3D orientation and kinematic characteristics of zygapophyseal joints while sitting

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Background: Orientation of the lumbar facet joints (FJs) in the transverse plane is associated with degenerative lumbar spine disease. However, there is a lack of measurements of the sagittal and coronal facet angles, and the effect of 3D facet angles on joint motion in the sitting position is unknown. The present study was to investigate the 3D orientation and *in vivo* motion characteristics of the FJ in the sitting position.

Methods: Dual fluoroscopic imaging system and computed tomography (CT) were used to determine the 3D orientation and kinematic characteristics of FJs. L3-S1 segments were studied in 10 asymptomatic participants (5 male and 5 female, age: 25–35 years, body mass index: 22.4±1.8). Angles of the facet in the sagittal, coronal, and axial planes, and the range of motion of the FJs in seated flexion and extension movements were measured.

Results: The difference in sagittal facet angles between the 2 sides of the L3-S1 facet joints was not significant. The superior coronal facet angle on the left side of L5 was significantly smaller than that on the right side by 6.4° (P=0.01). The inferior transverse facet angle on the left side of L5 was greater than that on the right side by 7.1; the results were not statistically significantly different. In the sitting position, the range of motion of the left and right sides of L5-S1 differed significantly, with the right side being 5.5° (P=0.004) and 11.7° (P=0.026) greater than the left side in the sagittal and coronal planes, respectively. There was a correlation between mobility and the 3D orientation angle of the FJs in each segment.

Conclusions: Quantification of the 3D orientation of the lumbar spine FJs provides new perspectives to study the kinematics of the lumbar spine and the etiology of lumbar degenerative diseases. In sitting flexion and extension movements, there is a significant difference in the left-right lateral mobility of the FJs of the L5-S1 segments. With the exception of the transverse facet angle of the lumbar spine FJs, the sagittal and coronal facet angles also have an effect on lumbar spine mobility.

Keywords: Zygapophyseal joint; 3D orientation; facet tropism (FT); sitting

Introduction

The sitting position is widely chosen as the position for work or rest in daily life (1,2). Unlike common positions, such as supine and standing, the sitting position is characterized by a greater load on the lumbar spine and is often accompanied by lower back pain (LBP) (3,4). Some young

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LBP patients have no significant changes in imaging (5). In physiological situations, LBP is often associated with abnormal activity of some tissues, such as the facet joint (FJ), intervertebral discs, ligaments, and muscles (6). Previously published studies on the causes of LBP in the sitting position have focused on the intervertebral discs and muscles (7,8). However, as one of the structures that supports and maintains stability in the spine, the FJ has been identified as a potential source of pain, and its degeneration can also accelerate disc degeneration and lumbar spondylolisthesis. The orientation and kinematic characteristics of FJ are important to understand sitting-related LBP (9). In previous studies of other functional activities, facet tropism (FT) and potential abnormal activity under prolonged loading have been widely recognized as causes of LBP (10-12).

FT refers to differences in orientation between the right and left FJs of the lumbosacral spine (13). Previously published studies have shown that FT increases the shear force on the intervertebral disc, resulting in abnormal strain distribution and motion patterns in the lumbar spine, which in turn induces intervertebral disc degeneration (14-16). Several methods (such as computer tomography and direct measurement on cadaver specimens) have been used to describe the FT and to verify the relationship between joint asymmetry and degenerative diseases of the lumbar spine (17,18). Due to the limitations of experimental techniques, most previous studies have been based on the measurement in the transverse plane, lacking 3D measurements, such as sagittal and coronal facet angles.

In addition, the *in vivo* kinematic parameters of the FJ in the physiological state can be used as a baseline for assessing traumatic and degenerative changes, and as a reference for judging the effectiveness of posterior element replacement surgical techniques (17). Previous kinematic assessments of the FJ of the lumbar spine have been performed in the standing position; however, the kinematic characteristics of the FJ in the sitting position are not known (19).

To investigate the 3D orientation and *in vivo* motion characteristics of the FJ in the sitting position, we used the dual fluoroscopic image system (DFIS) and computed tomography (CT) to measure the 3D facet angle and kinematic characteristics of the L3-L4, L4-L5, and L5-S1 segments in healthy participants in the sitting position. In addition, we explored the relationship between lumbar FJ motion and its 3D orientation, hoping to analyze the kinematics parameters in sitting position from the perspective of 3D orientation of lumbar FJs in different planes. We present the following article in accordance with the MDAR reporting checklist (available at https://atm.amegroups.com/article/view/10.21037/atm-22-969/rc).

Methods

Participant recruitment

Ten asymptomatic participants (5 male and 5 female), aged 25–35 years with a body mass index of 22.4±1.8, were recruited in the present study. Study of asymptomatic participants is representative of lumbar spine kinematic changes in a healthy population. Exclusion criteria included scoliosis, history of spinal surgery, symptoms or history of LBP, functional spinal problems, and musculoskeletal lesions of the lower extremities or neurological disorders in the past 12 months. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Research Ethics Committee of Tianjin Hospital of Tianjin University and informed consent was taken from all the patients.

Reconstruction of 3D models of the lumbar spine

The L3-S1 segments (thickness of 0.625 mm with no gap) of all participants were scanned in the supine position with CT with a resolution of 512×512 pixels. The obtained lumbar scans were then imported into MIMICS version 19.0 (Materialise, Leuven, Belgium) for reconstruction. We chose specific bony thresholds to better separate the surrounding soft tissues from the lumbar spine and obtained the reconstructed lumbar spine with FJ (L3, L4, L5, S1) (*Figure 1*).

Instantaneous motion acquisition of the lumbar spine

The participant was seated on a height-adjustable seat with feet shoulder width apart, lower legs perpendicular to the ground, thighs parallel to the ground, arms hanging in front of the chest, and hands clenched in fists on either side of the neck. This posture was maintained throughout the experiment. The 2 fluoroscopes (Phillips, Berlin, Germany) were positioned crosswise, but at a distance to avoid image interference due to diffraction of X-rays. Height-adjustable seats were placed near the receivers. Participants were asked to perform maximum flexion to maximum extension movements in the sitting position to simulate daily life, and fluoroscopic images were collected in the neutral sitting
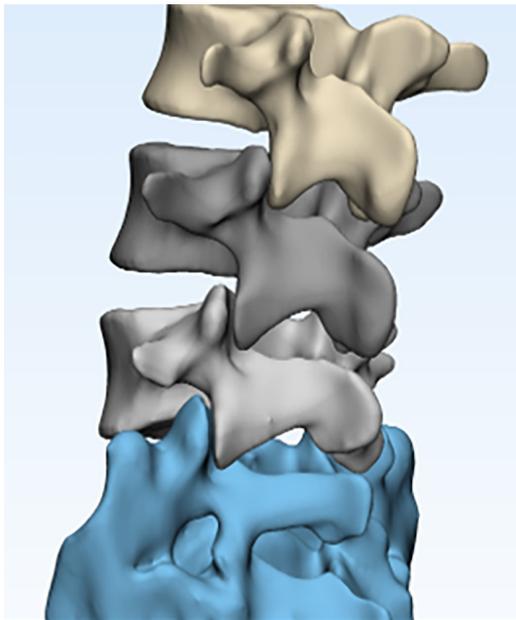
Figure 1 3D reconstruction of L3-S1 segments based on computed tomography using MIMICS (Materialise's interactive medical image control system) software. Different colors of the lumbar vertebrae represent different lumbar segments.

position, maximum forward flexion sitting, and maximum extension sitting (*Figure 2*). The range of motion was at the individual's maximum tolerance and did not exceed the fluoroscopes range. Two transient lumbar spine fluoroscopic images were obtained separately in each position.

Reproduction of in vivo lumbar spine motion in virtual space

According to the method of Li *et al.* (20), a set of orthogonal virtual camera sources and receivers were created in Rhinoceros (Robert McNeel & Associates, Seattle, WA, USA) software to simulate the location of the fluoroscopic image intensifier in a real situation. Lumbar spine images were acquired by the fluoroscopes, and a 3D reconstructed lumbar spine model was imported simultaneously. Lumbar spine edges were then depicted by tracing the difference in pixel values of the lumbar spine in the 2 perspective images. The reconstructed 3D model of the lumbar spine is translated and rotated so that its contour coincides with the outline of the bony feature drawn on the fluoroscopic images (*Figure 3*). With this method, the actual position of
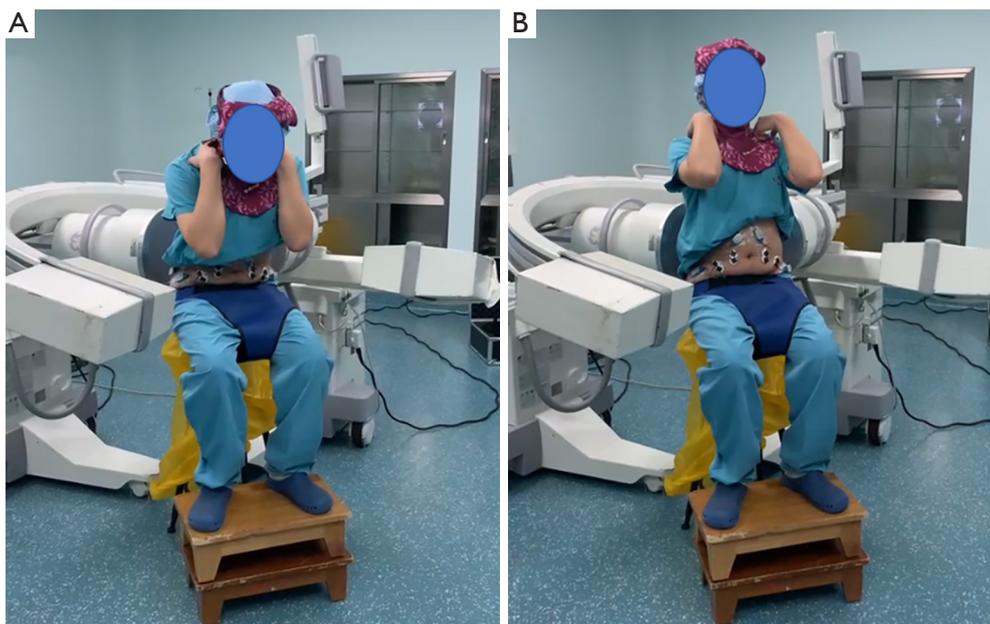

Figure 2 Experimental setup of the dual fluoroscopic imaging system. Participant subject sits in a height-adjustable seat, maintains body stability, and performs maximal forward flexion (A) and backward extension (B) movements.
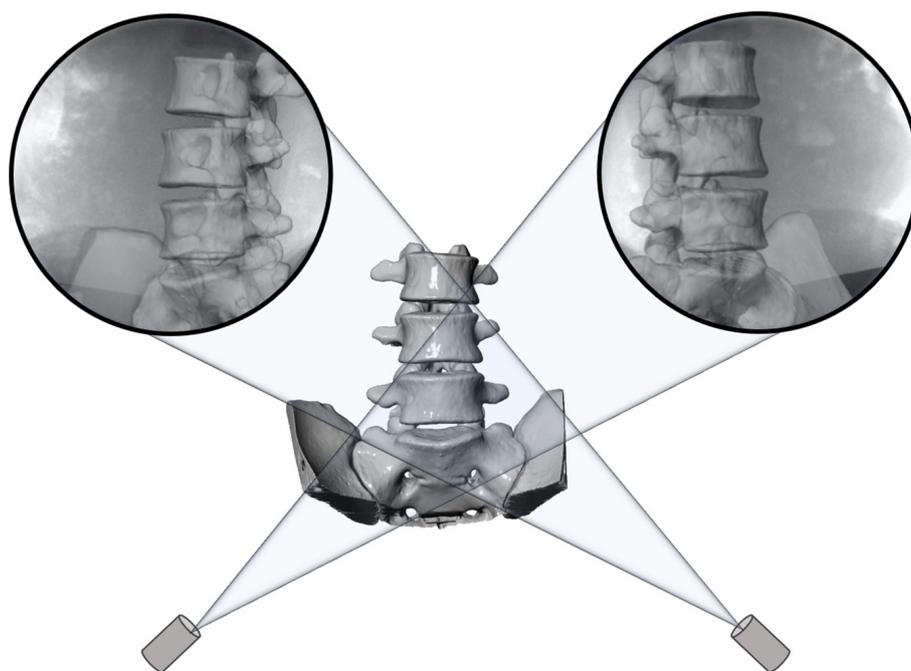
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Figure 3 Each 3D vertebral model was separately translated and rotated until their contours matched the corresponding vertebral bony outline captured on the 2 fluoroscopic images.

the *in vivo* FJ could be reproduced.

Establishment of a coordinate system of the FJ

Based on Chowdhury *et al.*'s method (12), a Cartesian coordinate system was established on the articular surface of each zygapophyseal joint, and the motion of the coordinate system was used to estimate the kinematic of the joint. Four points were selected at the uppermost, lowermost, innermost, and outermost sides of the surfaces. The origin of the coordinate system is the center of mass of the geometry formed by the 4 points. The vector connecting the innermost and outermost points was defined as the Y-axis; similarly, the vector passing through the line connecting the lowermost and uppermost points was defined as the Z-axis; the vector orthogonal to the Y–Z plane was defined as the X-axis; the coordinate system was established following the right-hand rule (*Figure 4*).

Definition and measurement of FJ orientation

The 3D facet angles were defined and measured in the sagittal, coronal, and transverse planes, respectively. The sagittal facet angle (α) was defined as the angle between

the projection of the line connecting the uppermost and lowermost points of the FJ in the sagittal plane and the transverse axis (*Figure 5A*). The coronal facet angle (β) was defined as the angle between the projection of the line connecting the uppermost and lowermost points of the FJ on the coronal plane and the transverse axis (*Figure 5B*). The transverse facet angle (γ) was defined as the angle between the projection of the line connecting the medial-most and lateral-most points of the FJ on the transverse plane and the sagittal axis (*Figure 5C*).

Measurement of FJ motion

The range of rotation within the FJ was calculated by measuring the motion of the inferior joint surface of the upper segment relative to the superior joint surface of the lower segment, with the superior articular surface as a reference (*Figure 6*). The following kinematic parameters could be obtained: (I) the range of rotation during the forward-flexion-backward extension motion in the sitting position; (II) the decomposition of the forward-flexion-backward extension motion of the lumbar spine into the following 2 submotion processes: neutral-anterior flexion and neutral-backward extension, to obtain the range
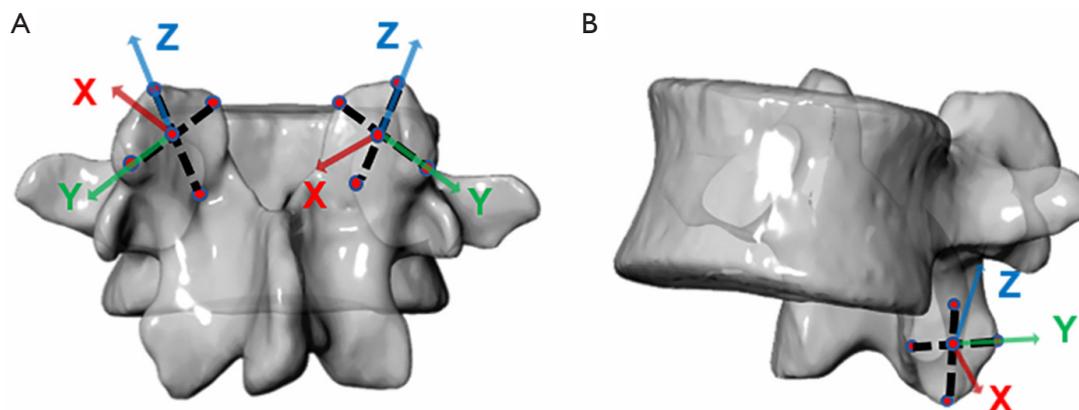
Figure 4 Establishment of the superior (A) and inferior (B) articular surface coordinate system. Four reference points are selected at the uppermost, lowermost, innermost, and outermost sides of the facet joints. Center of mass of the articular surface, defined as the origin to establish the Cartesian coordinate system, was selected through the area formed by the 4 reference points. X, Y, Z represents X axis, Y axis, Z axis of Cartesian coordinate system, respectively.
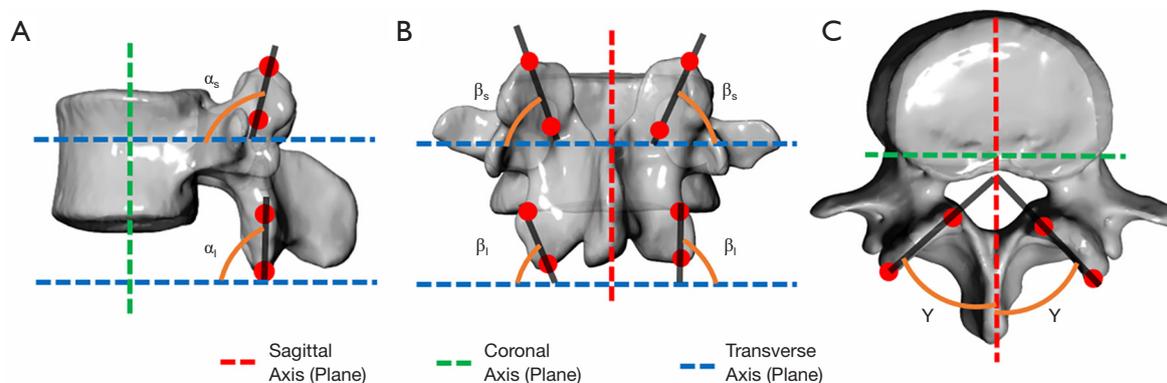

Figure 5 Definition of facet joint 3D orientation. (A) Sagittal facet angle (α), (B) coronal facet angle (β), (C) transverse facet angle (γ). α_S and β_S, α_I, and β_I indicate the superior and inferior articular surface angles, respectively.

of rotation of the FJ, respectively, and to compare the difference in the mobility of the 2 submotion processes.

Statistical analysis

Statistical analysis was performed using SPSS version 26.0 (IBM, Armonk, NY, USA). The facet angles of the FJ in the sagittal, coronal, and transverse planes were described as mean ± standard deviation. The results of all kinematic parameters were expressed as P50 (P25, P75). The differences in the mobility of the left and right FJ in flexion and extension movements were compared using Kruskal-Wallis test. Pearson correlation analysis was performed between the 3D facet angle and the mobility of the joint.

Statistical significance was set at P<0.05.

Results

3D measurement of FJ orientation

In the sagittal plane, the left superior facet angle of the L5 was 1.9° smaller than that of the right, and the remaining segments were greater on the left than on the right, with differences ranging from 0.5° to 1.8°, with no statistically significant differences (*Table 1*). In the coronal plane, the left side of the L5 vertebra had a significantly smaller facet angle of 6.4° than the right side (P=0.01), and the other 2 sides had close angles, with differences ranging from 0 to 0.7°, with no statistically significant differences (*Table 2*). In
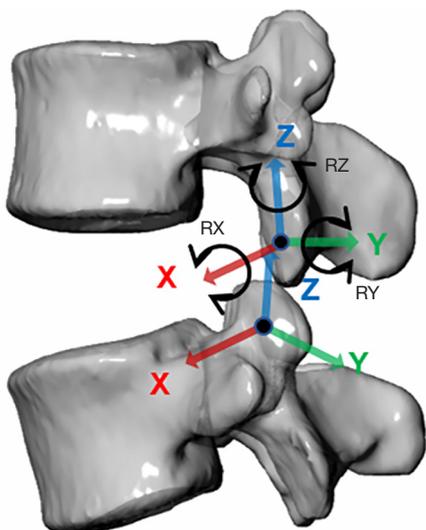
Figure 6 With the superior articular surface as a reference, the range of rotation of the inferior articular surface was measured in the seated position. RX, rotation along the X-axis; RY, rotation along the Y-axis; RZ, rotation along the Z-axis. X, Y, Z represents X axis, Y axis, Z axis of Cartesian coordinate system, respectively.

Table 1 Articular surface angles of the L3-S1 segments in the sagittal plane

Segment	Left	Right	P value
Inferior			
L3	79.3±6.0	77.5±5.1	0.710
L4	78.7±5.7	78.2±3.8	1
L5	68.4±4.4	66.6±4.9	0.710
Superior			
L4	98.4±2.3	96.6±4.5	0.710
L5	95.5±4.8	97.4±5.7	0.318
S	104.2±8.3	103.1±6.8	0.805

Table 2 Articular surface angles of L3-S1 segments in the coronal plane

Segment	Left	Right	P value
Inferior			
L3	88.5±7.3	88.5±3.9	0.805
L4	90.4±5	87.7±6.2	0.535
L5	77.7±6.7	77.2±8.8	0.902
Superior			
L4	78.8±2.1	79.1±4.4	0.620
L5	74.9±3.3	81.3±4.3	0.010*
S	82.7±2.2	82.7±4.5	0.902

*, statistically significant differences at $P<0.05$.

Table 3 Articular surface angles of L3-S1 segments in the transverse plane

Segment	Left	Right	P value
Inferior			
L3	40.9±11.3	40.8±10	0.805
L4	48.1±13.3	49.9±13.1	1.000
L5	52.2±9.1	45.1±13.7	0.383
Superior			
L4	41.9±7.7	41.8±6.3	0.805
L5	48.7±8.8	48±11.5	1.000
S	55.4±7.6	54.4±10.9	0.805

Lumbar FJ range of rotation

The range of motion of the FJ on the right side of L5-S1 was 8.8° and 14.9° in the sagittal and coronal planes during forward flexion and backward extension movements in the seated position, which were 5.5° (P=0.004) and 11.7° (P=0.026) greater than those on the left side, respectively (*Figure 7A-7F*). In the transverse plane, the range of rotation of the right side was slightly greater than that of the left in L5-S1, with no statistically significant differences (*Figure 7G-7I*). In the FJ of L3-L4 and L4-L5, the range of motion was slightly greater on the left side than on the right side in both L3-L4 and L4-L5. The range of rotation was 1.7° and 1.2° greater on the left side than on the right side in the sagittal plane, 0.8° and 0.9° greater in the coronal
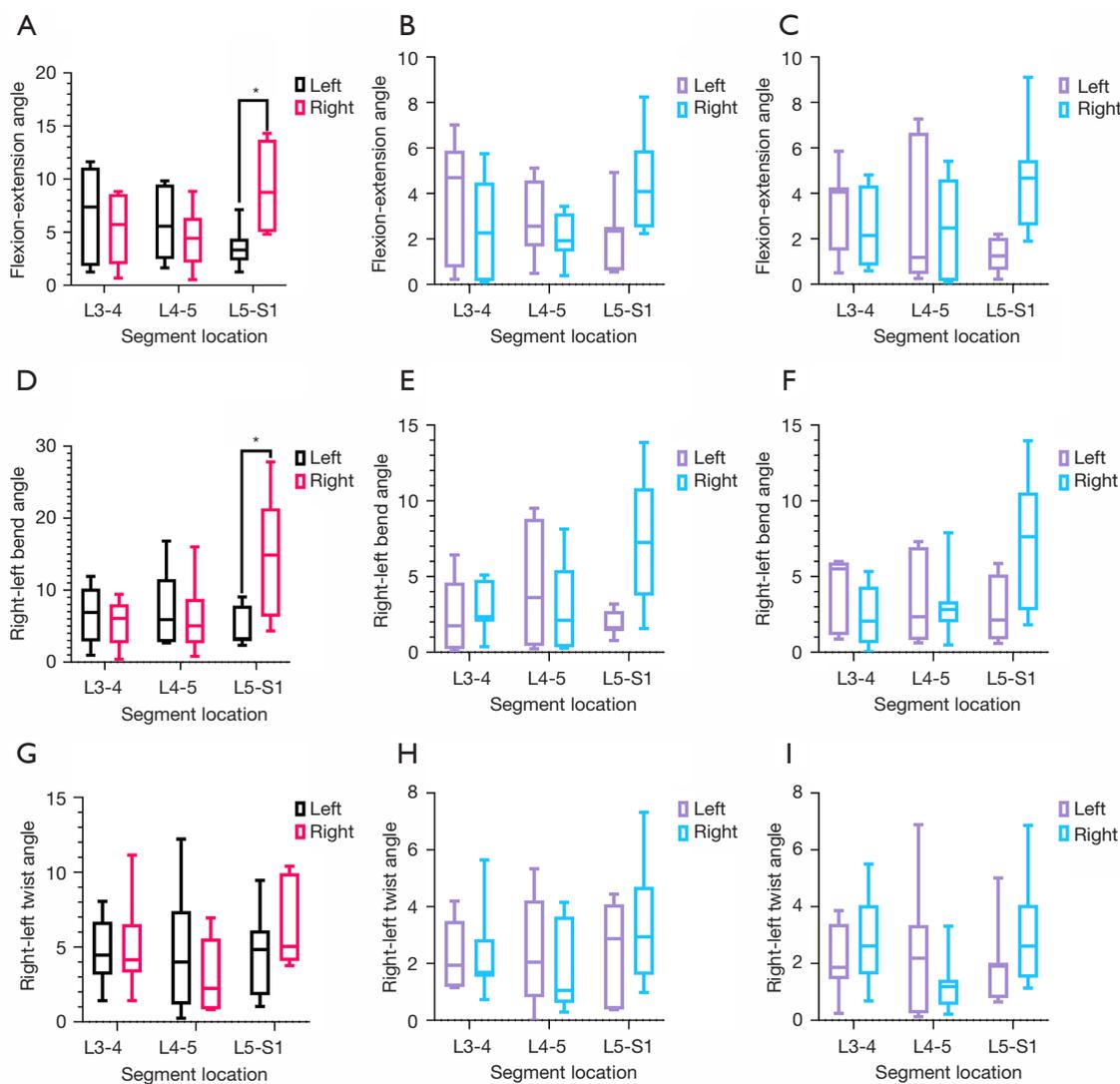
the transverse plane, the difference between the 2 sides of the inferior facet angles was greater in L4 and L5, with the left side being 1.8° smaller than the right side in the L4; the left side was 7.1° greater than the right side in the L5, with no statistically significant difference. The other segments had a slightly larger facet angle on the left side than the right side in the transverse plane, with a difference ranging from 0° to 0.7° (*Table 3*).

Figure 7 The range of rotation of the L3-S1 facet joint in F-E, RB-LB, and LT-RT, respectively (A,D,G). The overall flexion-extension motion was further divided into two subgroups of neutral-anterior flexion and neutral-posterior extension. (B,E,H) and (C,F,I) are the ranges of rotation of the FJ in F-E, RB-LB, and LT-RT in each segment in the neutral-anterior flexion and neutral-posterior extension motion, respectively. *, P<0.05. The unit of all the Y-axis of the figures were degree. F-E, flexion-extension; RB-LB, left-right lateral bending; LT-RT, left-right rotation.

plane, and 0.4° and 1.8° greater in the transverse plane, respectively.

The sitting flexion and extension motions were divided into neutral sitting to forward flexion sitting and neutral sitting to posterior extension sitting to compare the mobility of the FJ during sitting forward flexion and posterior extension, respectively. During both submovements, the range of rotation of the FJ on the left side of L5-S1 was smaller than that on the right side in all 3 planes. In the

sagittal plane, the range of rotation of the left FJ of L3-L4, L4-L5, and L5-S1 during anterior flexion was greater than that during posterior extension, increasing by 0.7°, 1.4°, and 1.1°, respectively; the range of rotation of the right FJ of L4-L5 and L5-S1 during anterior flexion was less than that during posterior extension, decreasing by 0.6°, while L3-L4 tended to be opposite to that of the caudal segment, increasing by 0.2° (*Figure 7B*,*7C*). In the coronal plane, the range of rotation of the left FJ of L3-L4 differed more in

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submotion, with the range of motion during forward flexion being 3.8° smaller than that during posterior extension (*Figure 7E,7F*). In the transverse plane, the range of rotation of the left FJ in L5-S1 was 1° greater during forward flexion than during posterior extension, and the right FJ in L3-L4 was 0.9° smaller during forward flexion than during posterior extension (*Figure 7H, 7I*). The range of rotation of the FJ on both sides of the remaining lumbar segments was less variable in the submovements, with a range of rotation between 0° and 0.3°.

Relationship between facet angle and motion

The magnitude of the left-side facet angles in the 3 planes correlated more with FJ motion. The range of rotation of the L3-L4 left joint in the coronal plane showed a positive correlation with the coronal inferior facet angle in L3 (P=0.016) and a negative correlation with the transverse facet angles of the L3 joints (*Table 4*). The range of rotation of the L4-L5 left joint in the coronal plane showed a negative correlation with the sagittal inferior facet angle of the L4 left joint (P=0.029) (*Table 4*). The range of rotation of the L5-S1 left joint in the sagittal and coronal planes showed a positive correlation (P=0.03) with the sagittal superior facet angle and a negative correlation (P=0.03) with the transverse superior facet angle in the S1 left joint (*Table 4*).

Discussion

Facet orientation and range of motion have been a topic of interest for scholars in studies of the FJ of the lumbar spine. FT is a potential anatomical factor for degenerative changes in the lumbar spine, which could increase the incidence of LBP and disc degeneration (21). In the past, FT and motion characteristics have been investigated in physiological and pathological conditions through *in vitro* and *in vivo* experiments. In their *in vitro* experiment, Masharawi *et al.* measured the facet orientation of cadaveric specimens, T1-L5 FJs, in the transverse and sagittal planes (22). In their *in vivo* experiment, Zhou *et al.* used CT to measure the transverse facet angle on the L1-S1 in 53 patients with lumbar disc herniation and 129 normal young adults (18). Ko *et al.* used CT to measure the transverse facet angle of L3-L5 in 462 patients with LBP (23). Most previously published studies on FT measurement have been limited to the transverse plane because of the limitation of experimental methods, which cannot fully reflect the orientation of FJ. Chowdhury *et al.* first quantified the

3D facet angles of L2-S1 in 14 healthy volunteers using a dynamic stereo-radiography system (12). However, 3D anatomical measurements of the FJ orientation have not been reported in the Chinese population. Furthermore, kinematic characteristics in the different activities of the FJ of the lumbar spine have been less frequently reported, and past studies have focused on the different movements in the standing position (12,19,24). Sitting is as common a physiological position as standing in daily life; however, the kinematic changes of FJ in the sitting position have not been studied extensively. The DFIS used in our study is capable of acquiring position information in 3D for each lumbar segment in the transient state. Moreover, compared to other radiographs, it can quantify the 6 degrees of freedom of movement in the bony structures of the joints and accurately measure kinematic changes with a rotational error of only 0.7°, which can better reflect the anatomical and kinematic characteristics of FJ (18). Therefore, we applied this method to study the facet orientation in the physiological situation and the motion characteristics of the FJ during anterior flexion and posterior extension movements in the sitting position.

Results from a previous study have found some parameters of the anatomical characteristics of the FJ. Masharawi *et al.* found that the articular facet angles of L3-L5 in the cross-section ranged from 40.4° to 56.3°, with good symmetry of the left and right lateral articular facet angles (22). Mohanty *et al.* found that the transverse facet angle in the physiological situation gradually increases from cephalad to caudal, and the L4-L5 and L5-S1 segments were more likely to show FJ asymmetry (17). Shin *et al.* found that the incidence of facet disease after total disc replacement increased when the difference between the right and left side facet angles was greater than 5° (13). In our study, we found that the range of articular facet angles of L3-S1 in the transverse plane was between 40.8° and 55.4° and showed a gradual increase from the cephalad to caudal side. Among the L5-S1 FJs, the inferior articular facet angle of L5 increased by 7.1° on the left side compared with the right side, while the difference in other articular facet angles was within 0.7°. The facet angles measured in our study were compared with those from Chowdhury *et al.*'s study (*Figure 8*) (12). We found that in the sagittal plane, the inferior facet angles on both sides of L4 and L5 were smaller in Chinese participants, and were specifically more distant from the coronal plane and biased toward the transverse plane, especially in the inferior facet surface of L5. In the coronal plane, the left superior articular surface

Table 4 Correlation between the 3D facet angle of L3-S1 segments and range of motion during sitting flexion and extension movements

Projection angles	Articular surface angle	Statistics	Left			Right		
			L3-L4	L4-L5	L5-S1	L3-L4	L4-L5	L5-S1
Flexion-extension ROM								
α	IFA	r	−0.01	−0.6	−0.1	0.1	−0.02	0.4
		P	0.986	0.137	0.875	0.894	0.962	0.315
	SFA	r	0.2	−0.4	0.8	0.1	0.6	0.2
		P	0.538	0.334	0.033*	0.841	0.136	0.734
β	IFA	r	0.7	−0.2	0.7	0.6	0.2	0.4
		P	0.08	0.636	0.066	0.133	0.614	0.34
	SFA	r	0.6	0.4	0.3	−0.1	−0.2	0.5
		P	0.193	0.326	0.459	0.895	0.747	0.204
γ	IFA	r	−0.5	0.2	−0.4	−0.7	0.4	0.05
		P	0.284	0.746	0.39	0.054	0.414	0.919
	SFA	r	−0.6	0.2	−0.6	−0.5	0.4	−0.1
		P	0.191	0.734	0.18	0.208	0.416	0.784
Right-left bending ROM								
α	IFA	r	−0.1	−0.8	0.1	0.02	0.3	0.3
		P	0.762	0.029*	0.864	0.965	0.55	0.558
	SFA	r	0.5	−0.2	0.8	0.1	0.7	−0.05
		P	0.224	0.66	0.029*	0.835	0.07	0.923
β	IFA	r	0.8	−0.4	0.9	0.6	0.2	0.6
		P	0.016*	0.422	0.001*	0.129	0.621	0.144
	SFA	r	0.6	0.5	0.6	−0.2	0.1	0.3
		P	0.178	0.251	0.126	0.741	0.77	0.494
γ	IFA	r	−0.8	−0.1	−0.5	−0.7	0.1	−0.04
		P	0.048*	0.802	0.296	0.058	0.82	0.934
	SFA	r	−0.8	−0.03	−0.8	−0.5	0.1	−0.2
		P	0.016*	0.946	0.029*	0.306	0.759	0.722
Right-left twisting ROM								
α	IFA	r	−0.5	0.1	−0.4	0.3	0.4	0.3
		P	0.205	0.83	0.318	0.5	0.403	0.462
	SFA	r	−0.1	−0.3	0.5	0.3	0.3	0.4
		P	0.879	0.583	0.299	0.512	0.496	0.36

Table 4 (*continued*)

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Table 4 (*continued*)

Projection angles	Articular surface angle	Statistics	Left			Right		
			L3-L4	L4-L5	L5-S1	L3-L4	L4-L5	L5-S1
β	IFA	r	−0.04	0.6	0.4	0.3	−0.1	0.3
		P	0.929	0.2	0.329	0.474	0.762	0.527
	SFA	r	−0.5	−0.1	−0.3	0.1	0.5	0.5
		P	0.267	0.822	0.537	0.776	0.301	0.226
γ	IFA	r	−0.1	−0.1	−0.5	−0.5	−0.2	0.1
		P	0.827	0.893	0.205	0.31	0.637	0.875
	SFA	r	−0.3	−0.3	−0.4	−0.7	−0.1	0.1
		P	0.526	0.507	0.316	0.099	0.864	0.912

*, statistically significant differences at $P<0.05$. α, β, and γ are the projection angles of the small joints in the sagittal, coronal, and transverse planes, respectively. r is the correlation coefficient between the facet angle and joint mobility in different planes. IFA, inferior articular surface angle; SFA superior articular surface angle; ROM, range of motion.

angles of L4 and L5 in Chinese participants were smaller than those of participants in Chowdhury *et al.*'s study (12); that is, they were more distant from the sagittal plane and biased toward the transverse plane. The rest of the results were not significant and were all within 1 standard deviation. Thus, the 3D orientation of zygapophyseal joints in the L4 and L5 vertebrae differs in Chinese from other ethnic groups, especially in the sagittal and coronal planes, with the articular surface orientation of L5 being more transverse. Analyzed from the perspective of FT, Chowdhury *et al.* found that FT was more significant at L3-L4 and L5-S1 (12). Nevertheless, our data suggest that there is 6.4° difference between the left and right lateral superior facet angles in the coronal plane for L5, and a 7.1° difference between the inferior articular surface angles in the transverse plane. The rest of the lumbar segments have similar facet angles on both sides. There could be some differences in 3D articular surface angles in different ethnic groups, and FT is more common in L4-L5 and L5-S1 segments. This could also explain the epidemiological investigation of degenerative spondylolisthesis prone to L4-L5 and disc and degeneration prone to the L5-S1 segment.

FJ kinematics can reflect the motion of joints in daily activities and help us to analyze the causes of joint degenerative diseases; therefore, it is a topic of interest to scholars. Kozanek *et al.* found that the range of rotation in the sagittal plane of the L2-L5 in forward flexion and extension in the standing position ranged from 2° to 6°, and the range of rotation in the sagittal plane of L4-L5 was

significantly smaller than that of L2–L3 and L3-L4, while there were no significant differences in the 3 segments in the coronal and transverse planes (19). In seated maximal forward flexion and back extension movements, our study found that in the sagittal plane the range of rotation of the L3-S1 was between 3.3° and 8.8°, and the range of rotation of the L4-L5 was less than that of L3-L4, supporting the findings of Kozanek *et al.* (19). In addition, differences in the mobility of the left and right FJs during forward flexion and backward extension movements were found in our study. The right FJ of L5-S1 was significantly more mobile in the sagittal and coronal planes than the left. However, the range of rotation of the left and right lateral joints of L3-L4 and L4-L5 was less different on the 3 planes. Movement from neutral position to forward flexion and posterior extension showed a similar pattern to the overall forward flexion and posterior extension movement, and the differences in left and right lateral joint mobility were mainly present in L5-S1. There was no significant difference in the range of motion of the FJ in each segment when comparing the 2 submovement processes.

The change in the 3D orientation of the FJ of the lumbar spine could be related to mobility. There have been few previously published studies on this due to the limitation of research conditions. In our study, we characterized the correlation between the 3D orientation of the FJs and their mobility. There was a correlation between the 3D orientation of the left small joint and its mobility. The L3-L4 and L5-S1 facet angles in the transverse plane were
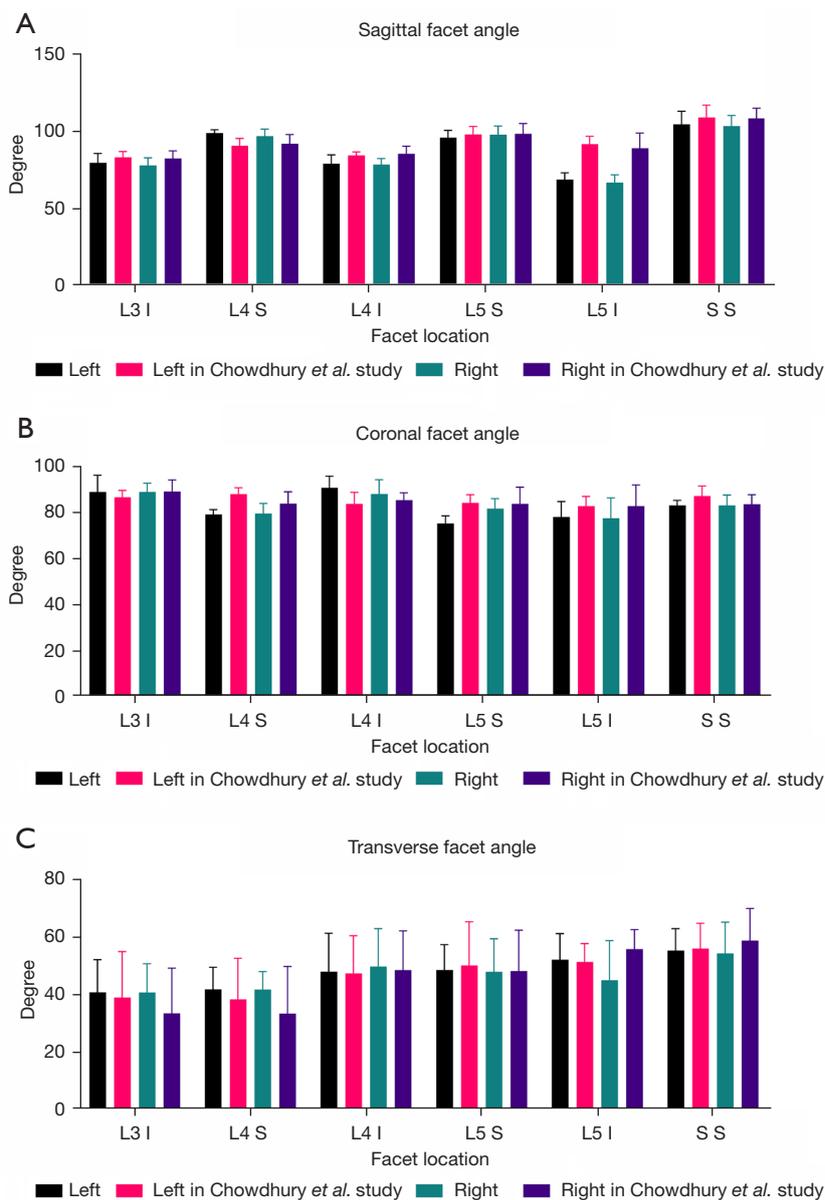
Figure 8 Bilateral facet angles of L3-S1 measured in our study compared with those of Chowdhury *et al.* (12). L3I, L4I, L5I, and L4S, L5S, and S S represent the inferior and superior articular facets of each segment, respectively. The unit of all the Y-axis of the figures were degree.

negatively correlated with the range of rotation of the joints in the coronal plane. The smaller the angle of the FJ on the transverse plane, that is, the closer the joint surface is to the sagittal plane, the greater its range of motion in the left-right side bending. In the sagittal plane, the L4 inferior facet angle was negatively correlated with the range of rotation of FJ in the coronal plane, and the S1 superior facet angle was positively correlated with it. The angle in the sagittal plane deviated from the sagittal plane

and was close to the transverse plane; the corresponding FJ had greater mobility of the lateral bending. The change of facet angle in the transverse plane influenced the axial torsional resistance, especially when the facet angle was biased toward the sagittal plane, decreasing axial torsional resistance (25). Reduced torsional resistance increases the rotational mobility of the FJ, which in turn increases the rotational strain on the disc, making lumbar disc degeneration more likely to occur unilaterally (17). Similar

to the change in facet angle in the transverse plane, the facet angle in the sagittal plane was close to the transverse plane, and the corresponding articular surface with which the FJs are formed has a reduced resistance to rotation and a corresponding increase in mobility.

The angles of the adjacent upper and lower articular surfaces of the FJ do not match perfectly on all 3 planes. The balance between mobility and stability of the lumbar segment is more in favor of the former than with the cervical and thoracic spine, and the imperfect matching of the articular surfaces helps to increase the range of motion of the FJ (22). In our study, we found that the range of motion of FJ was only highly correlated with independent articular surfaces, and not significantly correlated with the adjacent articular surfaces that comprise them.

In the present study, using DFIS and CT, we described the 3D orientation and asymmetry of the FJ and analyzed the data on the *in vivo* motion of FJ during sitting flexion and extension movements. From our experiments, it can be concluded that FT is more prevalent in the L4-L5 and L5-S1 segments than in L3-L4. The mobility of L5-S1 in the sagittal and coronal planes during seated flexion and extension was greater on the right side than on the left side. In the correlation analysis, the 3D orientation of the left FJ correlated highly with mobility. The more transverse facet angles in the L3-L4 and L5-S1 segments were biased toward the sagittal plane, the greater the range of mobility of the corresponding FJ in the coronal plane. The data analysis helps us to understand the physiological characteristics of FJ in the sitting position and the potential mechanism of lumbar spine disease occurrence, which provides a theoretical basis to guide clinical practice. The correlation between the 3D orientation and the spatial mobility of FJ also provides a new perspective for the study of joint kinematics. The orientation of the FJ in the sagittal and coronal planes could have a greater kinematic significance. The FJ mobility and the possibility of LBP can be better analyzed in sitting motion from the perspective of the 3D orientation of zygapophyseal joints. In addition, when there is a difference in the joints orientation between the two sides, appropriate adjustment of posture and motion during sitting may reduce the occurrence of FJ degeneration. Our study has several limitations. First, the sample size was small. Second, data were collected only for seated flexion and extension movements, lacking analysis of other positions in the seated position, such as lateral flexion and rotation. Third, only asymptomatic young participants were selected. Further analyses of 3D orientation and

kinematic parameters of FJ in different age groups and with different diseases should be performed in the future.

Footnote

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