of human spine posture and motion is a fundamental tool in many fields of research, including biomechanics, health care, and rehabilitation. [1]. Such biomechanical analysis is particularly complex: despite a huge effort in spine biomechanics research, there are no biomechanical models that are routinely used in clinics. While in vitro biomechanical analysis of intact, injured, or instrumented spine segments has been extensively investigated. In vivo biomechanical modelling is much less investigated and still raises scientific bottlenecks. Spinal alignment and function depend on complex interactions between bones, joints, ligaments, muscles, and neural elements. The dynamic forces acting on the spine during different physiological activities are often simplified in classical biomechanical models. However, these models frequently fail to explain the segmental variability observed in clinical practice. [2]. Movable structures within each spinal segment include the intervertebral disc and the facet joints, while the pedicle and pars are fixed components. [3]. The facet joints are a diarthrodial synovial joint that maintain lubrication for the articular surfaces and enable their frictionless motion [4]. The spine ligaments and muscles restrict these movements, thus keeping a normal distribution of power forces applied to the spine to maintain spine stability. [5] These joints, ligaments, muscles, with intervertebral discs play an important role in the dynamics and biomechanics of the human spine through changes of their angulation and orientation to distribute the load to all parts of the spine in a normal manner. Several scientific papers investigated the external loads that act on the intervertebral disc and stresses inside it in vivo over the past six decades [6]. These previous studies have examined spine biomechanics as one unit, but none of them have focused on the dynamics of each segment during various physiological activities.

Materials and Methods

A total of 80 patients aged 19–55 years were admitted after head injury or other reasons without a history of back pain. A CT spine was done as a routine survey. The data were collected from PACS (Picture Archiving and Communication System), where lumbar CT scans were analyzed in the supine position. Specific anatomical landmarks were used to draw lines representing the long axes of key structures in this theory. Disc height was also measured and compared to the angle changes of each segment. Angular comparisons were made side-to-side at the same level and between adjacent levels.

Theory Background

This Theory posits that the pressure forces during spine motion (e.g., sitting, standing, flexion, extension) are transmitted through segmental structures and must be equally distributed to all parts and surrounding supporting

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structures to maintain normal function and to avoid spine pathology. By analyzing segmental angles, this theory introduces O-M-A-R angles using sagittal CT images.

Study Design: The theory is derived from clinical observation and radiological measurement of segmental angular changes in living humans during the supine position and postulates the changes during spinal movement and loading. The Segmental Spine Dynamic (SSD) Theory postulates that global spinal alignment and dynamic behavior are determined by the segmental interactions of each vertebral segment. Alterations in one spinal segment are hypothesized to induce compensatory changes in adjacent segments to maintain an optimized alignment during different spine actions. These interconnected relationships underscore the necessity of assessing spinal mechanics at the segmental level rather than as a singular structural unit. Radiological evaluation provides a feasible approach for analyzing these segmental dynamics. According to the SSD theory, each motion segment exhibits specific angular relationships that reflect its mechanical behavior. These angles include:

- The angle between the vertebral bodies – pedicles' long axis with

- The angulation and orientation of the facet joints' long axis

- The angulation and orientation of the pars interarticularis long axis

- The angle of the long axis of the intervertebral disc with

-The angulation and orientation of the facet joints' long axis

-The angulation and orientation of the pars interarticularis long axis

Quantitative assessment of these radiographic angles at various spinal levels under different positions may offer insights into the normal biomechanical behavior of the spine. In the present study, we employed computed tomography (CT) imaging of the spine in the supine position, using multiplanar reconstructions to accurately measure these angles at various spinal levels. Due to current technical limitations of dynamic imaging capable of capturing these angles during spine motion, the SSD theory. Therefore, focused exclusively on angular changes detectable in the supine position, proposing that these static measurements act as a functional indicator of segmental biomechanical changes that contribute to global spinal dynamics during spinal activities. While plain radiographs may be used for dynamic assessments, their limited spatial accuracy renders them unsuitable for the precise angular analysis required.

Parameter prediction

Target structures

Key anatomical components analyzed include:

- pedicle
- Facet joint
- Intervertebral disc
- Pars interarticularis

O-M-A-R angles definition:

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- **O- angle:** Between the vertebral body-pedicle long axis and with facet joint long axis
- **M-angle:** Between the vertebral body-pedicle long axis and with pars interarticularis long axis
- **A-angle:** Between the disc space long axis and with facet joint long axis
- **R-angle:** Between the disc space long axis and with pars interarticularis long axis

These angles were measured from a single sagittal CT slice that visualizes all these key structures.

O-M-A-R angles are formed by the following lines:

First line: a line extending from the anterior edge of the vertebral body, passing to the long axis of the pedicle, crossing the facet joint and pars interarticularis**.** (The long axis of the pedicle is the horizontal line midway between the two edges of the pedicle.)

Second line: a line at the long axis of the disc space (midway between the upper and lower cartilaginous endplate) crossing the facet joint and pars interarticulars**.**

Third line: a line separating the upper and lower articulating parts of the facet joint. This line transects the first line to form (O angle) and transects the second line to form (M angle)

Fourth line: it is a line at the long axis of the pars interarticularis (midway between the two edges of the pars interarticularis), which transects the first line to form (A angle) and transects the second line to form (R angle)

The best cut at which we can measure these angles is the sagittal view, which shows the body, pedicle, pars, and facet joint at each side.

Theory explanation:

This theory suggest that the main pressure force on the spine during any activity as in* sitting, standing, walking, running, lifting, flexion, extension, bending, and * lateral rotation* is applied to the long axis of different parts of the spine segments affected by this activity, and is equally distributed along the whole spine with different intensity from one level to another according to site and strength of each force applied. These forces are controlled by ligaments, muscles, intra-abdominal, and intrathoracic pressure, as well as the resistance of each spinal segment. The human spine's inclinations and angulations between each spinal segment are due to the presence of joints, ligaments, muscles, and intervertebral discs. To understand this suggestion, we must know the normal degree of angles of distinct parts of the spinal segment at different levels. Therefore, by understanding this theory, we can explain the pressure forces applied to one part of the spine segment and to the whole spine by measuring the changes in angles that occur at these parts as an indicator of force applied compared to normal measurements. The facet joints, discs, and pars interarticularis are the main distributors of forces applied to the spine; therefore, this theory explains why most of the pathologies of the spine affect these parts.

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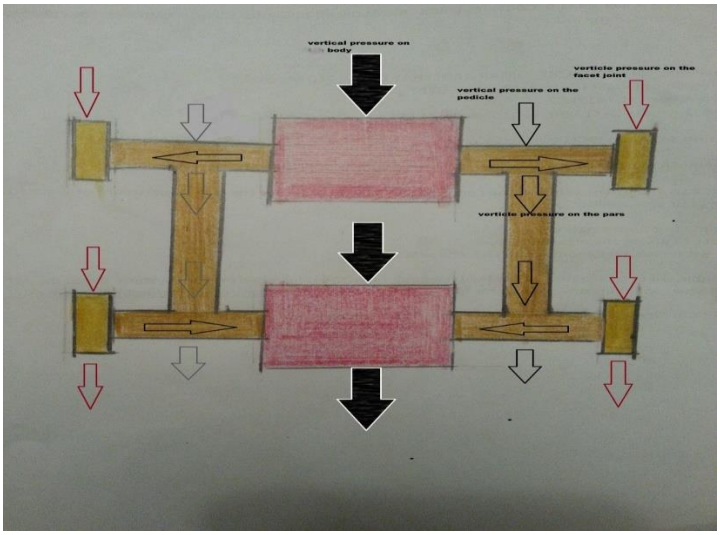


Figure 1. An illustrated diagram shows the distribution of axial pressure in axial cuts as an example of a different distribution of force. The same can be applied to different pressures to the spine in different cuts other than axial cuts.

All angles were measured on one side* compared to the other side at the same level to find the degrees of change of each side, then measured compared to the adjacent levels above and below that level to find the degree of change of each level, then fined the difference between the angles degrees to find the net result between (O-M and A-R angles). For example, to measure the changes on the L5-S1 level, the angles to be measured are the angles between L4-5 and L5-S1.

Results

The biomechanical integrity of the spine is influenced by the symmetry of loading during physical activity. Under ideal conditions, the spine maintains a balanced alignment that ensures the distribution of mechanical forces without pathological changes of the spinal segments. However, habitual asymmetrical movements—such as favoring one side during lifting or carrying loads-can disrupt this balance. These asymmetrical loading patterns may result in uneven stress distribution across different spinal segments, potentially leading to structural adaptations or pathological conditions over time. The biomechanics of the load absorption of the spine are totally dynamic, and it depends on nervous system integrity for transmission of any load into proprioceptors, mechanoreceptors, and other receptors of the spine.

The Clinical implications of these measures may help to understand the normal angles and direction of screw placement during spinal fixation to preserve the normal curvature and dynamic

The following normal variations were identified:

- Angles variation at the same level (right vs. left): <10°
- Angles variation between adjacent levels: <15°
- Disc height difference (same level, side-to-side): <1 mm
- Disc height difference (adjacent levels): <3 mm

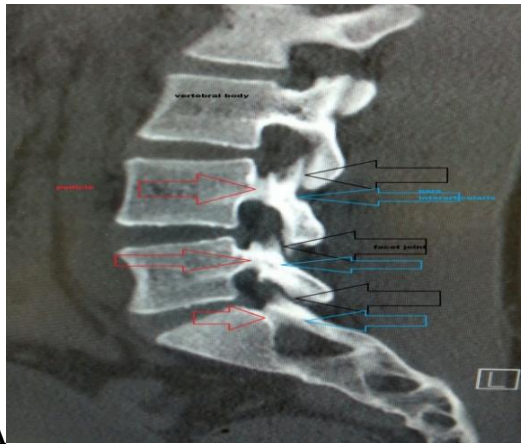
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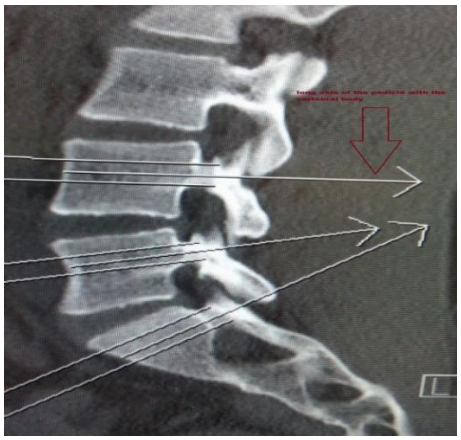
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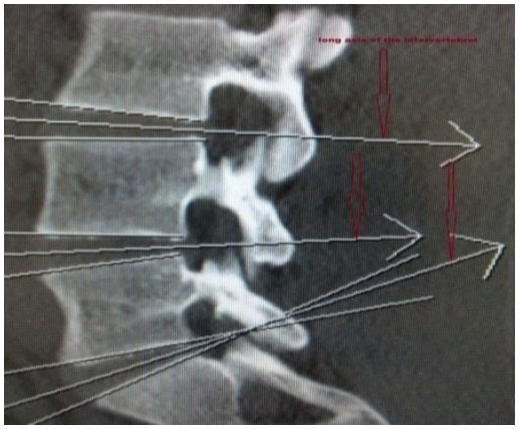
- Variation among OMAR angles: <15°

These changes may be due to a normal variant between two adjacent levels or due to positional or functional changes. So, if the changes are less than 10 degrees at each level, and less than 15 degrees at different levels can be accepted as a normal variant, at the same time, the changes between (O, M, A, R) angles, if less than 15 degrees between O-M, A-R angles, can also be accepted as a normal variant.

A (Figure 1) An illustrated diagram shows the distribution of axial pressure in axial cuts as an example of a different distribution of force. The same can be applied to different pressures to the spine in different cuts other than axial cuts.

A 

B 

C 

D 

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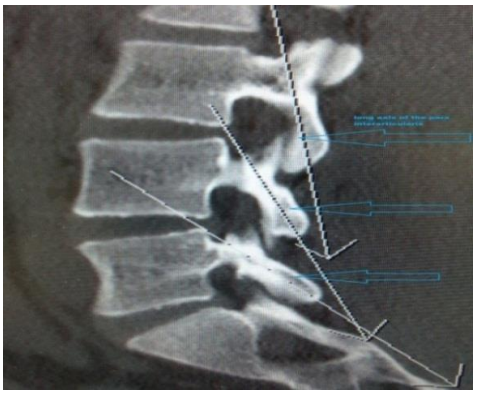
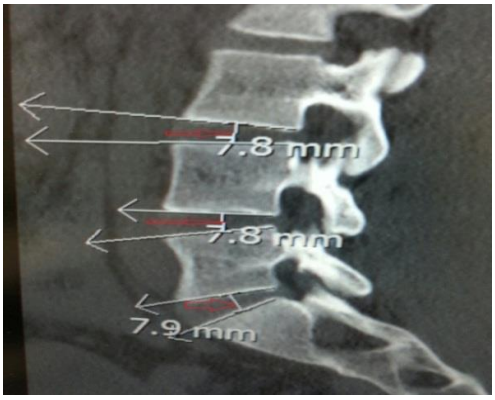
E  F 

Figure 2. A show a sagittal CT lumbar spine at which (O-M-A-R) angles are measured. The body, pedicle (red arrow), pars interarticularis (blue arrow), and the facet joint (black arrow) must be shown on the same sagittal CT cut. B. shows the long axis of the body with the pedicle. C: shows the long axis of the disc. D shows the long axis of the facet joint. E: shows the long axis of the pars interarticularis. F: shows disc height at different levels

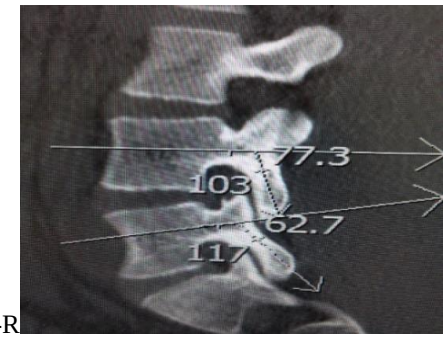
Case Presentations

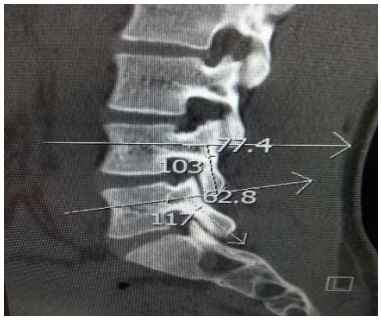
Normal spine without back pain

Case N. 1: An 18-year-old boy after a motorcar accident without a history of back pain.

O-R 

O-L 

M-R 

M-L 

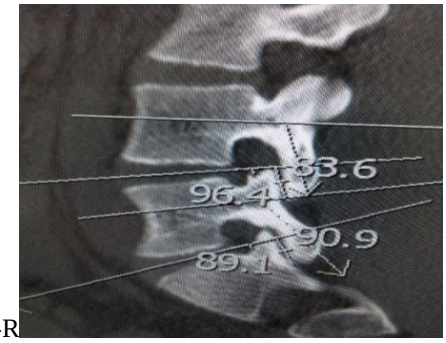
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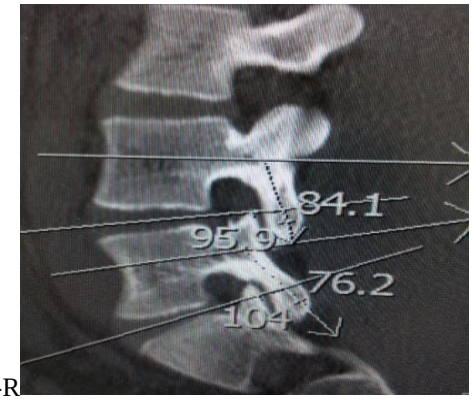
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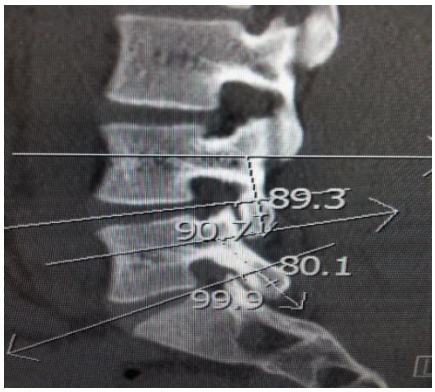
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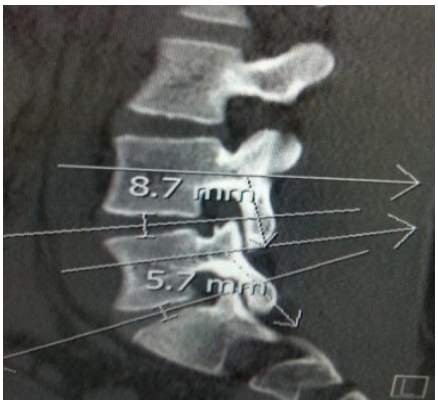
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A-R 

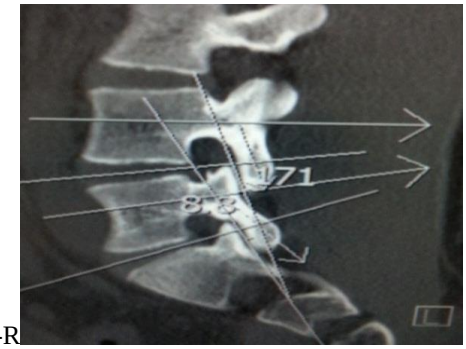
A-L 

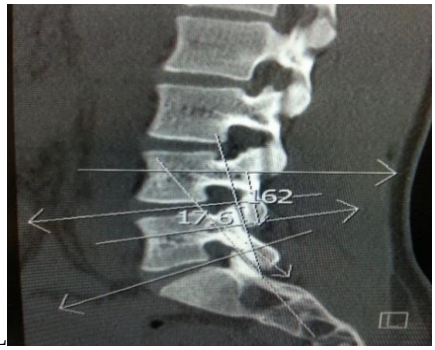
R-R 

R-L 

E-R 

E-L 

F-R 

F-L 

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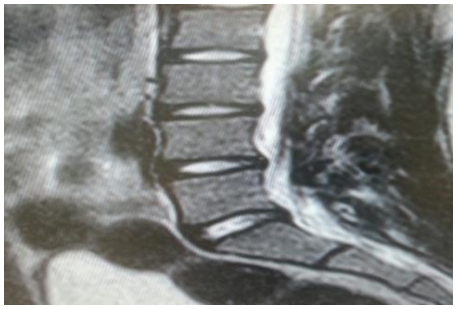
G  H 

Figure 3. Show measurements of O-M-A-R angles: (fig O-R): (O angle) on right side, (Fig O-L): (O angle) on left side, (Fig. M-R): (M angle) on the right side, (Fig. M-L): (M angle) on the left side, (Fig. A-R): (A angle) on the right side, (Fig. A-L): (A angle) on the left side, (Fig. R-R): (R angle) on the right side, (Fig. R-L): (R angle) on left side. (Fig. E-R): disc space height on the right side, (Fig. E-L): disc space height on the left side, (Fig. F-R): the angles plan on the right side, (Fig. F-L): the angles plan on the left side, (Fig. G-H): MRI Spine of the same patient.

side / angle in degree	Right L4-5 level	Left L4- 5 level	Right L5-S1 level	Left L5-S1 level	changes of L4-5 on both sides	changes of L5-S1 on both sides	changes between two levels on the right side	changes between two levels on the left side	Changes between (O, M) angles and (A, R) angles
O angle	105	102	96.2	104	3	-7.8	8.8	-2	6.2 on the right and 12 on the left
M angle	103	103	117	117	0	0	-14	-14	
A angle	96.4	90.8	89.1	94.3	5.6	-5.2	7.3	-3.5	0.8 on the right and 5.7 on the left
R angle	95.9	90.7	104	99.9	5.2	4.1	-8.1	-9.2	
Disc height	8.7	7.8	5.7	7.0	0.9	-1.3	3	0,8	

Table 1. shows the measurement of OMAR angles.

According to the above table, the changes of all angles between the right and the left side at the same level are less than 10 degrees, and the changes between two adjacent levels are less than 15 degrees. The disc height distance between the right and the left side on the same level is less than 1 mm.

The changes in disc height between 2 adjacent levels are less than 3 mm. The changes between O and M angles on the right side (8.8-14=6.2) and the changes on the left side (2-14=12), so the changes between the two angles on both sides are 6.2-12= -5.8 degrees. The changes between A and R angles on the right side (7.3-8.1=0.8), while the changes on the left side (3.5-9.2=5.7). The change between two angles on both sides is (0.8-5.7= 4.9).

Discussion

The human spinal column is a biomechanically sophisticated, load-bearing structure that plays a critical role in maintaining posture, enabling locomotion, and facilitating complex movements. It is composed of vertebrae, intervertebral discs (IVDs), facet joints, pars interarticularis, ligaments, and muscles that work in concert to support

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the body and allow for dynamic motion. Among these components, the IVDs and posterior spinal elements are particularly important, as they absorb and distribute mechanical loads while permitting controlled motion across the spinal segments. In clinical practice, subjective assessment techniques such as self-reported outcome measures and functional movement assessments (e.g., forward bend test) are used to screen for and identify the function of the spine limitation. [7]. Unfortunately, subjective visual assessments of movement patterns suffer from inter- and intra-rater reliability issues, which could lead to misdiagnosis. [8]

In laboratory settings, Optical motion capture OPT systems have been used to assess lumbar kinematics in patients with LBP during several functional tasks. However, these systems are expensive, have large space requirements, are not transportable, and require expert users to precisely place active/passive markers, run the system, and process the collected data. [9], [10]. These limitations have led to alternative technology (e.g., depth cameras, inertial measurement units (IMUs), etc.). However, their indoor usage is limited, as they are prone to errors and signal drift from sources such as magnetic distortion, equipment error, and signal contamination, limiting their usage to highly qualified personnel [11].

Therefore, there is a need for an accessible tool that uses available technology to objectively assess fine spinal movements to improve the diagnosis and treatment of LBP, among other spine disorders. In this paper, I propose the CT-based angular measurement technique, which represents an advancement in the biomechanical assessment of the lumbar spine. Unlike traditional approaches that analyze only global lumbar lordosis, in recent years, the incidence of lumbar spine surgeries—including fusion, microdiscectomy, and decompression for spinal canal stenosis—has risen significantly. Despite the increased surgical activity, definitive understanding of the biomechanical origins of degenerative spine pain remains limited. Current research increasingly recognizes the importance of sagittal spinal balance, yet consensus on precise mechanical contributors is lacking. [12]. Due to our limited ability to isolate causative sources and mechanisms of development of degenerative spine pain, there is little consensus regarding a definitive treatment approach. Various studies have discussed in detail the possibilities of a biomechanical role for lumbar spine morphology in the development of low back pain. [13]. Several other methods have been adopted to evaluate dimensions and angular properties of the lumbar vertebrae [14]. From these research skin markers [15], [external marker photo- or videography, [16]. Electromagnetic devices [17], flexible tape measurement [18], and ultrasonic digitizer [19]. These Traditional methods provide limited insight into intrinsic vertebral geometry. Most prior studies have focused on global lumbar lordosis rather than segment-specific changes. The proposed CT-based method allows accurate visualization of angular alterations of each lumbar segment. The only research found measuring specific angles was by Weishaupt in 1999, who measured the angles of facet joints at a single level, depending on facet joint space, not to the long axis of the facet joints. [20] This new non-invasive method is based on the measurement of different changes of angles in the normal spine, which can be compared to the pathological spine using CT spine. These angles are measured in the lying position without a vertical load applied to the spine, so they give the actual measurement, which is already established on the spine. The concept of understanding these measurements is relatively straightforward and can be visualized using simplified representations. Each change in the disc height could be associated with changes in the facet joints, pars interarticularis angulations on each side of

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the same level or in the adjacent levels. At the same time, any changes in the angulation in the facet joints could be associated with changes in the disc height. Each spinal segment has its own inclination and orientation, which are correlated with other spinal segments to maintain normal spinal curvature and function. Each inclination and orientation of each spine segment is due to different angles between each part of this segment and between different segments to give the spine its normal curvature. The theory postulated that these different angulations and orientations occur due to changes in these angles. These changes were measured by using a CT sagittal view in the supine position, and we postulated that if there are changes between each part of the spinal segment and different spinal segments during the supine position, it must be associated with changes of these parts during sitting, standing, movement, and during spinal loading to maintain normal spine curvature and function. Segmental angles' evaluation via supine CT imaging offers a promising, non-invasive technique for understanding the biomechanical interplay of pedicle, disc height, facet joint orientation, and pars interarticularis alignment. This approach may enhance diagnostic accuracy and treatment planning for degenerative lumbar conditions. As imaging technology advances, dynamic evaluation of these angles during movement and loading may refine diagnostics and improve surgical outcomes. Future research should validate this method in larger patient cohorts and investigate its prognostic value in predicting outcomes for various spine interventions.

Conclusion

This study proposes the "Segmental Pressure Distribution Theory," which offers a new model to explain how mechanical forces are transmitted and distributed across each spinal segment during various physiological movements. And proposing that the whole spine's dynamic motion and alignment depend on the dynamic relationships among each spinal segment. This Theory offers a novel framework to understand spine biomechanics by quantifying it as a segmental angular relationship. It holds promises for enhancing diagnostic precision and surgical planning, especially during spinal fixation.

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