



3D kinematic characteristics of lumbar facet joints in sitting position

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Abstract

Background Recognizing the kinematic characteristics of lumbar facet joints is important for the prevention and treatment of lumbar degenerative diseases. Previous studies have been conducted in either the supine or standing position, and there are no measurements regarding the kinematic characteristics of the lumbar facet joints while sitting. The aim of this study was to measure and analyze lumbar facet joint motion characteristics while sitting.

Methods Ten subjects (5 males and 5 females) performed the movements of flexion–extension, left bending–right bending, and left rotation–right rotation in a sitting position. Dual Fluoroscopic Image System and computed tomography technique were used to measure the displacement and rotation angle of the lumbar facet joints of the subjects for analysis. The movement characteristics of L3–S1 were measured.

Results When the subjects were in sitting position, the lumbar vertebra mainly changed in Z-axis and α , β angle when they performed flexion–extension activities. The displacement of the left facet joint was 4.65 ± 1.99 mm at L3–4, 1.89 ± 2.99 mm at L4–5, and 0.80 ± 2.27 mm at L5–S1 in the Z-axis, and the displacement of the right facet joint was 3.20 ± 2.61 mm at L3–4, 1.71 ± 3.00 mm at L4–5, and 0.31 ± 1.69 mm at L5–S1 in the Z-axis. The rotation in the α angle was $6.00 \pm 4.49^\circ$ at L3–4, $3.51 \pm 5.24^\circ$ at L4–5, and $0.97 \pm 4.13^\circ$ at L5–S1, which was significant different. The rotation in the β angle was $2.30 \pm 2.94^\circ$ at L3–4, $0.16 \pm 2.06^\circ$ at L4–5, and $0.35 \pm 1.74^\circ$ at L5–S1, which was significant different. When the lumbar spine performed the activity of left bending–right bending, there were changes in rotation mainly in the Z-axis and β angle. The displacement of left facet joint in the Z-axis was 1.34 ± 2.84 mm at L3–4, 2.11 ± 0.88 mm at L4–5, and 0.72 ± 0.81 mm at L5–S1; the rotation in the β angle was $5.66 \pm 2.70^\circ$ at L3–4, $7.89 \pm 2.59^\circ$ at L4–5, and $1.28 \pm 2.07^\circ$ at L5–S1; when the lumbar spine performed the activity of left rotation–right rotation, there were changes in the β angle. The rotation of β angle was $4.09 \pm 2.86^\circ$ at L3–4, $2.14 \pm 3.38^\circ$ at L4–5, and $0.63 \pm 1.85^\circ$ at L5–S1.

Conclusion The lumbar facet joint motion in sitting position is different in each mode of motion. The horizontal displacement and rotation are predominant during flexion and extension activities, while there are different rotation in bending and rotation. The study shows the coupled motion of the lumbar facet joints while sitting, providing a new perspective on the kinematics of the lumbar spine and the etiology of lumbar degenerative diseases.

Keywords Kinematic · Lumbar facet joints · Sitting · DFIS

Introduction

The kinematic characteristics of the lumbar spine have been the focus of research. The lumbar facet joint is the main structure that produces lumbar motion while bearing lumbar

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load. At present, the occurrence of lower back diseases is increasing year by year, of which facet joints account for a large proportion [7, 13–15].

Previous studies on facet joint motion have focused on standing or supine positions. While the human body is in a sitting position, the facet joints will be under pressure, which is more likely to produce lower back pain. Therefore, the study of the movement mode of lumbar facet joints in sitting position can help people to have a more comprehensive understanding of the movement mode of lumbar vertebrae, so as to prevent and treat lumbar diseases from the root. By measuring the movement characteristics of lumbar facet joints in normal people, it can also provide relevant basis for the manufacture of artificial lumbar intervertebral disc.

As so far, there are few studies on the movement of lumbar facet joints. Previous research methods include *in vitro* studies and *in vivo* studies. Commonly used *in vitro* research methods include cadaveric measurement, finite element analysis, and *in vivo* research including imaging analysis and dynamic system capture [1, 3, 4, 8, 9, 12]. Since *in vitro* studies cannot completely simulate the physiological environment of the human body, they can have an impact on the measurement results. The accuracy of dynamic capture system and imaging analysis is relatively poor.

Dual Fluoroscopic Image System (DFIS) is an advanced technique for *in vivo* motion research. The CT/MRI scan data are modeled by computer, and then the model is combined with the DFIS, which can truly reproduce the different movements of the human bone under physiological conditions, and then measure and study the related data. This technique was originally proposed and applied by the Harvard Mechanical Motion Laboratory with a displacement accuracy of 0.3 mm and a rotation angle accuracy of 0.7° in six degree freedom movements of flexion–extension, left bending–right bending, and left rotation–right rotation [16]. This technique not only reproduces the movement pattern of the spine in the body, but also can accurately observe the movement of the spine in the human body.

The purpose of this paper is to analyze the displacement and rotation of lumbar facet joints in sitting position by studying the normal population and using the technology of DFIS and CT, so as to describe the motion characteristics of facet joints. We assume that the motion of the facet joint depends on different spinal segments.

Methods

Time and locations

In this study, 10 asymptomatic people (5 males and 5 females) were recruited, aged from 25 to 39, with an average of 32–4.29 years, BMI 18.5–25, with an average of 22.19

and 2.375 years. Exclusion criteria: 1. History of lumbar surgery, lumbar trauma, low back pain; 2. Spinal diseases, such as idiopathic scoliosis, ankylosing spondylitis and other diseases causing lumbar deformity; 3. Pregnancy; 4. Severe osteoporosis and other diseases that may affect the test results. The study was conducted in accordance with the Helsinki Declaration (revised in 2013). This study was approved by the Research Ethics Committee of Tianjin Hospital of Tianjin University, and all the subjects had informed consent.

Reconstruction of lumbar 3D model

CT was applied to the subjects in the supine position with a slice thickness of 0.625 mm and a resolution of $512 * 512$ pixels. The acquired images were saved in DICOM format and then imported into MIMICS 19.0 for reconstruction. We selected a special skeletal threshold for lumbar 3D model reconstruction (Fig. 1).

Establishment of dual fluoroscopic image system

The DFIS system was composed by applying two C-arms placed perpendicularly to each other. The two C-arms were simultaneously transilluminated through debugging (Fig. 2). The X-ray transillumination (30 frames/second, 8 ms pulse width) lasted for 1 s at each position to obtain a clear lumbar spine image. Subjects were seated on a stool of adjustable height of about 1.2 m, which was adjusted according to personal height, to ensure the lumbar spine was the center of the tube ball projection. The subjects' pelvis was fixed, keeping their thighs parallel and their calves perpendicular to the ground. The subjects hold both upper limbs on the chest and place both hands on the shoulders. Each subjects performed

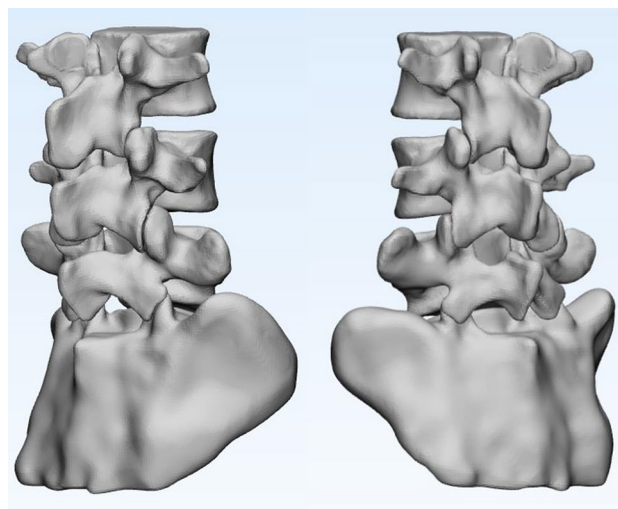


Fig. 1 Lumbar vertebra model reconstructed by Mimics 19.0

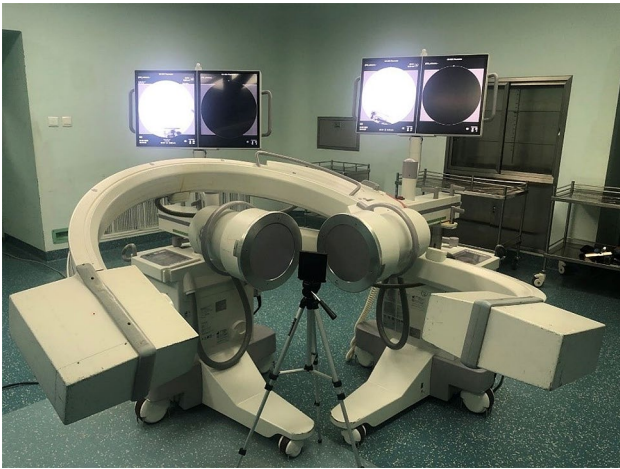


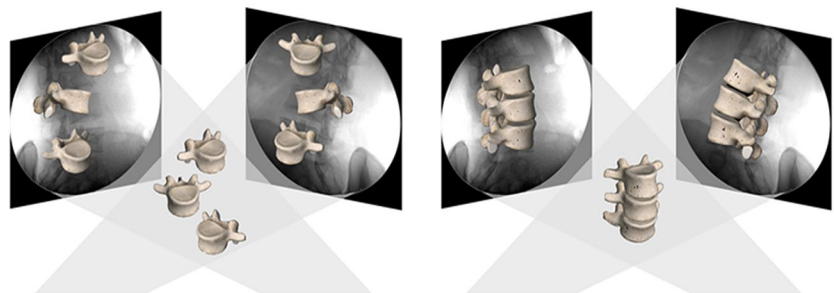
Fig. 2 Dual fluoroscopic image system: the DFIS system Was composed by applying two C-arms placed perpendicular to each other. Cross sections are radiolucent areas



Fig. 3 Participant subject sits in a height-adjustable seat, performs maximal flexion (a) and extension (b) movements

seven movements: neutral position, flexion position, extension position, left bending, right bending, left rotation, and right rotation, and the movement maintained the maximum amplitude. Each position switch was guided by two spine surgeons to ensure the accuracy of the maneuver (Fig. 3).

Fig. 4 Process of matching the lumbar spine model of 2D-3D through the Rhinocero software



After saving in DICOM format, USB export was applied to perform the orthopedic processing of the obtained X-ray images.

Reproduce lumbar facet joint motion in various positions in sitting position

The X-ray images were imported into rhinoceros software as background images. Import the established CT three-dimensional model into the software, adjust the position of each vertebral body according to the lumbar anatomy, so that it completely overlaps with the anatomical structure of the background image. The matching of the vertebral body position with different movements in 2D-3D can be completed. The lumbar movement state under physiological conditions in sitting position can be restored in different postures (neutral position, flexion position, extension position, left bending, right bending, left rotation, right rotation) (Fig. 4).

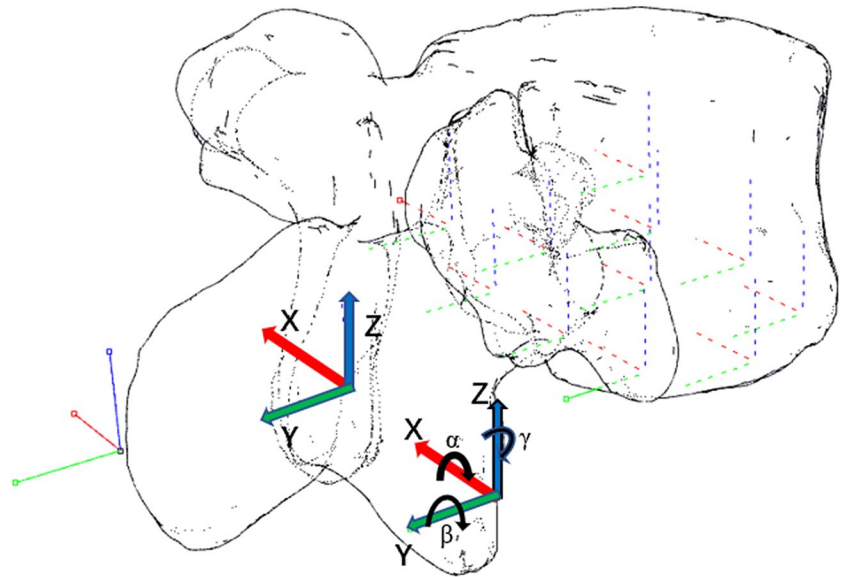
Establish coordinate system

The Cartesian coordinate system was established at the midpoint of the inferior articular process of the cephalic vertebral body and the midpoint of the articular process on the caudal vertebral body, which were X, Y and Z-axes, respectively. The X-axis (red) was defined as the horizontal line pointing to the left on the coronal plane, the Y-axis (green) as the horizontal line pointing back on the sagittal plane, and the Z-axis (blue) as the vertical line pointing to the head end on the sagittal plane. The movement of each point in the X-axis is left and right (x), in Y-axis is forward and backward (y), and in Z-axis is up and down (z). Define the clockwise rotation angle around the X-axis as α , the clockwise rotation angle around the Y-axis as β , and the clockwise rotation angle around the Z-axis as γ . It is recorded as a positive number in the same direction as the arrow and a negative number in the opposite direction of the arrow mark (Fig. 5).

Measurement of 3D lumbar model data

Through the changes in the relative position of lumbar facet joints, the position change data of their corresponding

Fig. 5 The coordinates are established in the articular process, spinous process and other positions



movements were obtained, that is, the position comparison of superior facet joint and inferior facet joint. The movement characteristics of the sitting facet joints under physiological conditions were studied by comparing the data of the subjects' flexion–extension, left bending–right bending, and left rotation–right rotation.

Data statistics and analysis

All collected data were analyzed using SPSS 26.0 (IBM, Armonk, NY, USA). The data were expressed as mean \pm standard deviation, one-way analysis of variance was used for comparison, and LSD test was used for pairwise comparison; test level $\alpha = 0.05$.

Results

By applying DFIS combined with the method of CT, we measured the motion of the lumbar facet joints while the subjects were seated.

ROM of lumbar facet joint flexion and extension

When the lumbar vertebra was flexion–extension, the translation from rostral to caudal increased gradually in the X-axis, while the translation decreased gradually in the Z-axis, and the difference in the Z-axis translation distance was statistically significant. At the same time, the flexion and extension activity angle, that is, the α angle, decreased continuously, while the lateral rotation activity, that is, the β angle, increased continuously, and both of these angles were statistically significant (Table 1).

ROM of lumbar facet joint left-bending and right-bending

When the lumbar spine was in left and right bending, the translation of L5-S1 was the largest and L4-5 was the smallest in the X-axis, and the difference was not significant. In the Y and Z-axes, the translation distance was inconsistent, and in the α and γ angles, there was no significant difference in rotation, while in the β angle, the rotation of L4-5 was the largest and the rotation of L5-S1 was the smallest, and the difference was significant (Table 2).

Table 1 Displacement and rotation angle of lumbar facet joints in flexion and extension

Segment	Left (mm)			Right (mm)			Angle ($^{\circ}$)		
	X	Y	Z	X	Y	Z	α	β	γ
L3-L4	0.00 \pm 1.01	-0.29 \pm 1.14	-4.65 \pm 1.99	-0.12 \pm 0.97	0.19 \pm 1.12	-3.20 \pm 2.61	-6.00 \pm 4.49	2.30 \pm 2.94	0.74 \pm 1.57
L4-L5	0.45 \pm 0.67	-0.41 \pm 1.02	-1.89 \pm 2.99	0.77 \pm 0.97	0.15 \pm 1.60	-1.71 \pm 3.00	-3.51 \pm 5.24	0.16 \pm 2.06	-0.94 \pm 2.82
L5-S1	1.43 \pm 2.79	-1.55 \pm 4.18	0.80 \pm 2.27	1.40 \pm 2.79	-0.51 \pm 3.37	0.31 \pm 1.69	0.97 \pm 4.13	-0.35 \pm 1.74	-1.12 \pm 2.83
P	0.197	0.489	<0.001	0.186	0.739	0.014	0.008	0.037	0.199

Table 2 Displacement and rotation angle of lumbar facet joints in left bending and right bending

Segment	Left (mm)			Right (mm)			Angle (°)		
	X	Y	Z	X	Y	Z	α	β	γ
L3-L4	1.68±0.85	-0.78±1.10	-1.34±2.84	1.45±0.88	0.52±0.47	0.49±2.07	-1.41±3.55	5.66±2.70	-2.56±2.05
L4-L5	0.91±1.39	-0.35±1.77	-2.11±0.88	0.62±1.14	0.53±0.87	1.61±1.00	-0.39±1.52	7.89±2.59	-0.84±3.65
L5-S1	2.19±2.28	-1.07±0.79	0.72±0.81	2.35±2.37	-0.86±2.88	1.53±0.57	0.60±2.95	1.28±2.07	0.03±2.02
P	0.221	0.456	0.004	0.070	0.144	0.141	0.292	<0.001	0.110

ROM of lumbar facet joint left-rotation and right-rotation

When the lumbar spine was left rotation and right rotation, the translation of L5/S1 on the X-axis was the largest, and the L4-L5 was the smallest, and the difference was not significant. In the Y and Z-axes, the translation distance was inconsistent. In the α and γ angles, the rotation was not significantly different. In the β angle, the rotation of L3-4 was the largest, and the rotation of L5-S1 was the smallest, and the difference was significant (Table 3).

Discussion

This study measured the displacement and rotation angle of the lumbar facet joints in a normal population during different movements while sitting. Overall, the results indicate that the range of motion of lumbar depends on different positions and lumbar segments. The study showed that the range of motion of lumbar facet joints was large. For example, during flexion and extension, the craniocaudal translation could reach 4.65 mm, while the rotation could reach 6.0°; during left-bending and right-bending, the translation could reach 2.35 mm, and the rotation could reach 7.89°; during rotation movements, the translation could reach 2.42 mm, and the rotation could reach 4.09°.

Pearcy studied the movement of the lumbar spine during maximal flexion–extension using biplane photographic techniques, in which the pelvis and buttocks restrict movement using a frame. Their study showed that the range of motion of all lumbar segments was similar [10]. Li et al. [6] found that the flexion and extension range of the upper

lumbar spine was relatively greater than that of the lower lumbar spine when the body did flexion and extension movements. In our study, when the lumbar spine was subjected to flexion–extension activities, there was not only a craniocaudal translational motion but also a concomitant rotation. At L3-4, the displacement of Z-axis and rotation in α and β directions are the largest, while L5-S1 angle is the smallest (except β angle). This shows that the ROM of the cranial facet joint is greater than that of the caudal facet joint during flexion and extension. Displacement is primarily translated at the cephalocaudal end, while the rotation angle of the cranial facet joint is also significantly increased compared with the caudal facet joint. We believe that the phenomenon is related to the direction of the articular surface. The direction of the lumbar facet joint at the cranial end tends to be more sagittal than that at the caudal end, and this structure may increase the displacement at the craniocaudal side and reduce the rotation angle. Compare to the study by Li et al. [6], our study indicated a large lumbar range of motion of the lumbar spine in the sitting position. This result may be due to the younger age of our subjects, while the older age of the subjects of Li et al. [6]. On the other hand, Li et al. [6] mainly studied the changes of facet joints in standing position, while our study was in sitting position. The pelvis is fixed in a sitting position, resulting in increased range of motion of the lumbar facet joints.

In review of previous studies, there are a few reports on the mode of motion of the lumbar facet joints during left and right bending. Kozanek found in his study that the movement of facet joints was found to be a coupling of rotation and translation in different directions during left and right bending movements [5]. Similar findings exist in our study, when the lumbar spine performs the activity of the

Table 3 Displacement and rotation angle of lumbar facet joints in left rotation and right rotation

Segment	Left (mm)			Right (mm)			Angle (°)		
	X	Y	Z	X	Y	Z	α	β	γ
L3-L4	0.14±1.77	-1.20±1.95	0.93±3.79	-0.10±1.82	0.67±1.31	0.70±2.10	1.04±1.95	4.09±2.86	-0.97±3.12
L4-L5	-0.01±0.80	-0.90±1.76	-1.79±1.83	0.04±0.79	0.68±0.91	0.25±0.98	0.93±1.76	2.14±3.38	-0.96±3.39
L5-S1	1.35±2.27	-2.42±1.16	-0.43±3.30	0.76±2.19	-0.04±2.55	0.57±2.01	-1.17±5.08	0.63±1.85	-3.91±2.95
P	0.174	0.113	0.163	0.486	0.574	0.840	0.278	0.032	0.073

left bending–right bending, it is a compound movement performed by translation and rotation. Interestingly, during left and right bending, facet joint rotation changes were dominated by rotation in the β angle. Rotation was most variable at L4–5, centered at L3–4, and least at L5–S1, indicating that displacement and rotation at L4–5 were predominant during bending movements, while movement at L5–S1 was likely due to sacral restriction with minimal rotational displacement during motion.

There are some studies that have measured the movement of left and right rotations [10, 11]. Percy and Tilbrenal [11] studied similar rotation movements while standing and showed a range of axial rotation of about 2°. Our study showed that when the lumbar spine performed the activity of left rotation–right rotation, the rotation was mainly concentrated in the left and right sides. Rotation was most variable at L3–4, intermediate at L4–5, and least at L5–S1. This indicated variation in the cranial segment is greater than the caudal segment during rotational motion. In our study, the maximum rotation angle was around 4°, which was greater than the study by Percy and Tilbrenal. This may be caused by different postures. In the sitting position, the pelvis is immobilized, causing the upper vertebral bodies to compensate and allow for greater range of motion.

In our study, left–right asymmetrical motor features were shown. Some previous studies have found a similar phenomenon [2, 9, 17–19]. For example, in our study, the *Y*-axis movement distance on the left and right sides was asymmetric on the left and right sides during flexion and extension. We believe that the reasons for this result may exist in the following aspects: (1) The articular surface of the articular facet is left and right asymmetrical, causing the left and right sides to move up and down not exactly the same; (2) The joint capsule and surrounding muscles and ligaments restrict movement in the scoliosis direction; (3) Neuromodulation causes changes in associated movement patterns.

By measuring the displacement and rotation of lumbar facet joints in different movements, we reveal the motion characteristics of lumbar facet joints in flexion and extension, bending and rotation. The measurement results can be used as a baseline and compared with the lumbar facet joints under pathological conditions. At the same time, it can also provide a relevant basis for the preparation of implants such as artificial intervertebral disc and artificial prosthesis.

Our reasons have some shortcomings: (1) The sample size is small: it takes a lot of time to collect the sample size and match the data, so we only selected 10 subjects for the test, although this is similar to most similar studies, but more samples can indeed reduce the error. We will further increase the sample size in future studies; (2) The age of the subjects is low: because the study needs to be measured and observed under the normal lumbar model, and the elderly patients often have lumbar degeneration, the recruited

subjects are generally young, which will cause some errors to the data. In future studies, we can improve the measurement of middle-aged and elderly healthy people. (3) Due to the visual field limitation of the mobile X-ray machine, our study only measured the facet joints of the L3–S1, but not the rest of the lumbar facet joints. In the follow-up study, we plan to further measure the motion characteristics of the facet joints of the upper lumbar vertebrae.

Although there are various shortcomings, our study reveals the motion characteristics of lumbar facet joints in sitting position. In the flexion and extension of the lumbar spine, the facet joint is mainly vertical displacement, accompanied by rotation in different directions, while in bending and rotation, the lumbar facet joint is mainly coupled motion, which composed by different rotations. This study provides data on the motion of lumbar facet joints in vivo in sitting position. From these data, we can further study the movement changes under the pathological condition of the spine, so as to improve the diagnosis and treatment of related diseases.

Conclusions

In the flexion and extension of the lumbar spine, the facet joint is mainly vertical displacement, accompanied by rotation in different directions, while in bending and rotation, the lumbar facet joint is mainly coupled motion, which composed by different rotations. Left–right facet joint asymmetrical motor features were shown at the same.

Author contributions JM contributed to data collection. YH studied the design. XW and SS wrote the manuscript. JW, XX and KL analyzed the data. All authors read and approved the final manuscript.

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Data availability The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethical approval The study had been approved by the ethical committee of Tianjin Hospital. All clinical investigations had been conducted according to the principles expressed in the Declaration of Helsinki.

Consent to participate All the subjects had informed consent.

Consent to publish Not applicable.

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