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Influence of Deviated Centers of Rotation on Kinematics and Kinetics of a Lumbar Functional Spinal Unit: An *In Vitro* Study

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Data Interpretation D
Manuscript Preparation E
Literature Search F
Funds Collection G

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Background: Center of rotation (COR) has been used for assessing spinal motion quality. However, the biomechanical influence of COR deviation towards different directions during flexion-extension (FE) remains largely unknown. This study aimed to investigate the alteration in the range of motion (ROM), compressive force, shear force, and neutral zone size (NZ) in a lumbar functional spinal unit (FSU), caused by the deviated COR in different directions during FE.

Material/Methods: Twelve human cadaveric lumbar FSUs (6 for L2–L3, 6 for L4–L5) were tested in a 6-degree-of-freedom servo-hydraulic load frame. These FSUs were firstly applied a 7.5 Nm pure moment to perform FE to obtain their natural COR during FE. Subsequently, they were subjected to FE around 9 established deviated CORs with 6 Nm cyclical loading.

Results: It was found that the ROM and NZ increased significantly when the COR moved from the superior plane to the inferior plane for the L2–L3 unit and when the COR located in the superior plane compared with the inferior plane for the L4–L5 unit. The compressive forces for both FSUs demonstrated significant changes caused by COR shift in the same horizontal plane, while the shear forces demonstrated significant changes caused by COR shift in the same vertical plane.

Conclusions: The ROM, NZ, and shear force of FSU are sensitive to the vertical COR shift, while the compressive force of FSU is highly sensitive to the horizontal COR shift. Additionally, the kinematics and kinetics of the L2–L3 unit are more sensitive to COR location than those of the L4–L5 unit.

MeSH Keywords: **Biomechanical Phenomena • *In Vitro* • Spine**

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Background

The helical axis of motion (HAM) is the axis about which the body rotates while the body simultaneously translates along the same axis and is used to depict the 3D movement of the cranial vertebra related to the caudal vertebra. The center of rotation (COR) is a 2D representation of 3D HAM when the vertebra moves from the flexion to extension and was proposed to represent the quality of spinal motion by Panjabi et al. [1–3].

The quality of spinal motion is usually affected by lumbar diseases, such as low back pain [4] and spondylolysis [5]. Abnormal COR location usually implies the abnormal quality of motion, although the range of motion (ROM) and magnitude of translation may be normal. Therefore, COR is a valuable parameter to identify normal and pathological spinal motion [5–7]. Gertzbein et al. [8] demonstrated that the COR was more scattered in a motion segment with a degenerated disc. In a study by Sengupta et al. [9], the COR showed significantly increased vertical translation with increasing grade of disc degeneration.

To improve the quality of spinal motion and strengthen the stability of the lumbar spine in patients with lumbar disc degenerative disease, artificial disc arthroplasty has been commonly used to correct the motion of 2 adjacent vertebrae and to effectively reduce the incidence of adjacent segment degeneration [10,11]. However, different structural designs of disc arthroplasty devices may constrain spinal motion to pure rotation such as the ball-and-socket-type device or coupled movements (translation and rotation). Thus, the motion pattern and location of the COR would be altered. The kinematics and kinetics of the lumbar spine may be sensitive to the location and radius of the COR. Alapan et al. [12] constructed and validated a 3D finite element model of an L4–L5 unit and then assessed the kinematic and kinetic changes in the lumbar spine in different COR positions. They found that ROM, facet forces, ligament loads, and disc stresses were strongly correlated with the location of the COR. Han et al. [13] developed a musculoskeletal model of the spine to investigate the effect of different CORs on muscle forces to simulate the COR deviation caused by surgery. They discovered that the COR due to the surgical placement of an artificial disc could cause considerable changes in muscle forces.

Both the finite element model and the musculoskeletal model simplified the properties of the disc, ligament, muscle, and other tissues. Although these models could represent kinematic and kinetic varying trends, the spinal properties of these models differed from the real spinal properties and could not simulate some biomechanical characteristics such as the neutral zone. Traditional *in vitro* methodologies, such as follower load and pure moment with or without preload tests, provide limited data or insight regarding the precise kinematic and kinetic status of the functional spinal unit (FSU). Therefore, the aim of this biomechanical study performed on the cadaveric lumbar spine was to investigate the biomechanical effects of deviated CORs towards different directions during FE on ROM, compressive force, shear force, and neutral zone size.

Material and Methods

Specimen preparation

Twelve adult human cadaveric lumbar FSUs, L2–L3 (n=6) and L4–L5 (n=6), from 6 spines stored at –20°C were thawed overnight at room temperature before testing. Computed tomography scans were performed to avoid the inclusion of specimens with preexisting fractures or signs of severe disc degeneration. Subsequently, muscular and fatty tissues were detached from the vertebral bodies, leaving the ligamentous structure, facet joints, transverse processes, and posterior elements intact. The cranial and caudal vertebrae of the FSUs were embedded with Wood's metal (melting point: 60–70°C). Then, Wood's metal was fixed in the upper and lower potting cup with 8 screws (Figure 1A). The intervertebral disc was oriented in the horizontal plane [14]. To increase fixation of the vertebrae, 5 screws were inserted into the cranial and caudal vertebrae in this study.

Testing apparatus

Biomechanical testing was performed using a spine simulator (MTS Bionix370.02A/T Systems Corp., Eden Prairie, MN, USA) with 6 channels, namely, Axial Displacement (Y channel), X-Axis Displacement (X channel), Z-Axis Displacement (Z channel), Flexion/Extension Rotation (FE channel), Lateral Bend Rotation (LB channel), and Torsional Rotation (TR channel). Three displacement transducers were integrated into 3 displacement channels to record the X-Axis, Z-Axis, and Axial displacement. Additionally, 3 encoders were integrated into 3 rotation channels to record the Flexion/Extension, Lateral bending, and Torsional rotation. Moreover, the system was equipped with a six-degrees-of-freedom (6DOF) force transducer (ATI-Mini45-SI-580-20, Schunk GmbH & Co. KG, Germany), which could record Tx, Ty, Tz, Fx, Fy, and Fz. The simulator is shown in Figure 1A.

Biomechanical tests protocol

Before testing, the embedded specimen was fixed in 2 parallel potting cups, namely, superior potting cup and inferior potting cup, which were part of the testing system (Figure 1A). Then, a pure moment without preload was applied to drive the FSU to conduct FE until the magnitude of the flexion and extension moment both exceeded 7.5 Nm [15].The maximum

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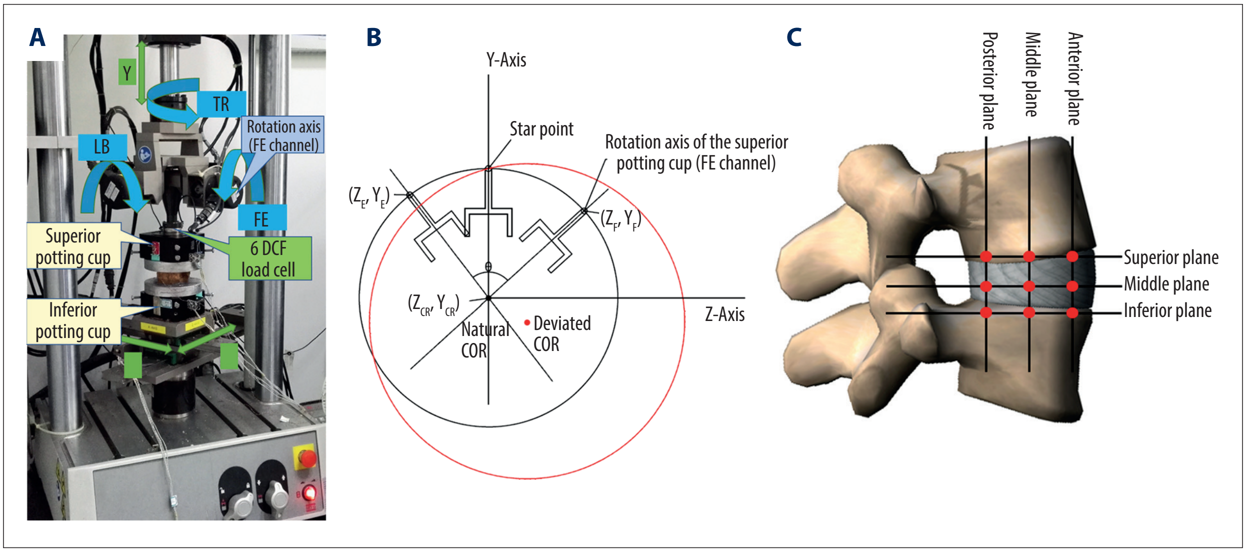

Figure 1. (**A**) The 6 DOF simulator used for kinematic and kinetic cadaveric testing. Three displacement channels to allow translate in x-axis, y-axis and z-axis. Three rotatory channels to allow rotation around x-axis, y-axis and z-axis. This simulator was also equipped with a 6DOF load cell. (**B**) The schematic of the calculation of natural COR and the design of the motion trajectory of rotation axis of superior potting cup based on start point and natural COR or deviated COR. (**C**) The schematic of the location of the 9 centers of rotation.

Table 1. Definition of the 9 centers of rotation.

Plane	Flexion-Extension		
	AC	MC	PC
SP	(x0+5 mm, y0+5 mm)	(x0, y+5 mm)	(x0–5 mm, y0+5 mm)
MP	(x0+5 mm, y0)	(x0, y0)	(x0–5 mm, y0)
IP	(x0+5 mm, y0–5 mm)	(x0, y0–5 mm)	(x0–5 mm, y0–5 mm)

x0 – Z-coordinate of the center of rotation in natural flexion-extension; y0 – Y-coordinate of the center of rotation in natural flexion-extension; AC – anterior center; MC – middle center; PC – posterior center; SP – superior plane; MP – middle plane; IP – inferior plane.

flexion angle and the extension angle were recorded when the torque reached the limit. Subsequently, the FSU conducted FE between the maximum flexion angle and maximum extension angle 3 times to make sure that the moment was well below the failure moment of every specimen. The displacements of all the 6 channels were recorded during the 3 trials and the data of the last trial was selected to calculate the natural COR (Figure 1B), using the following equations:

$$Z_{CR}=\tfrac{1}{2}(Z_F+Z_E)+\tfrac{1}{2}\cot\tfrac{\theta}{2}(Y_F+Y_E) \quad (1)$$

$$Y_{CR}=\tfrac{1}{2}(Y_F+Y_E)+\tfrac{1}{2}\cot\tfrac{\theta}{2}(Z_E+Z_F) \quad (2)$$

where Z_{CR} and Y_{CR} are the coordinates of the natural COR, Z_F, Y_F, and Z_E, Y_E are the coordinates of the rotation axis of the superior potting cup in its maximum flexion position and maximum extension position, and θ is the ROM in FE.

The coordinates of the start point and COR were used to design the motion trajectory of the rotation axis of the superior potting cup (Figure 1B). In this study, a fixed natural COR and 8 fixed deviated CORs were included. The 9 CORs are defined in Table 1 and illustrated in Figure 1C.

In order to make the specimen rotate around the defined 9 CORs in sequence without damaging the specimen, the simulator was programmed to apply torque control to make the rotation axis of the superior potting cup move along the calculated motion trajectory within ±6 Nm. Each test was repeated 3 times, and the data from the last trial was used for analysis. Before data analysis, the actual motion trajectories were used to calculated actual CORs to confirm that the actual CORs were consistent with the defined CORs. The validation is in Table 2. During the biomechanical tests, the specimens were kept moist using 0.9% NaCl solution to prevent their dehydration.

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Table 2. Offset validation of the 9 centers of rotation in flexion-extension.

	L2–L3		L4–L5	
	Z-offset ±SD (mm)	Y-offset ±SD (mm)	Z-offset ±SD (mm)	Y-offset ±SD (mm)
MP-MC	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
MP-AC	4.95 (0.05)	0.01 (0.19)	5.07 (0.10)	0.06 (0.13)
MP-PC	–5.26 (0.08)	–0.03 (0.14)	–5.14 (0.09)	–0.01 (0.18)
IP-MC	–0.09 (0.07)	–4.98 (0.11)	–0.06 (0.10)	–4.98 (0.17)
IP-AC	4.93 (0.13)	–4.96 (0.10)	4.98 (0.12)	–4.92 (0.11)
IP-PC	–5.28 (0.06)	–4.99 (0.13)	–5.13 (0.10)	–4.92 (0.10)
SP-MC	–0.01 (0.05)	5.02 (0.22)	0.04 (0.12)	4.93 (0.22)
SP-AC	4.96 (0.05)	4.96 (0.14)	5.06 (0.14)	4.95 (0.16)
SP-PC	–5.21 (0.07)	4.95 (0.17)	–5.12 (0.13)	4.91 (0.119)

AC – anterior center; MC – middle center; PC – posterior center; SP – superior plane; MP – middle plane; IP – inferior plane.

Data collection and process

During testing, the compressive force and the shear force were recorded using an integrated 6DOF force transducer. The ROM in FE was obtained using the integrated rotation transducer of the corresponding rotatory channels. NZ was defined as half the total laxity at zero load in the complementary direction, as described by Wilke et al. [16].

The effects of CORs on the compressive force, shear force, NZ, and ROM in FE were assessed using repeated-measures analysis of variance (ANOVA) with a statistical significance level of 0.05. Prior to the analysis, ROMs of flexion, extension, and NZ of FE were deemed a baseline when the COR was located at the middle point of the horizontal middle plane. Subsequently, ROMs of flexion, extension, and NZ of FE for the 9 CORs were normalized to this baseline, respectively. All statistical analyses were performed with MATLAB R2016 version (MathWorks, Natick, MA, USA).

Results

Range of motion in different centers of rotation

The mean (SD) ROM of the L2–L3 and L4–L5 units are shown in Figure 2. For the L2–L3 unit in flexion and extension, a significant increase in ROM was observed when the COR moved from the point in the superior plane (e.g. Anterior Center, 85.41±5.39% in flexion, 99.96±4.65% in extension) to the same point in the middle plane (e.g. Anterior Center, 99.66±3.51% in flexion, 123.44±9.69% in extension) and to the same point in the inferior plane (e.g. Anterior Center, 115.93±6.42% in flexion, 148.05±9.67% in extension).

For the L4–L5 unit in flexion and extension, a significantly greater motion was observed only at the points in the inferior plane (e.g. Anterior Center, 122.22±12.92% in flexion, 117.73±25.78% in extension) than at the points in the superior plane (e.g. Anterior Center, 88.00±20.41% in flexion, 87.27±13.33% in extension).

Forces of functional spinal unit

The mean (SD) compressive forces of the L2–L3 and L4–L5 units are shown in Figure 3. In both conditions, the compressive forces of both L2–L3 and L4–L5 units changed significantly between different CORs in every same horizontal plane.

The mean (SD) shear forces of the L2–L3 and L4–L5 units are shown in Figure 4. For the L2–L3 unit, the shear forces significantly decreased when the COR moved from the superior plane (e.g. Anterior Center, 16.13±5.27 N) to the middle plane (e.g. Anterior Center, 5.90±5.51 N) or from the superior plane (e.g. Anterior Center, 16.13±5.27 N) to the inferior plane (e.g. Anterior Center, –1.19±11.93 N) in flexion and increased in extension. Virtually no significant difference was found between the different CORs in the same horizontal plane. For the L4–L5 unit, a significant difference was found between the middle center in the superior plane (20.53±7.21 N) and the middle center in the middle plane (6.70 N ± 8.98 N), the posterior center in the superior plane (18.56±7.83 N) and the posterior center in the inferior plane (–0.33±6.20 N) in flexion, the anterior center in the superior plane (–12.93±7.25 N) and the anterior center in the middle plane (0.14±7.39 N), and the posterior center in the superior plane (–14.38±7.88 N) and the posterior center in the middle plane (–1.84±9.56 N) in extension.

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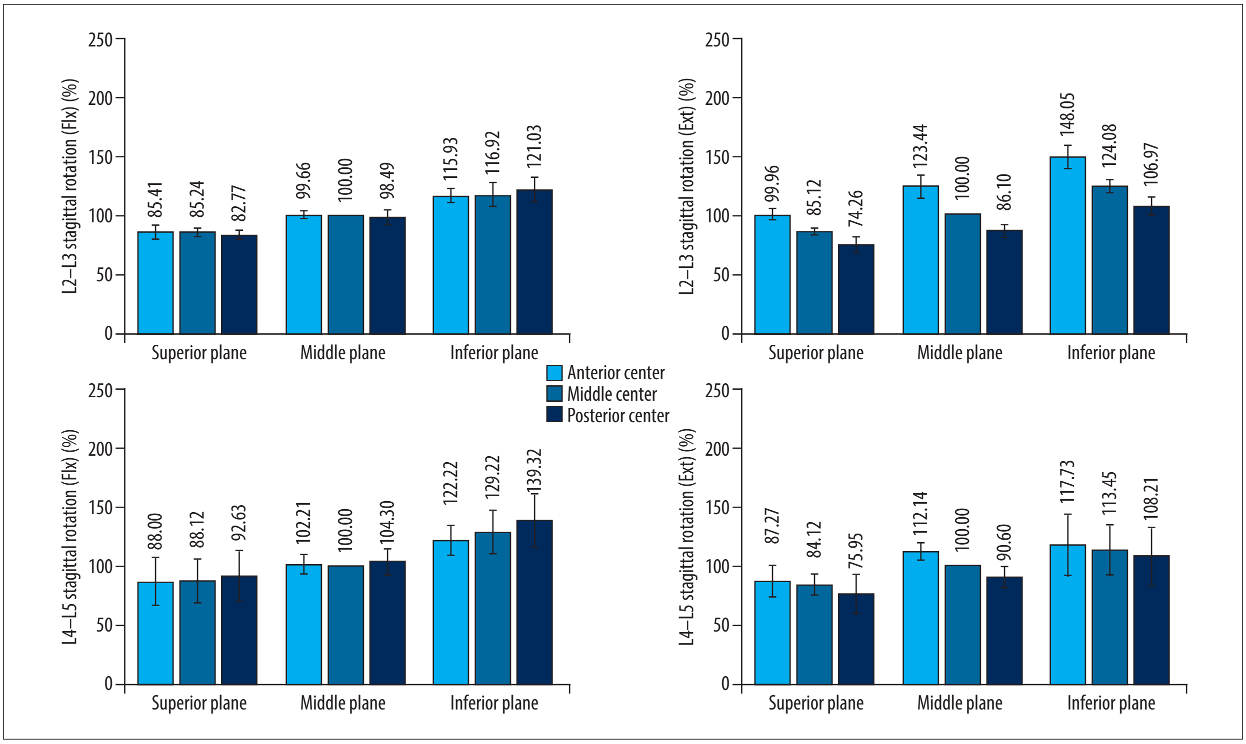

Figure 2. Range of motion for the L2–L3 and L4–L5 units in flexion-extension (Flx indicates flexion; Ext indicates extension; numbers in figure indicates the mean normalized range of motion).

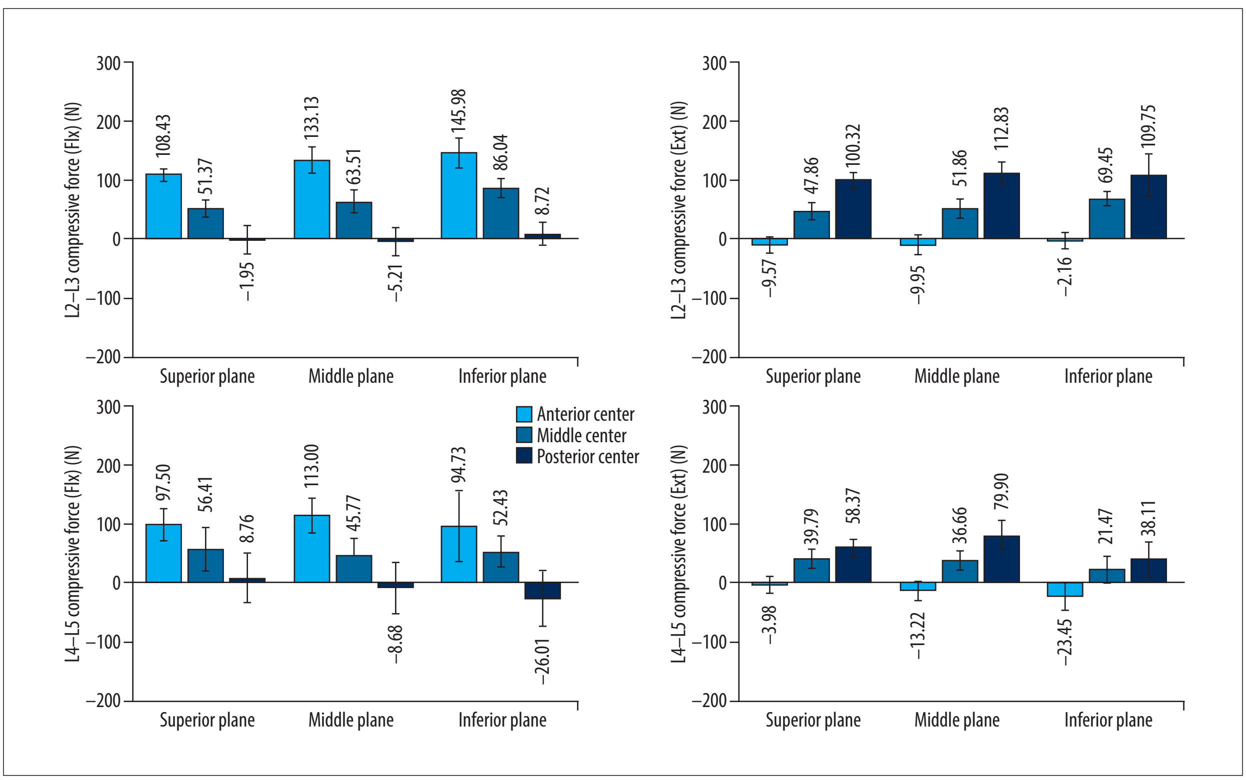

Figure 3. Compressive force for the L2–L3 and L4–L5 units in flexion-extension (Flx indicates flexion; Ext indicates extension; numbers in figure indicates the mean compressive force).

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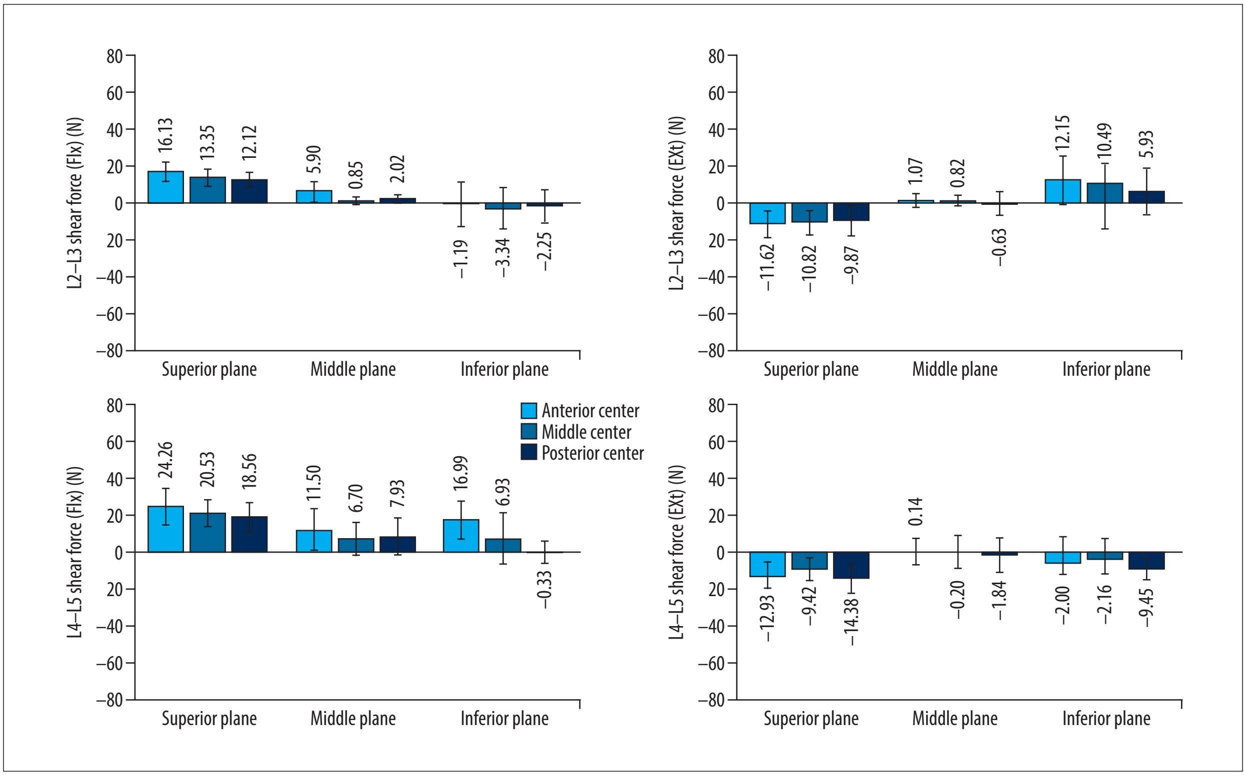

Figure 4. Shear force for the L2–L3 and L4–L5 units in flexion-extension and lateral bending (Flx indicates flexion; Ext indicates extension; numbers in figure indicates the mean shear force).

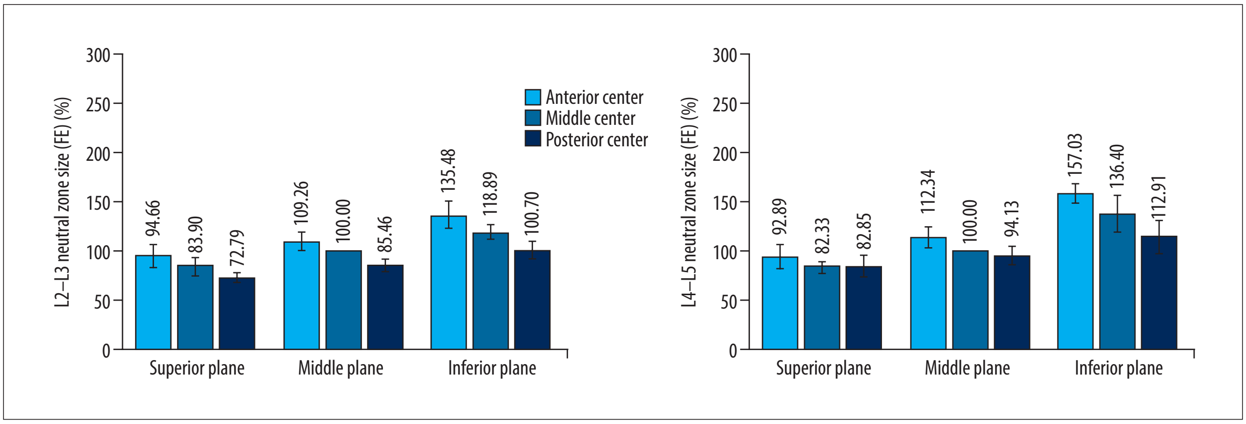

Figure 5. Neutral zone size for the L2–L3 and L4–L5 units in flexion-extension (FE indicates flexion-extension; numbers in figure indicates the mean normalized neutral zone size).

Neutral zone size

The mean (SD) NZ of the L2–L3 and L4–L5 units are illustrated in Figure 5. The NZ was significantly increased when the COR moved from the point in the superior plane (e.g. Anterior Center, 94.66±11.27% for the L2–L3 unit, 92.89±12.55% for the L4–L5 unit) to the same point in the inferior plane (e.g. Anterior Center, 135.48±13.70% for the L2–L3 unit, 157.03±9.51% for the L4–L5 unit) for both L2–L3 and L4–L5 units.

Discussion

The study aimed to investigate how a deviated COR affected the kinematics and kinetics of the human lumbar FSU. The deviated CORs were determined by enforcing the rotation around predefined fixed CORs and then the kinematic and kinetic responses of the FSU were observed. It was found that the ROM, NZ, and shear force of both L2–L3 and L4–L5 units were much more sensitive to the vertical variation than to the horizontal variation in FE. In contrast, the compressive force was more

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sensitive to the horizontal variation than to the vertical variation. Moreover, the L2–L3 unit was more sensitive to the COR deviation than the L4–L5 unit.

ROM is the extent of motion and can represent the ability of spinal motion. NZ is a measure of laxity and may be strongly related to the stability of the lumbar spine based on the marble-on-a-soup-bowl analogy by Panjabi [17]. The magnitude and direction of the compressive and shear forces represented the force condition when the FSU performed FE. Abnormal force condition for a long period on the FSU can cause tissue injury and further undermine the stability of the lumbar spine. Force condition, the ability of spinal motion, and stability would all be rebuilt if the COR deviated from its normal range.

In flexion, the inferiorly located CORs resulted in the greatest ROM and NZ, and lesser shear force magnitude for both L2–L3 and L4–L5 units. The disc and facet joint are the main structures that support and stabilize FSU motion [18]. In general, the facet joint participated little and provided shear force resistance in flexion. The shift of COR from superior points to inferior points reduced the interaction of the facet joint, leading to a less stable FSU system. Therefore, the magnitude of ROM and NZ were the highest and the magnitude of the shear force was less. Shifting of COR locations from anterior to posterior points along all the horizontal planes resulted in the reduction of compressive force resistance for both L2–L3 and L4–L5 units. Flexion around the posterior points was likely constrained by the compression of the anterior part of the intervertebral disc, whereas flexion around the anterior points was constrained by the tension in the posterior ligaments and posterior part of the intervertebral disc. The difference in the properties of different tissues in resisting the rotation around predefined COR, as well as the lever arm distance from the point of application of force to the COR location may explain the decreased compressive force from the anterior to posterior points.

In extension, shifting of COR locations from the superior to inferior plane also resulted in the ROM increase due to the similar factor. Central points resulted in the least magnitude of shear force resistance for both L2–L3 and L4–L5 units, which meant that the direction of application of force was nearly perpendicular to the line drawn from the point of force application to the current COR. Therefore, the variation of shear force did not change significantly when the COR location moved from the anterior to posterior points. The compressive force increased rapidly because in general, extension was greatly constrained by the facet joint. The horizontal change of COR location affected disc tension in the anterior disc region and facet joint interaction.

As with most cadaveric studies, the limited number of specimens limited the statistical power of the results. Also, the motion of the FSU was limited to 2-dimensional sagittal evaluation of the influence of COR location on ROM, NZ, compressive force, and shear force.

Conclusions

This study investigated the kinematic and kinetic influence of COR deviation. The motion of the FSU was mainly constrained by different tissues or structures. The different properties of these tissues, structures, and the mechanism of their co-function caused the difference in motion ability and stability. This study demonstrates that more stable systems lead to larger resultant force resistance and smaller ROMs and conversely, less stable systems lead to lesser resultant force resistance and larger ROMs. The natural COR was the result of balancing the force resistance, ROM, and stability. When the COR deviated from its normal location, force condition, spinal motion ability, and stability were sensitive to the variation in different directions.

Acknowledgments

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Conflict of interest

None.

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