In-vivo motion characteristics of lumbar vertebrae in sagittal and transverse planes

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Abstract

Lumbar vertebrae are complicated in structure and function. The purpose of this study was to investigate the in-vivo motion characteristics of different portions of the lumbar vertebrae during functional activities. Motion of L2, L3 and L4 was reproduced using a combined dual fluoroscopic and MR imaging technique during flexion–extension and left–right twisting of the trunk. The ranges of motion (ROM) of the proximal vertebra with respect to the distal one at 3 representative locations: the center of the vertebral body, the center of the spinal canal and the tip of the spinous process were measured. Centers of rotation (COR) of the vertebrae were then determined by calculation of the points of zero motion in 2D sagittal and transverse planes. During flexion–extension, the center of the vertebral body moved less than 0.6 mm, while the tip of the spinous process moved less than 7.5 mm in the sagittal plane. The CORs of both L23 (L2 with respect to L3) and L34 were located inside the vertebral body, at a distance about one-third the length of the vertebral body from the posterior edge. During left–right twisting, the center of the vertebral body moved less than 1.0 mm, while the tip of the spinous process moved less than 1.6 mm in the transverse plane. The CORs of both L23 and L34 were located approximately 30 mm anterior to the front edge of the vertebral body. The results of this study may be used to define the ideal locations for surgical placement of the disc prosthesis, thus help improve the prosthesis design and surgical treatment of various pathological conditions.

1. Introduction

Knowledge of motion patterns of lumbar vertebrae is important for motion preserving treatment of intervertebral disc diseases such as dynamic fusion or total disc replacement. Numerous studies have reported on the vertebral rotation under various simulated loading conditions (Kettler et al., 2004; SariAli et al., 2006; Wilke et al., 2001; Wong et al., 2006). Furthermore, many in-vitro investigations have measured intervertebral center of rotation (COR) using cadaveric spine specimens (Gertzbein et al., 1984; Hafer et al., 1992; Mansour et al., 2004; Rousseau et al., 2006a,b; White and Panjabi, 1990) or finite element (FE) analysis (Schmidt et al., 2008; Shirazi-Adl et al., 1986a,b; Shirazi-Adl et al., 1986a,b) under applied torques to simulate flexion–extension or left–right twisting. For example, flexion–extension COR in sagittal plane has been determined using cadaveric specimens by Gertzbein et al. (1984), Hafer et al. (1992) and White and Panjabi (1990), Shirazi-Adl et al. (1986a,b) and Schmidt et al. (2008) used FE models to analyze the center of rotation under various applied moments during flexion–extension and left–right twisting.

In-vivo studies have mostly employed X-ray images to determine the vertebral COR in sagittal planes (Cunningham et al., 2003; Ogston et al., 1986; Pearsy and Bogduk, 1988; Sakamaki et al., 2002; Yoshioka et al., 1990). Recently, CT, MRI and dual plane fluoroscopic imaging techniques have been used to investigate 3D motions of the vertebral body (Fujii et al., 2007; Haughton et al., 2002; Lee et al., 2002; Ochia et al., 2006). While these studies have reported 6DOF vertebral motion in terms of translation and rotation, no data has been reported on the CORs of the vertebrae in living human subjects under functional weightbearing conditions. This knowledge is especially important since prosthesis design and surgical implantation with different CORs can alter the motion characteristics, thereby directly affecting clinical outcomes (McAfee et al., 2005; Rousseau et al., 2006a,b).

Recently, we have applied the combined dual fluoroscopic imaging system (DFIS) and MR imaging technique to investigate the 6DOF motion of lumbar vertebral bodies during various functional weightbearing activities (Li et al., 2009; Wang et al.,...
In this paper, we have further investigated the motion characteristics of different portions of the vertebrae (i.e., vertebral body, spinal canal and spinous process) and the CORs in 2D sagittal and transverse planes in normal human subjects.

2. Method

Ten healthy subjects with an age ranging from 40–60 years (4 males and 6 females, average weight 65 ± 13 kg, average height 164 ± 8 cm) were recruited for this study. The experimental protocol was approved by the Institutional Review Board. Signed consent form was obtained from each subject. The subjects were evaluated for lower back pain and other spinal disorders by a spine surgeon. Pfirrmann grades (Pfirrmann et al., 2001) were also determined by a radiologist to ensure disc degeneration scores were less than or equal to 2 at all vertebral levels.

2.1. 3D model reconstruction

The lumbar segments of each subject underwent an MRI scan using a 3 Tesla scanner (MAGNETOM Trio, Siemens, Germany) with a spine surface coil and a T2 weighted fat suppressed 3D SPGR sequence (Disler et al., 1994). Subjects refrained from participating in weight-carrying activities for 4 h and rested for approximately 30 min in a supine position prior to scanning. Parallel sagittal images with a field of view of 18 × 23 cm² and a thickness of 1.5 mm without gap (voxel size 0.45 × 0.45 × 1.5 mm³) were obtained.

The MR images of the spinal segments were then imported into a solid modeling software (Rhinoceros, Robert McNeel & Associates, Seattle, WA) for construction of 3D anatomical vertebral models of the L2, L3 and L4 of the lumbar spine (Li et al., 2009). The contours of each vertebral segment were digitized manually using B-Spline curves. Polygon mesh models of the vertebrae were then created from the contour lines (Fig. 1).

2.1.1. Coordinate system of the vertebral body:

For each vertebra, the cylindrical volume of the vertebral body was obtained from the mesh model. The origin of the coordinate system was at the volumetric center calculated using the Rhinoceros software (Fig. 1). The x-y plane was parallel to a plane that fitted through the mesh vertices of the endplate. The y-axis was set along the spinous process, pointing in the posterior direction. The x-axis was set perpendicular to the y-axis, pointing in the left direction. The z-axis was set perpendicular to the x-y plane. The transverse plane was chosen to be the x-y plane of the proximal vertebra of the two vertebrae to study the relative motions of the vertebrae (e.g., L2 for L23, L3 for L34). The sagittal plane was chosen to be the y-z plane of the distal vertebra.

2.1.2. Coordinate system of the spinal canal:

The volumetric center of the cylindrical volume of the canal was defined as the origin of the spine canal (Fig. 1). The directions of the three axes were consistent with those of the vertebral body.

2.1.3. Coordinate system of the spinous process:

The origin of the coordinate system of a spinous process was chosen as the intersection point of the transverse plane of the vertebral body, the tip of the spinous process, and the line connecting the centers of the vertebral body and the spinal canal (Fig. 1). The directions of the three axes were consistent with those of the vertebral body.

2.2. Determination of lumbar spine position

The lumbar positions in space of each subject were captured using the DFIS (Wang et al., 2008). In this system, two fluoroscopes (BV Pulsera, Philips, Bothell, WA) are positioned with their image intensifiers perpendicular to each other (Fig. 2a). The subject was protected from radiation exposure using custom built lead shields. The subjects positioned their lumbar spines inside the common view zone of the two fluoroscopes (–30 × 30 × 30 cm³) and actively moved to different postures under the guidance of a spine surgeon to minimize the effect of hip motion while focusing only on lumbar spine. The studied postures were 45° flexion and maximal extension, maximal left and right twisting. As observed in this study, the maximal in-vivo flexion without involving noticeable hip flexion was approximately 45°. At each selected posture, two orthogonal images of the targeted spinal segments were taken simultaneously by the two fluoroscopes.

The pairs of the fluoroscopic images of the spine captured at a specific posture were imported into the Rhinoceros modeling software and placed in orthogonal planes, reproducing a virtual fluoroscopic system. The MR image-based 3D vertebral models were introduced into the virtual fluoroscopic system and viewed from the perspective views of the x-ray sources (Fig. 2b). The 3D models of the vertebrae were independently translated and rotated in 6DOF until their projections matched the osseous outlines captured on the fluoroscopic images. This process was performed using an existing protocol established in our laboratory (Bingham et al., 2008; Hanson et al., 2006; Li et al., 2008; Wang et al., 2008). Using this technique, the exact vertebral positions during the in-vivo flexion–extension and left–right twisting activities were reproduced.

2.3. Data analysis

Using the coordinate systems of the different portions of the vertebra, ROMs of L2 with respect to L3 (L23) and L3 with respect to L4 (L34) during the flexion–extension and left–right twisting activities were determined in the primary sagittal and transverse planes (Fig. 1). For each subject, the ROMs at the three anatomic locations were fitted using linear least squares to calculate the points of zero displacement in the sagittal plane, which was defined as the COR during flexion–extension in the sagittal plane (Fig. 3). Similarly, the COR of the vertebra during left–right twisting on transverse plane was determined. The lengths of the vertebral bodies from the anterior edge to the posterior edge were measured at the three levels of each subject. Considering the differences in the sizes of the vertebrae, the locations of CORs were normalized by the average length of the
vertebral bodies of all subjects. In this way, the average locations of the CORs of all subjects were determined under in-vivo weightbearing flexion–extension and left–right twisting activities.

A repeated measures ANOVA was used to compare the differences of ROMs at the center of the vertebral body, the center of the spinal canal and the tips of the spinous processes, and those between L23 and L34. Statistical significance was set at \( p \leq 0.05 \). When a statistically significant difference was detected, a Newman-Keuls post-hoc test was performed. The statistical analysis was performed using the Statistica® (Statsoft, Tulsa, OK) software.

3. Result

The average morphological parameters of the vertebrae were measured in each subject (Table 1) and no statistically significant difference among L2, L3 and L4 was found. ROMs of L23 (L2 with respect to L3) and L34 (L3 with respect to L4) were determined at the center of each vertebral body, at the center of the spinal canal, and at the tip of the spinous process (Table 2). The translation of L23 and L34 segments increased proportionally \((p < 0.05)\) from anterior to posterior locations. No statistically significant difference was found in the ROMs between L23 and L34. During flexion–extension, the ranges of rotations of L23 and L34 in sagittal plane were calculated to be 6.8 \( \pm \) 2.9° (mean \( \pm \) standard deviation) and 6.7 \( \pm \) 2.3°, respectively. During the left–right twisting, the ranges of rotations of L23 and L34 in the transverse plane were calculated to be 3.2 \( \pm \) 1.9° and for 2.8 \( \pm \) 1.7°, respectively.

After determining the ROMs at the three anatomic locations, linear least squares fits were used to calculate the point of zero displacement in the sagittal and transverse planes. The \( R^2 \) were larger than 0.99 with \( p \) smaller than 0.03 for each subject at different levels. The averaged slopes of the fitting lines were listed in Table 3. Normalized by the average size of the vertebrae (Table 1), the CORs of flexion–extension in sagittal plane for L23 and L34 were located at about 5.0 mm posterior to the central axis of the vertebral body (a distance about one-third the length of the vertebral body, from the posterior edge) (see Fig. 3a, Table 3). The CORs of left–right twisting, in the transverse plane, were about 30 mm anterior to the front edge of the vertebral body (see Fig. 3b, Table 3).

4. Discussion

Motion of the lumbar vertebrae is difficult to describe because of the complicated geometric structures involved. This study investigated the ranges of motion of different portions of the vertebrae and CORs of vertebral segments in sagittal plane during flexion–extension and transverse plane during left–right twisting of the body. The results showed that the anterior portion of the vertebrae had smaller ROM than the posterior portion. Concurrently, we observed that the vertebrae rotated with the CORs located at approximately the posterior one-third of the vertebral body in the sagittal plane. However, in the transverse plane the vertebrae rotated with respect to points which were approximately 30 mm in front of the vertebrae. The results demonstrated that the vertebrae have different CORs under different primary body rotations.

The majority of the previous in-vivo kinematic studies has focused on measurements of the rotational range of motion of the vertebral body and the translation of the proximal vertebrae with respect to the distal vertebrae (Fujii et al., 2007; Haughton et al., 2002; Lee et al., 2002; Ochia et al., 2006; Peary and Tibrewal, 1984). Peary and Tibrewal (1984) used a biplanar X-ray technique and found that coupled vertebral translations measured from the center of the vertebral body were less than 1.0 mm during flexion–extension and left–right twisting movements. Our study found similar translational range of motion for the center of the vertebral body.

There are several reports in the literature on the lumbar vertebral CORs in the sagittal plane during flexion–extension of the lumbar spine (Cunningham et al., 2003; Gertzbein et al., 1984; Hafer et al., 1992; Mansour et al., 2004; Ogston et al., 1986; Peary and Bogduk, 1988; Rousseau et al., 2006a,b; Sakamaki et al., 2002; Schmidt et al., 2008; Shirazi-Adl et al., 1986a,b; White et al., 1990; Yoshioka et al., 1990). Yoshioka et al. (1990) studied 61 healthy cases of L1–L5 lumbar segment using 2D X-ray measurements and concluded that the flexion–extension center of rotation was 2.6 to 5.9 mm posterior to the central axis of the vertebral body. Gertzbein et al. (1984) studied the flexion–extension CORs of 10 cadaveric specimens and reported an average location of the COR of 11.6 mm from the posterior edge of the vertebral body. Similar results have also been reported in separate cadaveric series by White and Panjabi (1990) and Rousseau et al. (2006a,b). In general, our data are in agreement with the data reported in the literature. We found that the COR in the sagittal plane was located posterior to the centers of the vertebral bodies for the L23 and L34 segments.
Table 2

| ROM (average ± SD) measured at different anatomical locations on the lumbar vertebral segments. |
|-------------------------------------------------|-----------------|-----------------|
| Translation during flexion/extension (mm)       | Center of vertebral body | Center of spinal canal | Tip of spinous process |
| L23                                             | −0.3 ± 0.3       | 2.3 ± 1.7        | 7.5 ± 3.2             |
| L34                                             | −0.6 ± 0.3       | 2.3 ± 1.1        | 7.3 ± 3.6             |
| Translation during left-right twisting (mm)      | Vertebral body    | Spinal canal     | Spine process         |
| L23                                             | 0.7 ± 0.4        | 1.1 ± 1.0        | 1.6 ± 0.9             |
| L34                                             | 1.0 ± 0.9        | 1.4 ± 1.3        | 2.3 ± 1.6             |

Table 3

| Average slope of the linear fitting lines. COR locations were calculated at point of zero motion (intersection) and normalized by the size of the vertebral body. (+) indicating a distance anterior to the anterior edge of the vertebral body and (−) indicating a distance posterior to that. |
|-------------------------------------------------|-----------------|-----------------|
| Flexion/extension slope (deg)                   | Twisting slope (deg) | Flexion/extension COR (mm) | Twisting COR (mm) |
| L23                                             | 6.8 ± 2.9       | 3.2 ± 1.9       | −19.0 ± 3.2           | +35.1 ± 6.7       |
| L34                                             | 6.7 ± 2.3       | 2.8 ± 1.7       | −20.5 ± 2.9           | +32.2 ± 6.1       |

In contrast, relatively few studies have reported on the CORs of the lumbar vertebrae in the transverse plane (Haher et al., 1992; Schmidt et al., 2008). Shirazi-Adl et al. (1986a,b) analyzed motion of the L23 segment under an axial torque alone and combined a compression load using a finite element (FE) model. They found that with the application of a small torque (1 Nm), the COR in transverse plane was located roughly at the center of the vertebral body. When a larger torque was applied, however, the COR shifted posteriorly and with hypertorsion (60 Nm) it was posterior to the vertebral body. Similarly, Schmidt et al. (2008) using an FE model found that when a larger torque (7.5 Nm) was applied, the COR was closer to the facet joints. Haher et al. (1992) applied rotational angle of 10° on each side of 10 cadaveric lumbar segments from T1 to S1 and found the COR at the vicinity of facet joints. More recently, Wachowski et al. (2009) performed a cadaveric study of 2 L3/L4 segments and reported instant helical axis migrated from one facet joint to the other along either ventrally or dorsally curved centrodires under combined compressive loads and axial torques. The CORs determined in our study during twisting were in front of the vertebral body and close to the center of the trunk in the transverse plane, which were different from the above literatures. The above literatures suggested that facet joints come into contact and the CORs of vertebrae shift towards the facet under large axial motion. In our study, the in-vivo facet joints (Kozanek, et al., 2009) and the vertebrae (Li et al., 2009) translated in a range within 2 mm and therefore facet joints might not provide the major constrains to vertebral motion under in-vivo loading conditions. There were contributions from all surrounding tissues. Furthermore, under in-vivo loading conditions the torques might be a combination of various moments that were different from those applied in FE and cadaver studies. In in-vitro tests, the axis measured may be the rotating axis imposed by the testing machines rather than the true rotational axis. Thus, a direct comparison of our in-vivo study data to the results reported in the literature is difficult, if not impossible.

The CORs obtained in this study may have important clinical implications for treatment of lumbar disc disease. Several short and mid-range follow-up studies have reported satisfactory clinical results using various total disc replacement designs (Blumenthal et al., 2005; Le Huec et al., 2005; Zigler et al., 2007). Other reports argued that long-term follow-up studies of the currently available total disc replacement designs do not show better results than spinal fusion surgeries (Putzier et al., 2006). There are studies showing that the location of the artificial disc during implantation can significantly affect the clinical outcome (McAfee et al., 2005). In general clinical practice, the artificial disc was positioned in a relatively posterior position during surgery. McAfee et al. (McAfee et al., 2005) described that the ideal location for placement of the Charité prosthesis is 2 mm posterior to the midpoint of the vertebral body in the sagittal plane. This is consistent with the fact that the COR in the sagittal plane is at the posterior portion of the vertebra. However, no study to date has investigated the effect of the COR of an artificial disc in the transverse plane. From a biomechanical standpoint, changes in the location of the COR in the transverse plane may introduce additional constraints to the rotational motion of the lumbar spine. Future studies are necessary to delineate the effect of the CORs of the disc replacement devices in transverse plane on biomechanics of the vertebral segments and on clinical outcomes.

There are certain limitations that should be noted in the current study. We only recruited patients between 40–60 years since this age range is typical for the occurrence of symptomatic degenerative disc diseases (DDD). Future studies may need to investigate subjects with a wider age range. Further, we only investigated the L2 to L4 segments, since the image intensifiers of the fluoroscopes are not large enough to capture the entire lumbar spine. Future study should pursue new technology development so that the total spinal motion can be examined. In addition, we treated the vertebrae as rigid bodies in reproduction of the vertebral motion. Bone deformation may occur during heavy weight-lifting (Hulme et al., 2008; Shirazi-Adl, 1994). An imaging technique should be developed to examine bone deformation under in-vivo loading conditions in future investigations. We only investigated the maximal lumbar motions with minimal pelvic motion, and the coupled motion of lumbar–pelvic rhythm was not considered. In fact, previous studies (Arjmand and Shirazi-Adl, 2005; Shirazi-Adl et al., 2005) have shown that pelvic tilt could affect the posture and motion of the lumbar spine. Finally, we only investigated the end positions of the maximal trunk movements and only used a 2D linear fit method to calculate CORs in the sagittal and transverse planes. In the future 3D dynamic motion of the entire spine should be studied to explore the in-vivo 3D helical axis of vertebral motions as well as to investigate the relationship between CORs and the range of spine motion.

In summary, we applied the combined dual fluoroscopic and MR imaging technique to investigate the motion characteristics of different portions of the vertebrae and CORs of lumbar vertebrae in 2D sagittal and transverse planes in normal human subjects. Of all portions of the vertebral segments, the vertebral body was found to have the smallest ROMs. In addition, the vertebral CORs were different under different physiological loading conditions. During flexion–extension of the torso, the COR was found at the posterior one third of the vertebral body in sagittal plane and during left–right twisting, the COR was found at about 30 mm anterior to the vertebral body. These data may have important implication for future total disc replacement design and surgical treatment.

**Conflict of interest statement**

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References


