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Sagittal Plane Rotation Center of Lower Lumbar Spine during a Dynamic Weight-lifting Activity

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ABSTRACT (239 words)

This study investigated the center of rotation (COR) of the intervertebral segments of the lower lumbar spine (L4-L5 and L5-S1 segments) in sagittal plane during a weight-lifting (3.6 kg in each hand) extension activity performed with the pelvis constrained. Seven healthy subjects were studied using a dual fluoroscopic imaging technique. Using the non-weightbearing, supine position during MRI scan as a reference, the average intervertebral flexion angles of the L4-L5 and L5-S1 were 6.6º and 5.3º at flexion position of the body, respectively, and were -1.8º and -3.5º at extension position of the body, respectively. The CORs of the lower lumbar spine were found segment-dependent and changed with the body postures. The CORs of the L4-L5 segment were at the location about 75% posterior from the anterior edge of the disc at flexion positions of the body, and moved to about 92% of the posterior portion of the disc at extension positions of the body. The CORs of the L5-S1 segment were at 95% posterior portion of the disc at flexion positions of the body, and moved outside of the posterior edge of the disc by about 12% of the disc length at extension positions of the body. These results could help understand the physiological motion characters of the lower lumbar spine. The data could also provide important insights for future improvement of artificial disc designs and surgical implantation of the discs that are aimed to reproduce normal spinal functions.

Keywords: lower lumbar spine; intervertebral disc; center of rotation; kinematics; fluoroscope.

INTRODUCTION

Human daily exercise is composed of a series of intervertebral segment motion. Centers of rotation (CORs) of the intervertebral segments are critically important for determination of the kinematic features of the lumbar spine (Gertzbein et al., 1984; Haher et al., 1992; Haughton et al., 2002; Pearcy and Bogduk, 1988; Xia et al., 2010). For example, the selection of CORs is a critical step for application of compressive loads in in-vitro human spine biomechanics experiments as well as for applying various loading conditions in finite element modeling of spinal biomechanics (Crisco et al., 1992; Patwardhan et al., 1999; Patwardhan et al., 2001). The COR is also important for development of total disc replacement and surgical positioning of the devices in patients in order to reproduce physiological motions of the diseased segment (Cunningham et al., 2003; Rousseau et al., 2006a).

A literature review indicated that many studies have investigated the CORs of human spine under various conditions (Gertzbein et al., 1984; Haher et al., 1992; Ogston et al., 1986; Pearcy and Bogduk, 1988; Rousseau et al., 2006a; Rousseau et al., 2006b; Schmidt et al., 2008; Xia et al., 2010; Yoshioka et al., 1990). X-ray and fluoroscopic imaging techniques were used to determine the quasi-static intervertebral CORs at selected postures of living subjects (Bifulco et al., 2012; Ogston et al., 1986; Pearcy and Bogduk, 1988; Xia et al., 2010; Yoshioka et al., 1990). For example, Xia et al. (2010) investigated the overall CORs of the lumbar intervertebral segments during a quasi-static flexion-extension and left-right twisting of healthy subjects. Bifulco et al. (2012) utilized 2D single sagittal fluoroscopic image sequences of 3 healthy subjects lying on a motorized table undergoing passive lumbar motion to study L2-L3 instantaneous center of rotation (ICR). Many in vitro experiments and finite element analysis have studied intervertebral CORs under simulated loading conditions (Gertzbein et al., 1984;

Haher et al., 1992; Rousseau et al., 2006a; Rousseau et al., 2006b; Schmidt et al., 2008). In in-vitro experiments of human spine biomechanics and finite element modeling of human spine behavior, the follower load concept has been widely adopted to overcome the difficulties caused by the complex lordosis of the lumbar spine (Patwardhan et al., 2003; Patwardhan et al., 2001; Rohlmann et al., 2001; Stanley et al., 2004). The follower load concept was introduced to describe the spinal loading path along the spine lordosis and was thought to approximately passing through the centers of rotation of the lumbar segments (Patwardhan et al., 1999). In addition, various optimization criteria have been used to define optimal follower load paths (Dreischarf et al., 2010; Kim et al., 2010, 2011). Park et al. (2012) reported changing locations of the CORs under different loading conditions using a global convergent optimization method. No study, however, has been reported to investigate the in-vivo CORs of the spine during dynamic functional activities.

Recently, we used a combined dual fluoroscopic imaging system (DFIS) and the MR imaging technique (Wang et al., 2009) to investigate the dynamic flexion-extension motion of intervertebral segments of the lumbar spine, and observed different motion patterns among the lumbar intervertebral segments (Wu et al., 2014). The purpose of this study is to investigate the intervertebral segment CORs of the lower lumbar spine (L4-L5 and L5-S1 segments) in sagittal plane during a weight-lifting flexion-extension activity using the DFIS technique. We hypothesized that the intervertebral segment CORs of the lumbar spine are segmental level dependent.

MATERIALS & METHODS

Ten asymptomatic subjects (5 males and 5 females, aged between 40 and 60 years) without history of low back pain and anatomic abnormalities were recruited for this study with IRB approval. A signed consent form was obtained from each subject before testing. Exclusion criteria included: current or prior back pain, anatomic abnormalities, or any spinal disorders. Three subjects were excluded from further investigation using the exclusion criteria in this research. There are 14 lumbar intervertebral segments (L4-L5 and L5-S1 of the seven subjects).

2.1 3D vertebral models

All subjects were MRI scanned in supine positions using a 3 Tesla scanner (MAGNETOM Trio, Siemens, Germany) with a spine surface coil and a T2 weighted fat suppressed 3D SPGR sequence. Parallel digital images of the lumbar spine with a thickness of 1.0 mm, no gap, and a resolution of 512 x 512 pixels were obtained. Three-dimensional models of the L4-S1 vertebrae were constructed using the 3D MRI images in solid modeling software (Rhinoceros®, Robert McNeel & Associates, Seattle, WA) (Wu et al., 2014).

2.2 In-vivo lumbar spine kinematics

The lumbar spine of each subject during a dynamic weight-lifting activity (with a 3.63 kg dumbbell in each hand) was imaged using a dual fluoroscopic imaging system (DFIS) (Wu et al., 2014). The subject performed the activity by extending the body from a flexion position (~45°) to the maximal extension position (**Fig. 1**). The pelvis of each subject was constrained during the test to standardize the activity (Wu et al., 2014). During experiment, the two fluoroscopes (BV Pulsera, Phillips, Bothell, WA) with their image intensifiers positioned perpendicular to each other were used to simultaneously capture orthogonal images of the spine segments (**Fig. 1a**) at 30 frames per second with an 8 micro-second pulse. The images had a resolution of 1024 × 1024 pixels with a pixel size of 0.3×0.3 mm^2. Each subject was exposed to about 2 second of fluoroscopic projections during the weight-lifting motion. The effective dose for the dual fluoroscopy procedure of the lumber spine is estimated to be 0.1248 mSv per subject, which is about 4% of the annual background radiation.

Five pairs of fluoroscopic images of each subject were evenly chosen from the flexion position (~45°) to the maximal extension position motion path, representing 0%, 25%, 50%, 75% and 100% of the extension path. The selected fluoroscopic images and the 3D vertebral models of each subject were input into the Rhinoceros software to create a virtual DFIS. Each 3D vertebral model was independently translated and rotated in the virtual DFIS until its projections match the osseous outlines captured on the two fluoroscopic images (Wu et al., 2014). The vertebral positions along the extension path were then represented by a series of vertebral models (**Fig. 1b**). Using similar error analysis method of Panjabi et al (1992), the overall precision of this technique has been estimated to be 0.3 mm in translation and 0.7° in orientation for determination of the vertebral positions in space in a previous study (Wang et al., 2008).

2.3 COR calculation

To calculate the kinematics of each intervertebral segment (L4-L5 and L5-S1), the origins of the coordinate systems were placed at the geometric centers of the lower and upper endplate surfaces of the two vertebrae of the segment, respectively. The x–y plane was parallel to the endplate surface. The x-axis was defined in the left and the y-axis posterior directions of the body. The z-axis was obtained as perpendicular to the x–y plane and in the proximal direction. The AP (anterior-posterior) length of the discs was measured as the distance between the anterior and posterior edges in the middle sagittal plane (y-z plane).

The coordinate system of the upper endplate surface of the lower vertebra was used as a reference for calculation of the relative motion of the upper vertebra. Therefore, the intervertebral segment motion was calculated as the position and orientation of the upper vertebral coordinate system in the lower vertebral coordinate system. The proximal-distal, anterior-posterior translations and sagittal plane flexion-extension angles of each intervertebral segment during the extension activity were analyzed. The intervertebral position captured in supine posture during the non-weightbearing MR scanning was used as a reference to measure the intervertebral motion (Wang et al., 2008; Wu et al., 2014).

To determine the intervertebral segment CORs, the AP axis of the upper vertebra was projected onto the middle sagittal plane of the lower vertebra of the segment. The cross point of the projection lines of two adjacent postures was defined as the center of rotation of the intervertebral segment (Dennis et al., 2005; Feng et al., 2015; Johal et al., 2005; Komistek et al., 2003; Moro-oka et al., 2008) (**Fig.2a**). The CORs of the intervertebral segments were thus determined along the extension motion path of the lifting activity. For each intervertebral segment, the average of all CORs along the motion path was also calculated. To quantitatively analyze the data of all subjects, the positions of the CORs were normalized using the dimension of the disc in anterior-posterior direction.

RESULTS

The anterior-posterior (AP) dimension of the L4-L5 disc was 34.4±1.5 mm and of the L5-S1 disc was 31.8±2.3 mm (**Fig. 2b**). The disc length of the L5-S1 was found to be significantly shorter than that of the L4-L5 segment ($p<0.05$).

The intervertebral segment L4-L5 experienced distal translation during the extension activity (**Fig. 3a**). The segment was at -2.1±0.7 mm at flexion position of the body and changed to -0.3±0.7 mm at maximal extension position of the body. The L5-S1 experienced a distal translation of -1.6±1.3 mm at flexion position of the body, but changed to a proximal position of 1.2±1.5 mm at maximal extension of the body. The flexion angles of the L4-L5 and L5-S1 were 6.6º±4.5º and 5.3º±1.6º at the flexion position of the body, respectively (**Fig. 3b**). The flexion angles changed to -3.5º±2.4º for L5-S1 and to -1.8º±2.0º for L4-L5 at extension position of the body. The L4-L5 experienced an anterior translation of 1.7±1.1 mm at flexion position of the body, but changed to a posterior position of -0.6±0.7 mm at maximal extension of the body (**Fig. 3c**). However the L5-S1 experienced anterior translation during the extension activity.

For both segments, the CORs were at posterior half of the discs and consistently moved posteriorly with extension of the body. At the first flexion position, the COR of L4-L5 was at 25.6±4.5mm posterior to the anterior edge of the disc (73.4±12.5% of the disc length, COR-1/2 in **Table 1**), and moved posteriorly to 26.5±19.9mm at middle flexion position (77.7±57.2% of the disc length, COR-2/3 in **Table 1**). At upright position and extension positions, the COR moved to 29.2±24.5mm (84.4±70.3% of the disc length, COR-3/4 in **Table 1**) and 31.1±5.9mm (92.4±23.3% of the disc length, COR-4/5 in **Table 1**), respectively. The overall average COR of the L4-L5 was at 28.1±16.7mm from the anterior edge of the disc (82.0% of the disc length).

For the L5-S1 segment, the COR also moved consistently towards posterior direction with the body extension. At the flexion position, the COR was at 30.1±5.9mm posterior to the anterior edge of the disc (94.3±22.2% of the disc length) and moved to 30.1±8.4mm (95.5±24.5% of the disc length) at middle flexion position. At extension position, the COR moved posteriorly to 35.1±3.1 mm (113.8±16.6% of the disc length) from the anterior edge. The overall average COR of the L5-S1 was at 32.6±10.3mm from the anterior edges of the disc (103.8% of the disc lengths).

The CORs of the two segment levels at the same selected body positions were compared using the percentile along the lengths of their corresponding discs. The CORs of the L5-S1 were significantly more posterior than the L4-L5 at each of the selected spinal positions.

DISCUSSION

This study investigated the CORs of the lower lumbar segments L4-L5 and L5-S1 during a dynamic weight-lifting extension motion of the body. The CORs were found to move posteriorly with the extension of the body. Distinct segmental differences were observed between the two segments. The L4-L5 had CORs at ~75% posterior portion of the disc at the beginning of the activity, and the COR moved posteriorly with body extension to ~92% at hyperextension of the body. For the L5-S1 segment, the COR was found at ~95% posterior portion of the disc at the beginning of the extension activity and moved outside of the posterior edge of disc by over 10% of the disc length beyond upright extension of the body.

Many studies have investigated the CORs of the lumbar segments (Gertzbein et al., 1984; Patwardhan et al., 2003; Patwardhan et al., 1999; Rousseau et al., 2006a; Rousseau et al., 2006b; Stanley et al., 2004; Xia et al., 2010; Yoshioka et al., 1990). Gertzbein et al. (1984) found that the average location of the L4-L5 flexion–extension CORs was 11.6 mm from the posterior edge of the vertebral body in an in-vitro study of 10 cadaveric specimens. Rousseau et al. found that the CORs of L5-S1 were 6.8 to 12.3mm (Rousseau et al., 2006b) and 5.7 to 10.6 mm (Rousseau et al., 2006a) posterior to the center of the vertebral body from the experiments of 12 healthy specimens. While in this study, the COR of L5-S1 was 16.67 to 22.12 mm posterior to the center of the L5-S1 disc, even outside of the posterior disc edge by 2.59±2.33 mm (**Fig.2**). In a study of

61 healthy cases of L1–L5 lumbar segment using 2D X-ray images, Yoshioka et al. (1990) found that the flexion–extension CORs were 2.6 to 5.9 mm posterior to the vertebral centers while our study showed a COR of 11.59±4.23 mm posterior to the vertebral center of the L4-L5 segment. Xia et al. (2010) reported that the static flexion-extension CORs (during static 45° flexion, maximal extension) were located at about 5 mm posterior to the center of the vertebral body for L23 and L34 segments.

In general, these studies indicated that the CORs were posterior to the centers of the discs in sagittal plane during flexion and extension motion of the body, and these data were consistent with the results of this study. However, our study indicated more posterior locations of the CORs, and the L4-L5 and L5-S1 segments had different COR motion characters during the extension activity of the body. However, a quantitative comparison between these studies could be difficult due to the differences in body activities (loading conditions) or segmental levels.

The distinct COR characteristics of the L4-L5 and L5-S1 segments reveal distinct spinal motion characters of different spinal segments (Wu et al., 2014) and may have interesting clinical relevance. In contemporary surgical treatment of severe degenerative disc diseases, such as spondylolisthesis and disc herniation, fusion and total disc replacement are similarly used to treat different segments (Freeman and Davenport, 2006; Herkowitz, 2006; McAfee et al., 2005; Rohan et al., 2009; Sim et al., 2015). However, patient follow-up studies reported different clinical outcomes when fusion or total disc replacement was used to treat disc diseases at L4-L5 or L5-S1 segments (Dewing et al., 2008; Okoro and Sell, 2010; Siepe et al., 2007; Sinigaglia et al., 2009). For example, Siepe et al. (2007) reported improved clinical outcomes in patients following monosegmental L4-L5 total lumbar disc replacement when compared to patients with L5-S1 disc replacements. Based on the COR data of this paper, positions of the lumbar disc replacement could be closer to the COR at L4-L5 segment than at L5-S1 segment. In fact, the clinical outcomes of total disc replacement were found to be affected by the implanted location of the artificial discs (McAfee et al., 2005). They indicated that ideal surgical placement of the artificial disc prosthesis correlates with improved clinical outcomes and improved flexion/extension range of motion, compared to poor surgical placement of the prosthesis. Therefore, the design and the implantation of artificial discs in total disc placement may need to consider the distinct characters of CORs of different lumbar segments.

There are certain limitations that should be noted in this study. The sample size in this study is relatively small. In addition, only subjects between 40–60 years were recruited due to the high occurrence of DDD in this age segment. It is difficult to study the age and gender effects on lumbar CORs using this sample size. Future studies should recruit more subjects to increase the sample size and with a wider range of ages. Only weight-lifting extension activity with one lifting weight was investigated. The COR could be activity or loading dependent (Kim et al., 2011; Park et al., 2012; Patwardhan et al., 1999; Rohlmann et al., 2001; Xia et al., 2010). Other daily activities, such as coupled with lateral bending and twisting of the body, and different lifting weights should be investigated in future studies. Finally and in contrast to the conditions in regular free lifting, we limited pelvic motion during the experiment to reduce variation among subjects. Future research should take into account the coupled lumbar–pelvic motion.

In conclusion, the CORs in the sagittal plane of the lower lumbar segments, L4/5 and L5-S1, were investigated during a dynamic weight-lifting extension activity using a combined DFIS and MR imaging technique. The CORs of the lower lumbar spine were found segment-dependent and changed with the body postures. While the CORs of the L4-L5 were at 75% to 92% of the posterior portion of the disc, those of the L5-S1 moved outside of the posterior edge of the disc.

These results may help understand physiological lumbar motion characters and imply future improvement of artificial disc designs and surgical implantation of total disc replacement. Future study also needs to focus on investigation of symptomatic subjects before and after surgeries during physiologically dynamic activities.

DECLARATIONS

Competing interests: None declared

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Ethical approval: Research protocol has been reviewed and approved by Massachusetts General Hospital IRB.

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FIGURE CAPTIONS

Figure 1. (a) Experimental setup of the dual fluoroscopic imaging system (DFIS) during the weight-lifting extension activity with the pelvis motion limited by a custom-made frame. (b) the lumbar vertebra models at different positions along the dynamic weight-lifting motion path, from ~45° flexion position (light-colored) to the maximal extension position (dark-colored) of the body.

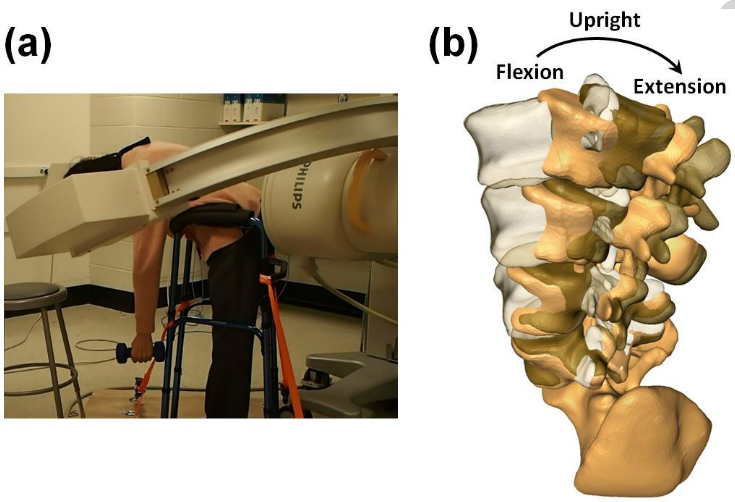
Figure 2. (a) The CORs of the L4-L5 and L5-S1 segments along the dynamic weight-lifting extension motion path. (b) The anatomy of the L4-L5 and L5-S1 segments, showing their disc lengths and the average CORs.

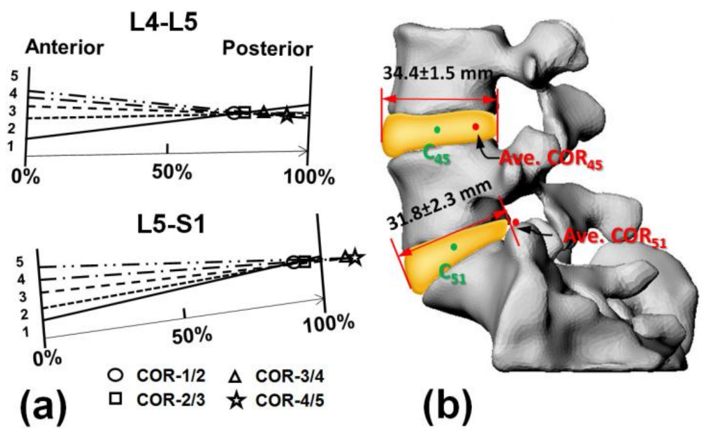
Figure 3. (a) The proximal (+)-distal (-) translation, (b) intervertebral flexion (+)-extension (-) angles of the L4-L5 and L5-S1 segments during the extension activity of the body, and (c) the anterior (+)-posterior (-) translation.

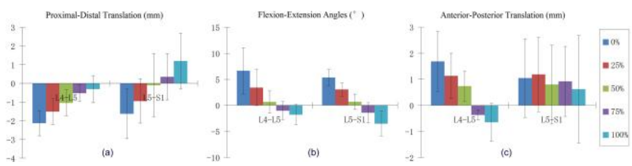
TABLES

Table 1. Locations of the CORs measured from the anterior edge of the discs and the corresponding intervertebral flexion angles at different body positions along the extension path. *: L4-L5 different from L5-S1; #: COR-4/5 different from COR-1/2 ($p<0.05$).

Body Position	Intervertebral Angle (º)		Center of Rotation (mm)	
	L4-L5	L5-S1	L4-L5	L5-S1
1/2	-3.2±2.6	-2.3±0.6	25.6±4.5 #	30.1±5.9 #
2/3	-2.8±1.6	-2.4±1.0	26.5±19.9	30.1±8.4
3/4	-1.6±1.0	-2.1±1.3	29.2±24.5	35.1±17.0
4/5	-0.8±0.6	-2.1±1.1	31.1±5.9 *#	35.1±3.1 *#
Ave.			28.1±16.7 *	32.6±10.3 *




L4-L5
Anterior
Posterior
0%
50%
100%
L5-S1
0%
50%
100%
COR-1/2
COR-2/3
COR-3/4
COR-4/5
(a)
34.4±1.5 mm
Ave. COR45
31.8±2.3 mm
Ave. COR51
(b)


Proximal-Distal Translation (mm)
Flexion-Extension Angles (°)
Anterior-Posterior Translation (mm)
L4-L5
L5-S1
(a)
(b)
(c)
0%
25%
50%
75%
100%