Eur Spine J (2009) 18:1013–1021
DOI 10.1007/s00586-009-0936-6

ORIGINAL ARTICLE

Segmental in vivo vertebral motion during functional human lumbar spine activities

**Guoan Li · Shaobai Wang · Peter Passias ·
Qun Xia · Gang Li · Kirkham Wood**

Received: 20 August 2008 / Revised: 13 February 2009 / Accepted: 5 March 2009 / Published online: 20 March 2009

Abstract Quantitative data on the range of in vivo vertebral motion is critical to enhance our understanding of spinal pathology and to improve the current surgical treatment methods for spinal diseases. Little data have been reported on the range of lumbar vertebral motion during functional body activities. In this study, we measured in vivo 6 degrees-of-freedom (DOF) vertebral motion during unrestricted weightbearing functional body activities using a combined MR and dual fluoroscopic imaging technique. Eight asymptomatic living subjects were recruited and underwent MRI scans in order to create 3D vertebral models from L2 to L5 for each subject. The lumbar spine was then imaged using two fluoroscopes while the subject performed primary flexion-extension, left-right bending, and left-right twisting. The range of vertebral motion during each activity was determined through a previously described imaging-model matching technique at L2-3, L3-4, and L4-5 levels. Our data revealed that the upper vertebrae had a higher range of flexion than the lower vertebrae during flexion-extension of the body (L2-3, 5.4 ± 3.8°; L3-4, 4.3 ± 3.4°; L4-5, 1.9 ± 1.1°, respectively). During bending activity, the L4-5 had a higher (but not significant) range of left-right bending motion (4.7 ± 2.4°) than both L2-3 (2.9 ± 2.4°) and L3-4 (3.4 ± 2.1°), while no statistical difference was observed in left-right twisting among the three vertebral levels (L2-3, 2.5 ± 2.3°; L3-4, 2.4 ± 2.6°; and L4-5, 2.9 ± 2.1°, respectively). Besides the primary rotations reported, coupled motions were quantified in all DOFs. The coupled translation in left-right and anterior-posterior directions, on average, reached greater than 1 mm, while in the proximal-distal direction this was less than 1 mm. Overall, each vertebral level responds differently to flexion-extension and left-right bending, but similarly to the left-right twisting. This data may provide new insight into the in vivo function of human spines and can be used as baseline data for investigation of pathological spine kinematics.

Keywords In vivo spine motion · Vertebral kinematics · Spine biomechanics · Lumbar spine · Dual fluoroscopes

Introduction

Accurate knowledge of the physiological kinematics of the lumbar spine vertebrae is important for understanding the etiology of spinal diseases such as discogenic lower back pain. This knowledge is also necessary for the improvement of surgical treatments of spinal diseases that involve either segmental arthrodesis (fusion) or artificial disk arthroplasty (replacement), which may alter the vertebral motion patterns. In vitro experiments using cadaveric spinal segments have been pursued for decades in order to understand spinal biomechanics [25, 26]. Numerous studies have reported on spine kinematics [1, 14, 15, 20, 30, 31, 35, 36] when a spine segment specimen was subjected to simulated loading conditions.

In order to better understand the biomechanical factors that affect spinal pathology among treated patients, it is

G. Li (✉) · S. Wang · P. Passias · Q. Xia · G. Li · K. Wood
Bioengineering Laboratory, Department of Orthopaedic Surgery,
Massachusetts General Hospital/Harvard Medical School,
55 Fruit St., GRJ 1215, Boston, MA 02114, USA
e-mail: gli1@partners.org

S. Wang
Department of Mechanical Engineering,
Massachusetts Institute of Technology, Cambridge, MA, USA

Q. Xia
Tianjin Orthopaedic Hospital, Tianjin, China

necessary to determine the spinal kinematics in living human subjects. However, the limitations of current technology and the complicated anatomy of the lumbar spine have made it difficult to measure the vertebral motion under physiologic loading conditions. In vivo spinal research to date has mainly concentrated on the measurement of range of motion and the evaluation for instability using methods such as bilateral radiographs, magnetic resonance imaging (MRI) [5, 11, 12, 16, 29], computerized topography (CT) [32], electrogoniometer [4, 10, 22, 33], and videofluoroscopy [7, 17]. For example, early research used plain radiographs to examine the spinal motion of living subjects during flexion-extension positions [27, 28]. Subsequently, MR imaging technique [3, 6, 9] and CT-based methodology [23, 24] have been used to measure 3D spinal segmental positions in human subjects while lying in supine positions. To date there has been no accurate information published concerning in vivo lumbar vertebral motion during functional activities.

Recently, we validated a combined dual fluoroscopic and MRI technique to investigate in vivo human spine kinematics [34]. The system was shown to be appropriate for the investigation of lumbar spine motion during weightbearing functional activities. In this paper, we used this technique to determine the 6 degrees-of-freedom (DOF) vertebral motion of the lumbar spine of living asymptomatic human subjects in flexion-extension, left-right side bending, and left-right twisting. We hypothesized that the lumbar vertebrae at different levels demonstrated distinct motion characters during active in vivo spine motion. The purpose of this study was to determine segmental in vivo vertebral motion during functional human lumbar spine activities.

Methods

Eleven asymptomatic subjects with an age ranging from 50 to 60 years (5 males and 6 females) were recruited for this study (mean age 54.4 years; mean height 134.7 cm; mean weight 63.5 kg). Approval of the experimental design by the authors' Institutional Review Board was obtained prior to the initiation of the study. The subjects were evaluated for the absence of lower back pain and other spinal disorders. The presence of any of the following were used as indications for exclusion from the study based on the evaluation by an attending spine surgeon (senior author) prior to participation: current or prior back pain, history of spinal surgery, a diagnosis of disease or anatomical anomaly in the spine, prior radiation within a year, and pregnancy. A signed consent form was obtained from each subject before any testing was performed.

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. The subject rested for about 30 min and was then scanned in a supine, relaxed position. Parallel digital images with a thickness of 1.5 mm without gap and with a resolution of 512 × 512 pixels were obtained. The MR images of each subject were carefully examined. Two subjects were found to have the presence of early disk degeneration in the absence of clinical symptoms as determined by the radiologist. Additionally, one subject was found to have early scoliosis (>10°) without symptoms. These three subjects were excluded from further investigation.

The MR images of the spinal segments were then imported into a solid modeling software (Rhinoceros®, Robert McNeel & Associates, Seattle, WA) in order to construct 3D anatomical vertebral models of L2, L3, L4, and L5 of the lumbar spine using a protocol established in our laboratory [18]. The contours of the vertebrae were digitized manually using B-Spline curves in the software. Polygon mesh models of the vertebrae were then created from the contour lines (Fig. 1a, b). Of note, few authors have validated the accuracy of the MR image-based mesh models of the vertebrae by comparing them with those constructed using CT images as has been described in our previous work [34]. The mean accuracy of our technique in determining translation has been shown to be 0.40 mm for the image matching technique. The repeatability of the method in reproducing in vivo human spine 6DOF kinematics was less than 0.3 mm in translation and less than 0.7° in orientation.

Following MR scanning, the lumbar spines of the subjects were imaged using a dual orthogonal fluoroscopic system. Two fluoroscopes (BV Pulsera, Phillips, Bothell, WA) were positioned with their image intensifiers perpendicular to each other in order to capture images of the spine segments at different postures from orthogonal directions simultaneously (Fig. 2a). The fluoroscope has a clearance of approximately 1 m between the X-ray source and the receiver, allowing the subject to be imaged by the fluoroscopes simultaneously as he or she actively performs different maneuvers. The total imaging volume can reach up to 30 × 30 × 30 cm^3.

During fluoroscopic imaging, the subject was protected from radiation exposure with appropriate lead shielding. The subject was protected from above and below their lumbar spine by specifically designed skirts, vests, and thyroid shields. A surgeon constantly checked the lead protections to ensure that they did not slip away during the experiment.

The target spinal segments were then exposed to fluoroscopic scanning. The subject was asked to stand and position their lumbar spines within the view of both fluoroscopes and actively move to different postures in a predetermined sequence: standing position, 45° flexion of

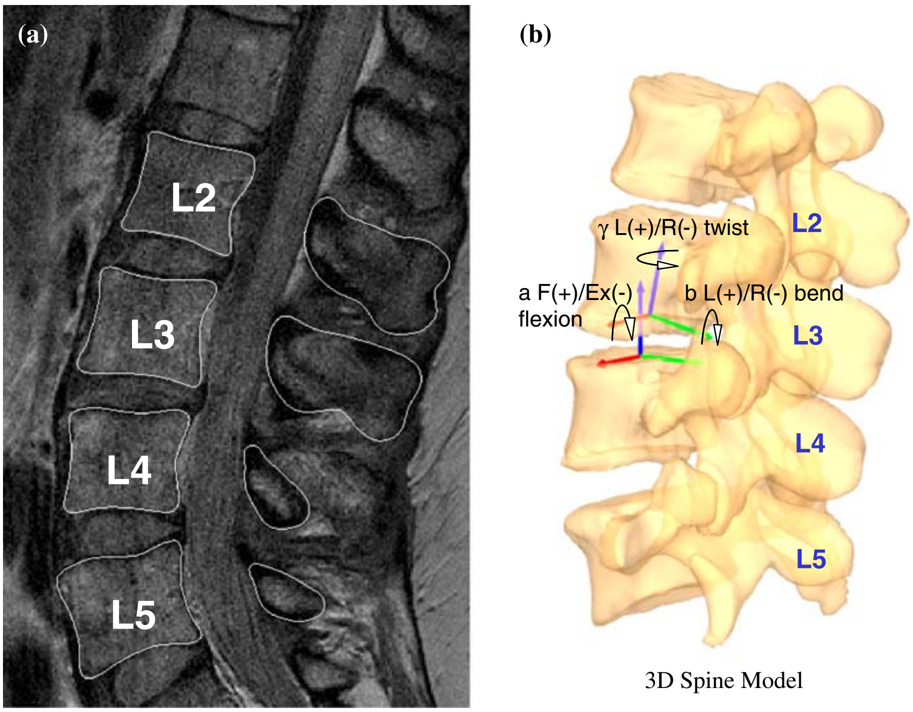

Fig. 1 **a** A typical MR image of a human lumbar spine in sagittal plane with segmentation lines present; **b** 3D anatomic vertebral model from L2 to L5 constructed using the MR images. Local coordinate systems at the endplates were used to calculate the relative 6DOF kinematics of the proximal vertebra with respect to distal vertebra

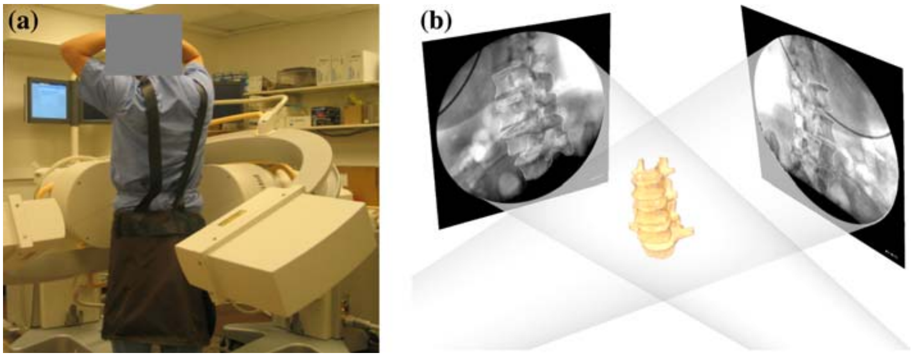

Fig. 2 **a** The experimental setup of the dual fluoroscopic system for capturing the lumbar spine positions of living subjects; **b** the virtual dual fluoroscopic system that mimics the actual fluoroscopic system and was used to reproduce the in vivo vertebral positions

the trunk relative to the vertical, maximal extension, maximal left-right bending, maximal left-right twisting. The two laser pointers attached to the fluoroscopes helped to position the target lumbar spine segments inside the field of view of the two fluoroscopes. At each selected posture, two orthogonal images were taken simultaneously from two directions of the targeted spinal segment. The subject then moved to the next posture under the direction of an orthopedic surgeon. The subjects were asked to position themselves in the various postures to the maximum extent that they were able to so as to replicate their normal physiological limitations. The exception to this was forward flexion that was limited to 45° (using a protractor) in order to keep the subject within view of the fluoroscopes. Care was taken to ensure that no constraint was applied to the hips of the subjects while performing the active motions in order to replicate normal activity. During testing, the subject was exposed to approximately seven pairs of fluoroscopic projections. The entire experiment took about 10 min. The images were processed in the Digital Imaging and Communications in Medicine (DICOM) and Bitmap file formats.

The in vivo positions of the vertebrae at various weightbearing body positions were reproduced in the Rhinoceros® solid modeling software using the 3D models of the vertebrae and the orthogonal fluoroscopic images [34]. The pair of fluoroscopic images of the spine captured at a specific posture were imported into the modeling software and placed in calibrated orthogonal planes, reproducing the actual positions of the image intensifiers of the fluoroscopes. Two virtual cameras were created inside the virtual space to reproduce the positions of the X-ray sources with respect to the image intensifiers. Therefore, the geometry of the dual-orthogonal fluoroscopic system was recreated in the solid modeling program. The MR image-based 3D vertebral models were introduced into the virtual fluoroscopic system and viewed from the perspective views of the two virtual cameras (Fig. 2b). The 3D models of the vertebrae could be independently translated and rotated in 6DOF until their outlines match the osseous outlines captured on the two orthogonal fluoroscopic images. This process was executed using an existing protocol established in our laboratory [2, 8, 19, 34]. The software allowed the model to be manually translated and rotated in increments of 0.01 mm and 0.01°, respectively. Using this technique, the vertebral positions during in vivo weight-bearing activities were reproduced, representing the 6DOF kinematics of the vertebrae at each in vivo posture (Fig. 3).

After reproducing the in vivo vertebral positions using the 3D anatomic vertebral models, the relative motions of the vertebrae were analyzed using right hand Cartesian coordinate systems constructed at the endplates of each vertebra (Fig. 1b). The geometric center of the endplate was chosen as the origin of the coordinate system. The *X*-axis was in frontal plane and pointed to the left direction; the *Y*-axis was in sagittal plane and pointed to the posterior direction; and the *Z*-axis was vertical to the *X*–*Y* plane and pointed proximally.

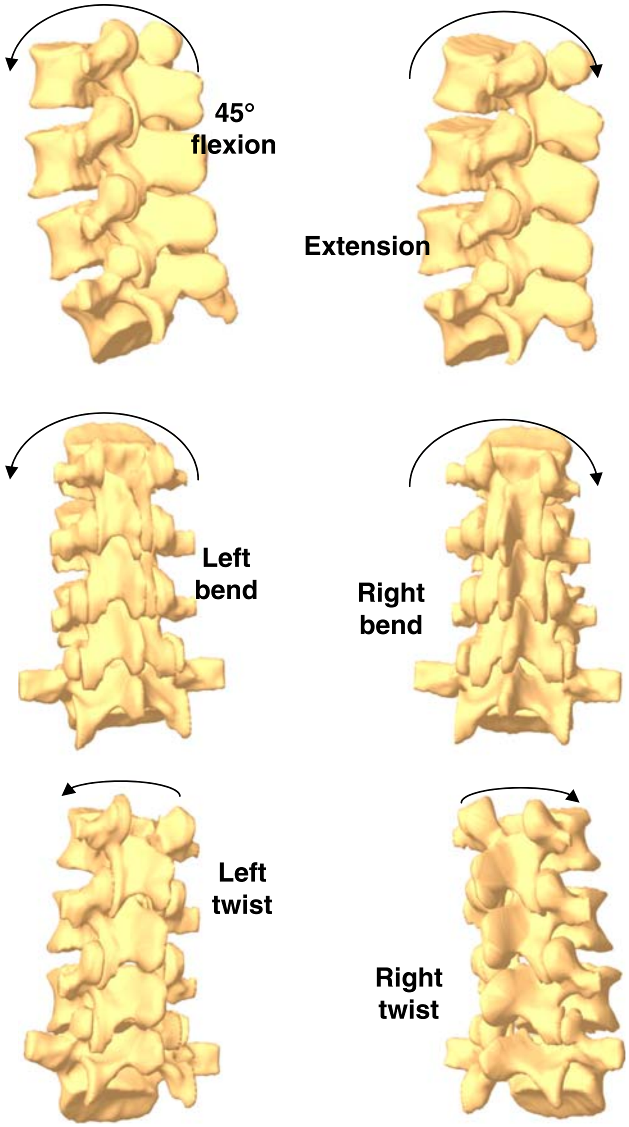

Fig. 3 The lumbar spine segment in flexion-extension; left-right bending; and left-right twisting positions

The relative motions of the proximal vertebrae with respect to the distal vertebrae were calculated at three vertebral levels: L2-3, L3-4, and L4-5. Three translations were defined as the motions of the proximal vertebral coordinate system origin in the distal coordinate system: anterior-posterior, left-right, and distal-proximal translations. Three rotations were defined as the orientations of the proximal vertebral coordinate system in the distal vertebral coordinate system using Euler angles (in *X*–*Y*–*Z* sequence): flexion-extension, left-right bending, and left-right twisting rotations (Fig. 1b).

After the determination of vertebral positions at each posture, we determined the range of motion of each vertebral level between flexion-extension, left-right bending, and left-right twisting. The range of motion data included both the primary rotations and coupled translations and rotations in all six DOFs. A repeated measure ANOVA was used to compare the range of motion at L2-3, L3-4, and L4-5 vertebral levels at each of the three functional activities. Statistical significance was set at $p < 0.05$. When a statistically significant difference was detected a Newman-Keuls post hoc test was performed. The statistical analysis was done using software (Statistica, Statsoft, Tulsa, OK).

Results

Primary rotations

The vertebrae at different vertebral levels had different range of flexion during the designed flexion-extension motion (Fig. 4a). The flexion ranges were 5.4 ± 3.8°, 4.3 ± 3.4°, and 1.9 ± 1.1° for L2-3, L3-4, and L4-5 levels, respectively. The L2-3 and L3-4 measurements are not statistically different in flexion range ($p = 0.06$). However, both levels had significantly higher flexion ranges than the L4-5 vertebral level ($p < 0.05$).

During left-right bending motion, the upper level generally had a lower range of lateral bending than the lower level (Fig. 4b). The L2-3 and L3-4 had left-right bending rotation ranges of 2.9 ± 2.4° and 3.4 ± 2.1°, respectively; but neither of these were statistically different ($p < 0.05$). The L4-5 had a range of rotation during bending of 4.7 ± 2.4°, which was statistically larger than that at L2-3 level ($p < 0.05$).

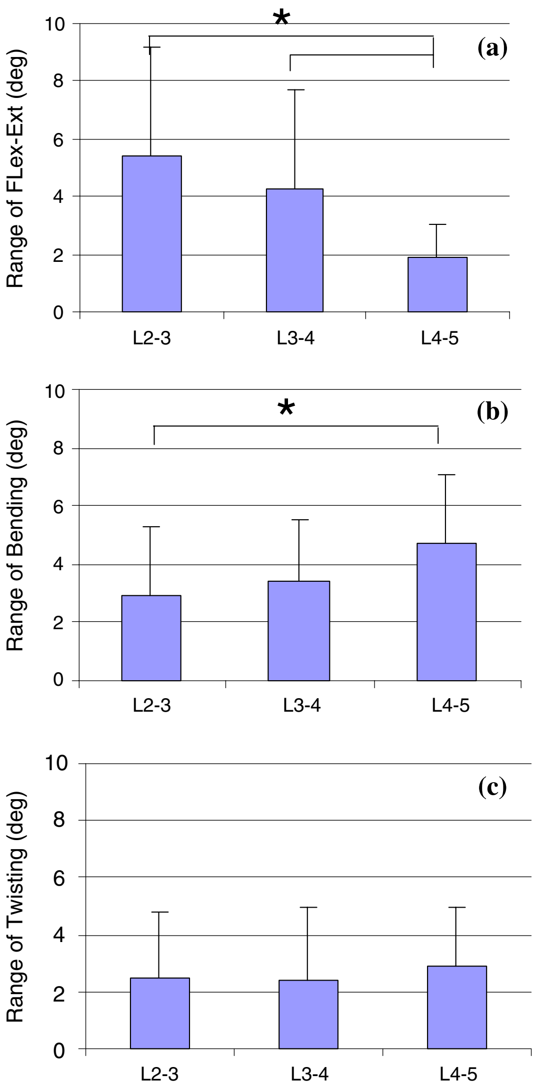

Fig. 4 The range of primary rotations of the three vertebral levels during three functional body motions: **a** flexion-extension; **b** left-right bending; and **c** left-right twisting (* $p < 0.05$) for Newman-Keuls post hoc test

For the left-right twist activity, the three vertebral levels showed no significant difference in the range of twist rotations (Fig. 4c) ($p < 0.05$). The twist rotation ranges were 2.5 ± 2.3° for L2-3, 2.4 ± 2.6° for L3-4, and 2.9 ± 2.1° for L4-5.

We did not detect any trends in movement patterns based on the available anthropometry or age of the subjects.

Table 1 The range of motion of the lumbar vertebrae at different levels during the three weight-bearing body activities: flexion-extension, left-right bending and left-right twisting

	Translation (mm)			Rotation (°)		
	LR	AP	PD	FE	Bend	Twist
Flexion and extension						
L2-3						
Mean	1.5	1.0	0.2	*5.4*	2.3	1.9
SD	0.9	0.8	0.2	*3.8*	2.6	2.1
L3-4						
Mean	1.1	0.7	0.6	*4.3*	2.0	1.7
SD	0.7	0.6	0.4	*3.4*	1.6	1.5
L4-5						
Mean	1.0	1.4	0.7	*1.9*	2.1	2.9
SD	0.7	1.1	0.6	*1.1*	1.8	2.9
Bending left and right						
L2-3						
Mean	0.9	0.8	0.4	2.1	*2.9*	2.2
SD	0.4	0.6	0.4	1.2	*2.4*	2.2
L3-4						
Mean	0.8	0.8	0.3	1.3	*3.4*	3.8
SD	0.9	0.7	0.2	0.8	*2.1*	2.3
L4-5						
Mean	1.0	1.1	0.6	1.9	*4.7*	2.8
SD	0.6	1.2	0.4	2.1	*2.4*	2.6
Twisting left and right						
L2-3						
Mean	0.7	1.1	0.6	1.7	2.6	*2.5*
SD	0.4	0.7	0.5	2.9	1.2	*2.3*
L3-4						
Mean	1.0	1.2	0.4	2.3	2.0	*2.4*
SD	0.9	1.1	0.3	2.9	2.0	*2.6*
L4-5						
Mean	0.5	1.1	0.3	0.9	3.0	*2.9*
SD	0.6	0.6	0.2	0.8	1.6	*2.1*

The ranges of primary rotations were *italicized*. The coupled translation ranges were labeled as LR (left-right translation), AP (anterior-posterior translation) and PD (proximal-distal translation). The ranges of the three rotations were labeled as FE (flexion extension), Bend (left-right bending) and Twist (left-right twisting)

Coupled translations and rotations

During the active flexion-extension motion, there were coupled translations in all three directions (Table 1). The coupled motions in left-right and anterior-posterior directions were not significant different and were, on average, between 0.7 and 1.5 mm. The coupled translation in proximal-distal direction is significantly lower at L2-3 (0.2 ± 0.2 mm) than at L3-4 (0.6 ± 0.4 mm), and L4-5 (0.7 ± 0.6 mm) ($p < 0.05$). The coupled rotations in left-right bending and twisting were not significant different and were, on average, between 1.7° and 2.9°. They are significantly lower than primary rotations at L2-3 and L3-4 levels.

During the active left-right bending motion, the coupled translations in left-right and anterior-posterior directions were not significantly different in all the vertebral levels and on average, ranged between 0.8 and 1.1 mm (Table 1). The coupled translation in proximal-distal direction (between 0.4 and 0.6 mm) was lower when compared with those at the other directions ($p < 0.05$). The coupled flexion rotation range was between 1.3° and 2.1° at the L2-3, L3-4, and L4-5 levels, which was lower than their corresponding primary bending rotations ($p < 0.05$). However, the coupled twist rotations were at similar magnitudes as the primary bending rotation; ranged between 2.2° and 3.8°.

During the active left-right twisting motion, on average, the translation in anterior-posterior direction was between 1.1 and 1.2 mm, while in left-right direction was between 0.5 and 1.0 mm and in proximal-distal direction was between 0.3 and 0.6 mm. The anterior-posterior translation is significant larger at L2-3 and L4-5 levels than that in the other two directions. Both left-right and anterior-posterior showed significantly larger translation than proximal-distal translation at L3-4. The coupled flexion range was between 0.9° and 2.3° and the coupled bending rotation was between 2.0° and 3.0°. The only statistical difference was found at L4-5 flexion range compare to those of bend and twist (Table 1).

Discussion

Quantitative data on in vivo vertebral motion is critical to enhance our understanding of spinal pathology and to improve the current surgical treatment methods for spinal diseases. In this study, we investigated the range of lumbar vertebral motion in asymptomatic living subjects when they performed unrestricted weightbearing activities. The data demonstrated that the upper vertebrae had larger ranges of flexion than the lower vertebrae during functional flexion-extension of the body. During the functional bending activity, the L4-5 had a larger range of left-right bending motion than both L2-3 and L3-4, while no statistical difference was observed in left-right twist among the three vertebral levels. This could be related to the different anatomic orientation of the facet joints at different levels as the L2-3 facet is oriented more vertically than L4-5 [21] which facilitates flexion. Besides the primary rotations, coupled motions were found in all other DOFs. The coupled translation in left-right and anterior-posterior directions, on average, reached above 1 mm, while in the proximal-distal direction this remained less than 1 mm. Coupled bending and twisting motions were found to have a larger range of motion than coupled flexion.

This data provides necessary preliminary information on the normal ROM of the lumbar vertebrae. Overall, segmental ROM measured was small with a mean of <2 mm and <6°. For clinical purposes, several radiographic diagnostic criteria have been proposed for lumbar spinal instability: vertebral translation >3–5 mm or relative endplate orientation >10–20° in the sagittal plane. However, at present, there is no consensus [13]. In the future, we intend to increase the number of subjects tested to increase the statistical power in order to help establish a standard, and to include translational and rotational limits in the coronal plane for this new standard.

Numerous studies have been carried out using in vitro experimental setups to investigate the biomechanics of the lumbar spine. For example, Kettler et al. [14] indicated that the finite helical axes of motion are useful tools to describe the 3D in vitro kinematics of the intact and stabilized spine. Fujiwara et al. [7] conducted an in vitro anatomic and biomechanical study using human cadaveric lumbar spines. They evaluated the changes in the intervertebral foramen during flexion and extension, lateral bending, and axial rotation of the lumbar spine. The authors correlated these changes with the flexibility of the spinal motion segments by imaging the spine before and after the application of rotational and loading movements. All these studies used invasive techniques to measure spine motion, which are not possible when applied to an in vivo, which makes them difficult to compare with in vivo studies and to interpret in the clinical setting for living patients.

To our knowledge, no previous study has reported data regarding in vivo vertebral motion during unrestricted functional activities in humans. Pearcy [27] investigated lumbar vertebral motion during maximal flexion-extension using a biplanar radiography technique, where the pelvis and hips were limited in motion by using a frame. Their data showed similar ranges of motion for all vertebrae. Our study found the upper levels had a larger range of flexion than the lower levels. This differing trend in flexion range may be due to two factors. First, in our testing the subject was allowed free weightbearing motion of the body. No restriction was applied to the pelvis or hips. Therefore, pelvic rotation could conceivably affect the rotation of the lumbar vertebrae. A second factor may be that we only allowed maximal flexion to approximately 45° for the upper body which is not the maximal flexion angle of the body. While overall, their coupled range of translation was found to be similar in magnitude to our data, the coupled rotation data was lower in magnitude than our data. The differences between the two studies emphasize the importance of weightbearing conditions and motion patterns when investigating the vertebral kinematics.

Pearcy and Tibrewal [28] also investigated left-right bending rotation motion (also referred to as lateral bending rotation) of asymptomatic living subjects using their biplanar radiography technique. Overall, they found larger ranges of lateral bending rotation than we did in our studies. They also reported larger bending ranges in the upper segments when compared with the lower levels of the vertebrae. In our data, however, we found that the lower level L4-5 had a larger range of bending rotation than the upper two levels. Similarly to the flexion-extension motion, the lateral bending motion was also affected by the motion of the pelvis and hips. In our study, an unrestricted lateral bending was performed by all subjects. It might be difficult to directly compare the results between different studies given that the weightbearing conditions were different.

There are several studies that have investigated left and right twisting (also referred to as axial rotation in literature) of lumbar spine in living subjects under various conditions [9, 23, 27, 28]. For example, Pearcy and Tilbrewal [28] studied a similar twisting movement while standing and showed a range of axial rotation of approximately 2° at each vertebral level, which is similar to our findings. Breen et al. described a novel technique (Objective Spinal Motion Imaging Assessment system—OSMIA) based on low-dose fluoroscopy and image processing to study in vivo lumbar spine motion. Although this technique has the benefit of minimizing radiation exposure, the major limitation of this technique was the exclusion of translations and axial rotations, making the possibility of combining the data to measure coupled and 3-dimensional motion impossible. In addition, it requires skillful radiography to achieve optimal positioning and dose limitation. Haughton et al. [9] investigated lumbar twisting using MR image scan with the subject lying supine and showed an average range of axial rotation between 1 and 2° in the three vertebral levels. Their measurement was carried by rotation of the lower body ±8° to examine the rotation range of the vertebrae. More recently, Ochia et al. [23] determined that the upper lumbar motion segments had greater amounts of axial rotation range compared to the lower segments when the upper body was passively rotated to ±50° in the supine position while undergoing CT scanning. Their range of rotation was almost twice that found in the above mentioned studies.

These large discrepancies in vertebral rotation data could be explained by the various loading conditions used in these studies that were caused by different experimental setups. Pearcy and Tibrewal studied similar active weightbearing axial rotations compared with our study. However, both Haughton et al. [9] and Ochia et al. [23] studied passive axial rotation of the body in the supine position. Haughton et al. rotated the subject's hip ±8° to investigate the lumbar spine rotation while Ochia et al. rotated the upper body ±50°. In both of these two studies, however, the spine was not under weightbearing conditions. A quantitative comparison between these studies might be difficult and a comparison of lumbar vertebral motions has to consider the different loading conditions that were present among these studies.

Few studies have gone further to investigate coupled vertebral motions with the primary rotations [23, 27]. Pearcy and Tibrewal [28] found that coupled translation in left-right and anterior-posterior directions were around the range of 1 mm during primary flexion-extension motion, which are similar to our findings. However, the accuracy of their system was around 1 mm. Their coupled motion in left-right bending and axial rotation was also similar to ours. During primary axial rotation, Ochia et al. [24] found that the coupled range of translation in the left-right direction was over 8 mm at L2-3, over 4 mm at L3-4, and over 1 mm at L4-5 levels. These values are larger than those measured from our study during standing weightbearing axial rotation. Their coupled translations in the anterior-posterior and proximal-distal directions were lower than those reported in our study. These comparisons indicated again that the coupled vertebral motions are also dependent upon weightbearing condition.

There are several limitations to the current study. Our small sample size limited our ability to detect differences in movement patterns. This may also explain why some of the differences that were found were not statistically significant as well as the relatively large SDs that were seen. Even though no restriction was applied to body motion, the flexion was not studied at the maximal flexion position of the subject. In order to keep the targeted lumbar spine within the field view of the two fluoroscopes, the subject was instructed to limit flexion to approximately 45° from a standing position. Also, we only examined the range of motion of the L2-3, L3-4, and L4-5 segments during the three functional body motions. We did not examine the in vivo instantaneous positions of the vertebrae during dynamic motion of the body. Finally, the subjects were within the age distribution of 50–60 years. In future, living subjects in various age ranges should be investigated to examine the age effect on vertebral kinematics. Nevertheless, the data obtained from this study will hopefully contribute to our knowledge on physiological motion of the human lumbar vertebrae.

In conclusion, this study used a dual fluoroscopic system to investigate functional lumbar spine motion in human subjects under weightbearing conditions. The advantage of this system for spinal research is its flexibility to accommodate various functional activities. This paper reports data on lumbar vertebral motion ranges during three unrestricted body motions commonly used during clinical examinations of the spine. We found that vertebral motion at different levels may respond to external loads differently. These data may provide new insight into the in vivo function of human spines. Future investigations will be directed at examining the intervertebral disk deformation of the lumbar spine segments using 3D finite element analysis while using the 6DOF kinematics determined in this study as boundary conditions. We also hope to focus on studying the in vivo vertebral kinematics of patients with diseased disks and to analyze how surgical treatment will affect the spinal biomechanics.

Acknowledgments The financial support from a NASS research grant and Department of Orthopaedic Surgery of Massachusetts General Hospital was greatly appreciated. This research was also supported by the Orthopaedic Department at Tianjin Orthopaedic Hospital. We also thank Drs. Brian Grottkau and Michael Kozanek for technical assistance.

References

1. Auerbach JD, Wills BP, McIntosh TC, Balderston RA (2007) Evaluation of spinal kinematics following lumbar total disc replacement and circumferential fusion using in vivo fluoroscopy. Spine 32:527–536. doi:10.1097/01.brs.0000256915.90236.17
2. Bingham J, Li G (2006) An optimized image matching method for determining in vivo TKA kinematics with a dual-orthogonal fluoroscopic imaging system. J Biomech Eng 128:588–595. doi:10.1115/1.2205865
3. Blankenbaker DG, Haughton VM, Rogers BP, Meyerand ME, Fine JP (2006) Axial rotation of the lumbar spinal motion segments correlated with concordant pain on discography: a preliminary study. AJR Am J Roentgenol 186:795–799. doi:10.2214/AJR.04.1629
4. Burnett AF, Cornelius MW, Dankaerts W, O'Sullivan PB (2004) Spinal kinematics and trunk muscle activity in cyclists: a comparison between healthy controls and non-specific chronic low back pain subjects-a pilot investigation. Man Ther 9:211–219. doi:10.1016/j.math.2004.06.002
5. Fazey PJ, Song S, Monsas S, Johansson L, Haukalid T, Price RI, Singer KP (2006) An MRI investigation of intervertebral disc deformation in response to torsion. Clin Biomech (Bristol, Avon) 21:538–542. doi:10.1016/j.clinbiomech.2005.12.008
6. Fujii R, Sakaura H, Mukai Y, Hosono N, Ishii T, Iwasaki M, Yoshikawa H, Sugamoto K (2007) Kinematics of the lumbar spine in trunk rotation: in vivo three-dimensional analysis using magnetic resonance imaging. Eur Spine J 16:1867–1874. doi:10.1007/s00586-007-0373-3
7. Fujiwara A, Lim TH, An HS, Tanaka N, Jeon CH, Andersson GB, Haughton VM (2000) The effect of disc degeneration and facet joint osteoarthritis on the segmental flexibility of the lumbar spine. Spine 25:3036–3044. doi:10.1097/00007632-200012010-00011
8. Hanson GR, Suggs JF, Freiberg AA, Durbhakula S, Li G (2006) Investigation of in vivo 6DOF total knee arthroplasty kinematics using a dual orthogonal fluoroscopic system. J Orthop Res 24:974–981. doi:10.1002/jor.20141
9. Haughton VM, Rogers B, Meyerand ME, Resnick DK (2002) Measuring the axial rotation of lumbar vertebrae in vivo with MR imaging. AJNR Am J Neuroradiol 23:1110–1116
10. Holt PJ, Bull AM, Cashman PM, McGregor AH (2003) Kinematics of spinal motion during prolonged rowing. Int J Sports Med 24:597–602. doi:10.1055/s-2003-43273
11. Jinkins JR, Dworkin JS, Damadian RV (2005) Upright, weight-bearing, dynamic-kinetic MRI of the spine: initial results. Eur Radiol 15:1815–1825. doi:10.1007/s00330-005-2666-4
12. Karadimas EJ, Siddiqui M, Smith FW, Wardlaw D (2006) Positional MRI changes in supine versus sitting postures in patients with degenerative lumbar spine. J Spinal Disord Tech 19:495–500. doi:10.1097/01.bsd.0000211213.98070.c2
13. Kasai Y, Morishita K, Kawakita E, Kondo T, Uchida A (2006) A new evaluation method for lumbar spinal instability: passive lumbar extension test. Phys Ther 86:1661–1667. doi:10.2522/ptj.20050281
14. Kettler A, Marin F, Sattelmayer G, Mohr M, Mannel H, Durselen L, Claes L, Wilke HJ (2004) Finite helical axes of motion are a useful tool to describe the three-dimensional in vitro kinematics of the intact, injured and stabilised spine. Eur Spine J 13:553–559. doi:10.1007/s00586-004-0710-8
15. Kotani Y, Abumi K, Shikinami Y, Takada T, Kadoya K, Shimamoto N, Ito M, Kadosawa T, Fujinaga T, Kaneda K (2002) Artificial intervertebral disc replacement using bioactive three-dimensional fabric: design, development, and preliminary animal study. Spine 27:929–935. doi:10.1097/00007632-200205010-00008 discussion 935–926
16. Kulig K, Powers CM, Landel RF, Chen H, Fredericson M, Guillet M, Butts K (2007) Segmental lumbar mobility in individuals with low back pain: in vivo assessment during manual and self-imposed motion using dynamic MRI. BMC Musculoskelet Disord 8:8. doi:10.1186/1471-2474-8-8
17. Lee SW, Wong KW, Chan MK, Yeung HM, Chiu JL, Leong JC (2002) Development and validation of a new technique for assessing lumbar spine motion. Spine 27:E215–E220. doi:10.1097/00007632-200204150-00022
18. Li G, DeFrate LE, Park SE, Gill TJ, Rubash HE (2005) In vivo articular cartilage contact kinematics of the knee: an investigation using dual-orthogonal fluoroscopy and magnetic resonance image-based computer models. Am J Sports Med 33:102–107. doi:10.1177/0363546504265577
19. Li G, Wan L, Kozanek M (2008) Determination of real-time in vivo cartilage contact deformation in the ankle joint. J Biomech 41:128–136. doi:10.1016/j.jbiomech.2007.07.006
20. Lindsey DP, Swanson KE, Fuchs P, Hsu KY, Zucherman JF, Yerby SA (2003) The effects of an interspinous implant on the kinematics of the instrumented and adjacent levels in the lumbar spine. Spine 28:2192–2197. doi:10.1097/01.BRS.0000084877.88192.8E
21. Masharawi Y, Rothschild B, Dar G, Peleg S, Robinson D, Been E, Hershkovitz I (2004) Facet orientation in the thoracolumbar spine: three-dimensional anatomic and biomechanical analysis. Spine 29:1755–1763. doi:10.1097/01.BRS.0000134575.04084.EF
22. McGregor AH, Patankar ZS, Bull AM (2005) Spinal kinematics in elite oarswomen during a routine physiological "step test". Med Sci Sports Exerc 37:1014–1020. doi:10.1097/00005768-200505001-00140
23. Ochia RS, Inoue N, Renner SM, Lorenz EP, Lim TH, Andersson GB, An HS (2006) Three-dimensional in vivo measurement of lumbar spine segmental motion. Spine 31:2073–2078. doi:10.1097/01.brs.0000231435.55842.9e
24. Ochia RS, Inoue N, Takatori R, Andersson GB, An HS (2007) In vivo measurements of lumbar segmental motion during axial rotation in asymptomatic and chronic low back pain male subjects. Spine 32:1394–1399. doi:10.1097/BRS.0b013e318060122b
25. Panjabi MM, Takata K, Goel VK (1983) Kinematics of lumbar intervertebral foramen. Spine 8:348–357. doi:10.1097/00007632-198305000-00002
26. Panjabi MM, White AA 3rd (1980) Basic biomechanics of the spine. Neurosurgery 7:76–93. doi:10.1097/00006123-198007000-00013
27. Pearcy MJ (1985) Stereo radiography of lumbar spine motion. Acta Orthop Scand Suppl 212:1–45
28. Pearcy MJ, Tibrewal SB (1984) Axial rotation and lateral bending in the normal lumbar spine measured by three-dimensional radiography. Spine 9:582–587. doi:10.1097/00007632-198409000-00008

29. Perie D, Iatridis JC, Demers CN, Goswami T, Beaudoin G, Mwale F, Antoniou J (2006) Assessment of compressive modulus, hydraulic permeability and matrix content of trypsin-treated nucleus pulposus using quantitative MRI. J Biomech 39:1392–1400. doi:10.1016/j.jbiomech.2005.04.015
30. SariAli el H, Lemaire JP, Pascal-Mousselard H, Carrier H, Skalli W (2006) In vivo study of the kinematics in axial rotation of the lumbar spine after total intervertebral disc replacement: long-term results: a 10–14 years follow up evaluation. Eur Spine J 15:1501–1510. doi:10.1007/s00586-005-0016-5
31. Siddiqui M, Karadimas E, Nicol M, Smith FW, Wardlaw D (2006) Effects of X-STOP device on sagittal lumbar spine kinematics in spinal stenosis. J Spinal Disord Tech 19:328–333. doi:10.1097/01.bsd.0000211297.52260.d5
32. Simon S, Davis M, Odhner D, Udupa J, Winkelstein B (2006) CT imaging techniques for describing motions of the cervicothoracic junction and cervical spine during flexion, extension, and cervical traction. Spine 31:44–50. doi:10.1097/01.brs.0000192679.25878.f9
33. Steffen T, Rubin RK, Baramki HG, Antoniou J, Marchesi D, Aebi M (1997) A new technique for measuring lumbar segmental motion in vivo. Method, accuracy, and preliminary results. Spine 22:156–166. doi:10.1097/00007632-199701150-00006
34. Wang S, Passias P, Li G, Li G, Wood K (2008) Measurement of vertebral kinematics using noninvasive image matching method-validation and application. Spine 33:E355–E361. doi:10.1097/BRS.0b013e3181715295
35. Wong KW, Luk KD, Leong JC, Wong SF, Wong KK (2006) Continuous dynamic spinal motion analysis. Spine 31:414–419. doi:10.1097/01.brs.0000199955.87517.82
36. Zhu Q, Larson CR, Sjovold SG, Rosler DM, Keynan O, Wilson DR, Cripton PA, Oxland TR (2007) Biomechanical evaluation of the Total Facet Arthroplasty System: 3-dimensional kinematics. Spine 32:55–62. doi:10.1097/01.brs.0000250983.91339.9f