Three-dimensional movements of the lumbar spine facet joints and segmental movements: in vivo examinations of normal subjects with a new non-invasive method

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Abstract

Introduction Examination with CT and image registration is a new technique that we have previously used to assess 3D segmental motions in the lumbar spine in a phantom. Current multi-slice computed tomography (CT) offers highly accurate spatial volume resolution without significant distortion and modern CT scanners makes it possible to reduce the radiation dose to the patients. Our aim was to assess segmental movement in the lumbar spine with the aforementioned method in healthy subjects and also to determine rotation accuracy on phantom vertebrae.

Material and method The subjects were examined in flexion–extension using low dose CT. Eleven healthy, asymptomatic subjects participated in the current study. The subjects were placed on a custom made jig which could provoke the lumbar spine into flexion or extension. CT examination in flexion and extension was performed. The image analysis was performed using a 3D volume fusion tool, registering one of the vertebrae, and then measuring Euler angles and distances in the registered volumes.

Results The mean 3D facet joint translation at L4–L5 was in the right facet joint 6.1 mm (3.1–8.3), left facet joint 6.9 mm (4.9–9.9), at L5–S1: right facet joint 4.5 mm (1.4–6.9), and for the left facet joint 4.8 mm (2.0–7.7). In subjects the mean angles at the L4–L5 level were: in the sagittal plane 14.3°, coronal plane 0.9° (–0.6 to 2.8), and in the transverse plane 0.6° (–0.4 to 1.5), in the L5–S1 level the rotation was in sagittal plane 10.2° (2.4–16.1), coronal plane 0° (–1.2 to 1.2), and in the transverse plane 0.2° (–0.7 to 0.3). Repeated analysis for 3D facet joint movement was on average 5 mm with a standard error of mean of 0.6 mm and repeatability of 1.8 mm (CI 95%). For segmental rotation in the sagittal plane the mean rotation was 11.5° and standard error of mean 1°. The repeatability for rotation was 2.8° (CI 95%). The accuracy for rotation in the phantom was in the sagittal plane 0.7°, coronal plane 1°, and 0.7 in the transverse plane.

Conclusion This method to assess movement in the lumbar spine is a truly 3D method with a high precision giving both visual and numerical output. We believe that this method for measuring spine movement is useful both in research and in clinical settings.

Keywords Computed tomography · Joint visualization · 3D-presentation

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Introduction

Many methods have been used in an attempt to quantify range of motion in the lumbar spine. The easiest and most common is flexion–extension provocation in lateral view plane radiographs [1–3]. The error of such an examination can be as much as 4 mm [4]. Improvement of the accuracy to around 1.2 mm in anterior–posterior translation depending upon the depth of the vertebra is possible with a specific technique called distortion corrected radiographic analysis (DCRA) in which the lateral view radiographs are computer processed [2].

In bi-planar radiography, orthogonal radiographs with coordinates for anatomical landmarks on the vertebrae in both projections have been used to calculate three-dimensional (3D) movements with a accuracy of 2 mm and 1.5° of rotation [5]. However, there have been some problems determining anatomic landmarks on bi-planar radiographs. Additionally, its complexity, including the requirement for special equipment, makes this method difficult to use in routine clinical settings [6], more invasive methods involve either inserting wires into the spinous process [7] or, as in radiostereometric analysis (RSA), insertion of tantalum balls into the bone during surgery [8–10]. The reported precision for measurement of lumbar spine translation using RSA is 0.2–0.6 mm [8–10].

New devices such as disc prosthesis can change the movements and magnitude of the individual facet joint, causing more stress to the joint, which could lead to earlier degeneration. Therefore, we believe that it is important to analyse if there is any changes in the individual facet joint after disc prosthesis operations. To our knowledge no method has focused or seems to have the ability to analyse movement of the individual segmental facet joint in 3D. The new generation of multislice computed tomography (CT) units offers highly accurate spatial volume resolution without significant distortion. By adjusting settings such as pitch, voltage, and collimation, it is possible to significantly reduce the radiation dose to the patients. Using CT scanning coupled with volume registration to study the spine is an evolving technique. One research group has used Euler angles and volume registration generated from CT reconstructions to analyse axial rotation around the longitudinal axis from L1 to S1 in both asymptomatic and symptomatic subjects [11, 12]. We have also used CT scanning coupled with volume registration to assess 3D motion in the lumbar spine with an accuracy of 0.6 mm in all segmental translations in a phantom [13–15].

The primary aim of the present study was to assess 3D movement of the facet joints and the segmental rotation of the vertebrae in the lumbar spine with the aforementioned method in healthy subjects. A secondary aim was to assess

the repeatability of the method and to determine the accuracy of rotation using a phantom.

Materials and methods

Eleven healthy asymptomatic subjects with no history of low back pain were recruited from the hospital staff in the current study, five males and six females with a mean age of 35 years (28–49) and a mean BMI of 24. In one male a spondylolysis at L4 was revealed and he was excluded from further analysis. Each subject signed an approved informed consent form (Ethical committee Approval No. 03-663).

The subjects were placed on a custom made jig (OT-Center, Danderyd, Sweden), which can with different blocks provoke the lumbar spine into flexion or extension. A provocation of the spine was made in supine position for extension and in prone position for flexion (Figs. 1, 2). Low back pain during examination was assessed using a Visual Analogue Scale (VAS). The subjects were gradually provoked in the jig up to maximal flexion or extension but stopped if the low back pain was over 70 on the 100 VAS scale or if in prone position the space between the top of the CT scanner tunnel and the subject's spine was too small. The subjects underwent two CT scans, one in flexion provocation and one in extension provocation. Subjects were examined using a fourth generation spiral computer tomography unit (Light Speed QX/i, General Electric Medical Systems, Milwaukee, WI, USA). Images were acquired with 1.25 mm collimation and a pitch of 3 (0.75 mm/rotation), at 250 mA, 120 kV, from L4 vertebra to S1 vertebra. Images were reconstructed with 1.25 mm slice thickness. The radiation dose was calculated to be 0.68 mSv per scan. Image post-processing was performed using a 3D volume fusion tool. This semi-automated tool has a graphical interface and is used to perform landmark-based fusion of two volumes, registering the “target” volume with the “reference” volume. A more detailed technical description can be found in our previous publications [13, 16–18].

Fig. 1 A subject on the jig in extension provocation

Fig. 2 A subject on the jig in flexion provocation

The measurement of movement in the spine between extension and flexion examinations were performed in two steps:

1. The two volumes were registered so that the volumes of the L5 vertebra in the flexion and extension acquisition were fused in spatial alignment in the same coordinate system i.e. the entire volumes are now placed in the same coordinate system by rigid body transformation. The coordinate system was defined by the CT scanner and the origin of this system was located in the centre of the CT volume. All rotations and translations were calculated in this system.
2. Facet joint translation and segmental rotation of L4 and S1 in respect to L5 where measured in the registered volumes.

The first step was to register L5. We placed nine co-homologous landmarks in the L5 vertebra in the extension and flexion CT volumes. To create a stable rigid body, the landmarks were spread widely in 3D throughout the vertebrae. To determine how well the vertebra was registered we used both visual and numeric analysis. In the visual analysis we superimposed the registered and the reference vertebra in 2D (Fig. 3), and in 3D (Fig. 4).

Fig. 3 2D slice image of the L5 vertebra after registration. The window is split so that the *bottom half* is the reference volume, and the *top half* is the registered volume

Fig. 4 3D isosurface representation of L5 after registration. The reference and registered volume are represented by *different colours*. Note the “zebra-like” interference pattern between the colours, indicating a good match. This pattern arises when the overlap is better than the smallest image element (the voxel). These images can be viewed from an arbitrary angle

For the numeric analysis, we first transformed the landmarks in the target volume using the same transform as had been applied to the entire volume. The distance differences between the reference landmarks and the transformed target landmarks were then calculated. If the mean landmark distance was 0.9 mm or less, which is smaller than the slice thickness, then the registration was deemed acceptable. When the registration was accepted, the transformed volume was saved, giving us two volumes with the L5 vertebra in nearly the same position in the same coordinate system. This transformed volume was then used as the target volume in the rest of the analysis.

In the second step we used these registered L5 volumes; we placed nine co-homologous landmarks in L4 and S1, respectively, spread in 3D for stability. To check that these landmarks are co-homologous we registered L4 and S1, respectively, and if this brought these vertebrae into alignment, then (using our visual and numeric analysis as above) the landmarks were accepted. From the rotation matrix generated from the rigid body transformation we obtained the Euler angles by decomposing the matrix in the following order: $R_z R_y R_x$ where R_x is the rotation about the X-axis (i.e., the sagittal plane) and was applied first, into the cardinal axes of the vertebra L4 and S1 in relation to L5.

In the facet joint analysis we used the volumes created in the first step, we registered four landmarks in each individual joint at the L4 and S1 level. The landmarks were placed co-homologous in the two volumes as follows, one in the most cranial point, one in the most caudal point, one in the most anterior point and one posterior point in the periphery of each joint facet (Fig. 5). The same registration test was performed using these landmarks as mentioned above. From the translation matrix generated from the rigid body transformation we obtained the 3D movement of the

left and right facet joint in L4–L5 and L5–S1. This was expressed as the translation of the rigid body in 3D.

Repeatability is defined as the precision under conditions where independent test results are obtained with the same method on identical test items in the same laboratory by the same operator using the same equipment, within a short interval of time [19]. We performed a repeatability test by post-processing and analysing five of the subject's volumes twice, iterating the entire sequence of image post-processing described above. Since we had not sought approval from the ethical committee for repeated examinations, we were not able to examine the subjects twice using CT. The repeatability test was therefore limited to the method itself and not to possible variations due to inconsistencies caused by repetition of the prone and supine provocation in the individual subject. The repeatability of this method has been previously validated in our previous study using the spine phantom [13]. In order to determine the accuracy, defined as the closeness of agreement between a test result and an accepted reference (a 'true') value, for rotation we used a phantom that has been used in a previous study in which we studied the translation [13]. The phantom consists of three plastic vertebrae (L3–L5) with 1 mm tantalum bullets. The L3 vertebra is connected into a gyro that can rotate in all three cardinal axes. We did 24 CT scans (12 cases) with the phantom with controlled rotations in different cardinal axes. The post-processing was done as described for the healthy subjects. Calculation of accuracy was made according to Ranstam [18, 19].

Evaluation of the measurement errors was performed according to International Standards Organization definitions (ISO 3534-3:1999) [19]. In a phantom study we have shown that there is no systematic error with this method

[13], but since we have only a small number of cases and we could not be sure that we had any systematic error we calculated the repeatability assuming both random and systematic errors.

Results

All subjects were able to extend and flex the spine in the jig with only moderate low back pain during examination (assessed as 30 on averages on the VAS scale during provocation in the jig). The space in the CT-tunnel was enough for provoking in flexion in all subject. All the vertebrae could be successfully recorded and analysed. There was no sign of movement artefacts in the CT volumes.

Image registration of the L5 vertebra was successful in all cases. In the numeric analysis the mean value for error in all the landmarks in the human vertebrae was 0.67 mm (0.49–0.83) and in the phantom 0.35 mm (0.20–0.57). The visual analysis of the registration of L5 is exemplified in Figs. 3 and 4.

Facet joint translation measurements in registered CT volumes are summarised in Table 1. In provocation CT from flexion to extension the mean facet joint 3D movement for L4–L5 was 6.1 mm (3.1–8.3) for the right facet joint, and 6.9 mm (4.9–9.9) for the left facet joint. The mean facet joint 3D movement for the L5–S1 segment was 4.5 mm (1.4–6.9) for the right joint, and 4.8 mm (2.0–7.7) for the left facet joint. Figure 6 illustrates facet joint translation after registration of the L5 vertebra.

Segmental rotation measurements are summarized in Table 2. The mean rotation at the L4–L5 level was 14.3° (9.8–16.2) in the sagittal plane, 0.9° (–0.9 to 2.8) in the coronal plane and 0.6° (–0.4 to 1.5) in the transverse plane.

Fig. 5 Close-up of the right L4 facet joint in a 3D volume. The landmarks are all placed on the L4 side of the facet joint; one in the most cranial point, one in the most caudal point, one in the most anterior point and one posterior point in the periphery of the facet

Table 1 Facet joint translation (mm) measured in registered CT volumes

Subject	Right joint L4–L5 (mm)	Left joint L4–L5 (mm)	Right joint L5–S1 (mm)	Left joint L5–S1 (mm)
1	3.1	6	6.9	5.9
2	6.9	7.1	3.2	4.5
3	5.5	5.8	3.9	4.2
4	3.8	4.9	1.8	2.0
5	6.7	7.8	6.5	7.7
6	8.3	9.9	1.4	2.4
7	6.4	6.7	6.3	5.9
8	6.4	6.8	3.8	3.4
9	6.6	7.2	5.7	6.1
10	6.9	6.7	5.5	5.8
Mean	6.1	6.9	4.5	4.8

Fig. 6 Facet joint movement in L4–L5 represented in 3D. Note the Zebra pattern in L5 that indicate a almost perfect match

The mean rotation for the L5–S1 was 10.2° (2.4–16.1) in the sagittal plane, 0° (−1.3 to 1.2) in the coronal plane, 0.2° (−0.7 to 0.3) in the transverse plane. Figure 7 illustrates segmental rotation after registration of the L5 vertebra.

Repeated analysis of five subjects of the facet joints and rotation for L4–L5 and L5–S1 are presented in Table 3. In summary, the mean of the repeated analysis for 3D facet joint movement was 5 mm and standard error of mean was 0.6 mm. The repeatability width was 1.8 mm (CI 95%). For rotation in the sagittal plane the mean was 11.5° and standard error of mean 1° . The repeatability for rotation was 2.8° (CI 95%). The accuracy for rotation in the phantom was in the sagittal plane 0.7° , coronal plane 1.0° and 0.7 in the transverse plane.

Fig. 7 On-screen representation of a L4–L5 flexion between measured to 9.8° in the sagittal plane. 3D isosurface display. The volume colours are reduced so they are more transparent which makes it easy to see the movement in L4. Note that L5 looks like a single vertebra due to an almost perfect match (fused)

Discussion

The presented method is a truly a non-invasive 3D method and has the ability to measure and visualise single facet joint movement in the vertebral segment. None of the other methods reported in the literature can address the facet joint as our method can. RSA is an invasive method, and therefore has its limitation. It is precise but also invasive, since tantalum markers have to be implanted in the vertebrae. Furthermore, the acquisition and analysis is not easy, the method is time consuming, and the output is purely numeric and can be difficult to interpret. Consequently

Table 2 Lumbar segmental rotation expressed in Euler angles ($^\circ$) in L4–L5 and lumbar segmental rotation expressed in Euler angles in L5–S1

Subject	Sagittal L4–L5	Coronar L4–L5	Transverse L4–L5	Sagittal L5–S1	Coronar L5–S1	Transverse L5–S1
1	9.8	2	0.9	8.5	−0.7	0.3
2	13.4	−0.6	1.5	3.6	0.2	−0.7
3	15.6	0.8	0.5	11.1	−0.2	−0.2
4	14.8	2.8	0	16.1	−0.3	−1
5	13.1	0.6	0.2	14	1.2	0.1
6	15.7	0.1	1	2.4	0.3	−0.1
7	16.2	2.1	1.2	9.2	−1.3	−0.4
8	15.6	0.5	0.6	14.8	−0.3	−0.6
9	14.1	0.9	−0.4	8.4	0.1	0.3
10	14.3	−0.4	0.2	14.3	0.4	−0.2
Mean	14.3	0.9	0.6	10.2	0	−0.2

Table 3 Repeatability test. For segmental rotation (°) in L4–L5 and L5–S1 and 3D translation for facet joints (mm)

Type of motion	Mean	SEM	CV%	Repeatability
Rotation (°)	11.8	1.0	8.5	2.8
Translation (mm)	5.0	0.5	12.9	1.8

RSA is not suitable for routine clinical use. The DCRA method is a 2D method that uses computerized analysis on lateral radiograph views. The reported errors are low, 1.2 mm and 1.6° [2] in a cadaver model with fixed vertebrae and should therefore be compared with the accuracy of 0.5 mm and 0.9° in our phantom study [13]. Other studies using CT examinations and image registration to investigate the lumbar spine movements have reported an accuracy of 0.1 mm in vertebral translation in the axial plane [11]. This supports our finding that this method is suitable for detecting segmental movements with a high accuracy.

The present study on healthy subjects, both visual and numeric analysis showed a symmetric movement of the two facet joints in the segment in almost all cases. The principle movements occurred in the sagittal direction and were on average 14.3° in L4–L5 and 10.2° in L5–S1. In the axial and coronal plane the movements were less than 3° in all cases. In the facet joints the 3D motion was around 7 mm and could be detected with a precision of 1.5 mm. The precision of 1.8 mm for facet joint translation and 2.8° for vertebra rotation are probably slightly underestimated since we, to be on the safe side, have calculated as if there were both systematic and random errors in the analysis though earlier studies with this method have indicated that the method does not produce systematic errors [13].

In the current study we found that ROM in L4–L5 (14.3°) segment was similar with previously published results, however, L5–S1 (10.2°) segment movement tends to be smaller compared to other studies [2, 6, 10, 20]. It might indicate the problem of provoking the subjects into full flexion in that segment because of the limitation of the space of the CT-tunnel. All subjects in the present study could perform the examination with only mild discomfort which indicated that this set-up could be used for clinical examination of patients if pain can be controlled. Obese persons with BMI over 35 is a definitive problem in provoking flexion in this jig because the space in the CT-tunnel might not be wide enough to allow the provocation in a larger flexion. CT examinations, in general, expose the patients to a higher radiation dose than conventional radiographic examination. However, with modern CT scanners the protocol can be optimized to reduce the radiation dose. We adjusted the protocol in our CT scans in order to reduce the radiation dose to as low as 0.68 mSv/CT scan which is almost equal to a conventional 2D radiographic exposure [21]. In this study there were limited

numbers of subjects, but one of the main aims with this study was to show that we can detect rotation and individual facet joint movements and for that aim we believe that the number of subjects is sufficient.

In the future, new CT scanners and new software are likely to lower the radiation dose further. We had no problem in detecting areas in the vertebra suitable to place a landmark in order to perform the analysis with the aforementioned software, despite our low dose CT protocol. This method gives the possibility to assess and analyse different parts of the vertebra. For example, apart from analysing the individual facet joint movement and vertebra rotation, we can address several issues about how different devices such as disc prostheses, influence lumbar spine mechanics. Since this method is non-invasive and the examination can be performed using any modern CT-machine, it is suitable to use routinely in the clinical setting.

Conclusion

A method, suitable for clinical use, for assessing lumbar segmental movements, expressed as facet joint translation and vertebra rotation, was presented. The method could assess the translations of the facet joints and segmental rotation of the vertebrae in different planes with a high precision. We believe that this method of detecting movement in the spine is useful for both research and for clinical use.

Conflict of interest None.

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