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Measurement of angular and linear segmental lumbar spine flexion-extension motion by means of image registration

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Abstract *Background* The presently available method of measuring segmental lumbar spine mobility by means of superimposition of lumbar spine radiographs in flexion and extension lacks precision due to differences in the cortical outline of the vertebral bodies in flexed and extended position. The introduction of digital image processing has opened the possibility of computerised superimposition ('matching') of digital vertebral body images by means of image registration. Theoretically this technique allows more accurate image matching and, consequently, greater precision of measurement because the whole vertebral body image (not only its cortical outline) can be chosen as region of interest, with registration of all available digital information within this region. *Methods* To check accuracy and convenience of the new method, two computer program experts performed five image registration measurements of the five lumbar motion segments in five consecutive flexion-extension studies of old lumbar fracture,

spondylolytic spondylolisthesis and degenerative anterolisthesis. For comparison an experienced radiologist performed the same repeated measurements with the manual superimposition method.

Results Measurement error of the image registration method proved to be significantly smaller than that of the manual superimposition method. There was no overlap between the 95% confidence intervals of the mean standard deviations of experts A and B using the image registration method and the 95% confidence interval of the mean standard deviations of the experienced radiologist using the manual superimposition method. Besides, the image registration method proved to be more convenient because the whole procedure from import of the image data to display of the measurement outcomes lasted 2–3 min compared to 3–6 min for the superimposition method.

Keywords Lumbar spine · Flexion-extension · Image registration · Segmental motion

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Introduction

Measurement of degree of segmental lumbar flexion-extension motion from flexion-extension radiographs may be performed in several ways. At our department the manual superimposition method of Begg and Falconer [1]

has been generally used to measure angular motion (Fig. 1). On a horizontal viewing box the smaller-sized extension film covers the larger-sized lumbar flexion film. After manual superimposition of the cortical outlines of the sacrum (S), a water-resistant pencil line is drawn along one edge of the overlying film on the underlying film.

The process is repeated for the body of the fifth lumbar vertebra (L5) and a second line is drawn. The angle between both lines represents the range of angular flexion-extension motion L5/S. By superimposition of the cortical body outlines of L4, L3, L2 and L1, and again drawing the corresponding lines, the ranges of angular flexion-extension motion L4/5, L3/4, L2/3 and L1/2 can be measured.

The method has rather large examiner variability [2, 8] due to differences in vertebral body outlines on the flexion and extension images. These differences are related to differences in positioning and differences in vertebral projection as the result of motion out of the sagittal plane [6].

Digital image processing including digital radiography has opened the possibility of computerised superimposition ('matching') of vertebral images by means of image registration. This technique makes it possible to choose the whole vertebral body as region of interest (ROI), and to register all available digital image information within this region. We expected this technique to result in more accurate image matching than with the manual superimposition method and, consequently, in more accurate determination of angular and linear motion. A small comparative pilot study was conducted to investigate this.

Materials and methods

Patients

Five sets of digital lateral radiographs of the lumbar spine in flexion and extension were analysed. The sets belonged to five orthopaedic patients who had been consecutively referred to the radiological department because of possible lumbar spine instability related to old L1 injury (one patient), spondylolytic spondylolisthesis (three patients) and degenerative anterolisthesis (one patient).

Measurements

Two computer program experts A and B were familiarised with the computer program and instructed how to perform the procedure. In order to assess the repeatability of results, each expert performed the procedure five times, including import of the digital images into the computer. For each expert the mean values and standard deviations (SDs) of the five measurements were calculated (Tables 1 and 3). Measuring time for each expert for each patient, including import of the images into a 1.2 GHz processor, was registered.

To ensure trustworthy comparison, the manual measurements of angular motion, described in Fig. 1,

Table 1 Segmental angular flexion-extension motion (degrees) of patients I–V measured by observers A and B with the image registration method. Each value represents the mean $\pm$ SD of five measurements

Level	Patients					
		I	II	III	IV	V
L1/2	A	10.5±0.5	5.5±0.3	5.5±0.3	10.5±0.6	5.5±0.7
	B	11.2±0.3	6.0±0.5	5.7±0.1	10.0±0.3	5.9±0.3
L2/3	A	7.5±0.5	4.5±0.4	6.0±0.1	10.8±0.2	5.5±0.6
	B	7.0±0.7	4.4±0.3	6.3±0.4	11.3±0.1	5.7±0.4
L3/4	A	5.5±0.3	6.5±0.5	6.5±0.1	4.3±0.3	4.7±0.3
	B	5.1±0.8	6.1±0.8	6.3±0.1	3.8±0.6	4.9±0.1
L4/5	A	11.3±0.8	7.5±0.3	4.3±0.3	16.8±0.3	5.5±0.5
	B	11.5±0.3	7.4±0.5	3.8±0.3	17.0±0.5	5.2±0.5
L5/S1	A	3.5±0.7	12.5±0.1	9.9±0.5	13.1±0.4	4.8±0.4
	B	3.1±0.9	12.4±0.3	10.1±0.8	13.5±0.3	5.1±0.3

were performed by an experienced radiologist who had used the method for many years. Transparent film copies of the five sets of digital flexion-extension images were used. Complete investigation of each set was carried out five times (Table 2). After each investigation a 96% alcohol solution was used to remove the water-resistant lines from the films without leaving a trace.

The image registration method started with import (in DICOM format) of the digital flexion and extension images into the computer. After visualisation of the flexion and extension image on the monitor screen, the expert indicated the ROIs (vertebral body images) by placement of guiding crosses by means of a mouse pointer. As only corresponding vertebral bodies should be matched, the guiding crosses were placed in strict order, starting with the flexion images ('input images') from S1 to L1, followed by the extension images ('base images') from S1 to L1. The guiding crosses were placed within the cortical outline of each vertebral body, their exact position in the vertebral body image remaining arbitrary (Fig. 2).

After placement of the guiding crosses, the edge detection algorithm of Zheng et al. [9] defined the ROIs by computing the cortical outlines of the corresponding vertebral body images. Subsequently, image registration recorded the intensity values of all pixels within the cortical outlines. According to the order of placement of the guiding crosses, the computer started with matching the input ROI and base ROI of the sacrum (S).

With the ROIs of the sacrum matched, the ROIs of L5 were in the positions of flexion and extension with respect to the sacrum. To match the ROIs of L5, the L5 input ROI was spatially transposed to the L5 base ROI by angular rotation and linear displacement in the sagittal plane. This transposition allowed computation of angular rotation and linear displacement L5/S. Subsequently the images of L4 were matched, allowing computation of angular and linear motion L4/L5 etc..

Fig. 1 Larger-sized film with lumbar spine in flexion (*interrupted lines*) is covered by smaller-sized film with lumbar spine in extension (*drawn lines*). After exact superimposition of the outlines of the body of S, a line (*marked as S*) is drawn along one edge of the overlying film on the underlying film. The process is repeated for L5 and a second line is drawn. The angle between both lines indicates the range of angular motion L5/S1. By superimposition of L4, L3, and so on, and again drawing the corresponding lines, motion ranges of L4/L5, L3/L4, and so on, can be determined

Table 2 Segmental angular flexion-extension motion (degrees) of patients I–V measured with the manual superimposition method of Begg and Falconer. Measurement was performed by an experienced radiologist acquainted with the method. Each value represents the mean $\pm$ SD of five measurements. Magnification factor of the film copies of patients I, II, III and V was 0.39, and 0.5 in patient IV

Level	Patients				
	I	II	III	IV	V
L1/2	10.0 $\pm$ 1.4	5.6 $\pm$ 1.6	5.6 $\pm$ 1.4	10.6 $\pm$ 2.6	5.8 $\pm$ 0.8
L2/3	7.7 $\pm$ 0.5	4.4 $\pm$ 1.3	6.0 $\pm$ 1.1	11.0 $\pm$ 2.4	5.8 $\pm$ 1.7
L3/4	5.4 $\pm$ 0.3	6.4 $\pm$ 1.3	6.5 $\pm$ 1.1	4.0 $\pm$ 1.8	4.9 $\pm$ 1.9
L4/5	10.5 $\pm$ 0.8	7.3 $\pm$ 1.4	4.0 $\pm$ 1.0	16.8 $\pm$ 2.7	5.1 $\pm$ 1.5
L5/S1	3.8 $\pm$ 1.2	12.6 $\pm$ 1.2	10.3 $\pm$ 1.8	13.4 $\pm$ 2.0	5.6 $\pm$ 0.5

Table 3 Linear centroid displacement (mm) corrected for radiological magnification ($M_R = 1.2$) and pixel size ($p = 0.17$ mm) with the help of Equation 3 of patients I–V measured by observers A and B with the image registration method. Each value represents the mean $\pm$ SD

Level		Patients				
		I	II	III	IV	V
L1/2	A	3.5±0.6	1.7±0.6	1.7±0.4	3.5±0.7	1.8±0.3
	B	4.0±0.4	1.9±0.8	1.8±0.8	3.5±0.6	1.9±0.5
L2/3	A	2.3±0.8	1.3±0.5	1.7±0.6	3.1±0.6	1.7±0.2
	B	2.2±0.7	1.3±0.4	1.8±0.5	3.2±0.4	1.7±0.1
L3/4	A	1.9±0.3	2.1±0.3	2.1±0.3	1.5±0.7	1.3±0.7
	B	1.7±0.4	2.0±1.0	2.0±0.4	1.2±0.6	1.4±0.4
L4/5	A	3.7±0.3	2.3±0.7	1.3±0.4	5.7±0.4	1.9±0.4
	B	3.7±0.3	2.4±0.6	1.3±0.6	5.3±0.6	1.7±0.3
L5/S1	A	1.2±0.6	3.9±0.8	3.1±0.6	4.2±0.1	1.5±0.7
	B	1.2±0.8	3.8±0.8	3.1±0.1	4.7±0.6	1.6±0.8

Fig. 2 Monitor image of digital lateral radiographs of the lumbar spine in flexion (*left*) and extension (*right*), after vertebral body edge detection according to the method of Zheng et al. [9]. The ROIs are enclosed by the vertebral body outlines. To define the sequence of ROIs to be registered, placement of the guiding crosses (*x*) within the ROIs has to take place in strict order, starting with the flexion images ('input images') from S1 to L1, followed by the extension images ('base images') from S1 to L1

The image registration algorithm was programmed in MATLAB [7], which iteratively searches the ROI transposition that optimises the measure of similarity between the pixel values of the base and input ROIs [5]. For this purpose the cross-correlation coefficient between two images was chosen as measure. This had two reasons: (1) base and input ROIs may not be identical due to detector noise, image rotation and distortion; and (2) the pixel values of both ROIs are linearly related since both are acquired with similar settings.

To measure linear displacement, a fixed landmark was needed. As we had bony landmarks rejected as unreliable [6], the vertebral body centroid was chosen because it could be computed from the cortical vertebral body outline. As the outlines of the flexion and extension images tend to differ in shape, optimal matching of the image information of the flexion and extension ROIs was not accompanied by close fitting of their outlines, as

Fig. 3 Example of the two columns of ROIs corresponding with the flexion and extension image aligned at the level of L4. The outlines of the ROIs of L4 do not completely fit because of slight differences in vertebral body configuration in flexion and extension. Nevertheless, the image data within both ROIs are optimally matched by maximising the cross-correlation coefficient of the base and input images

shown for L4 in Fig. 3. To ensure identical position of the vertebral body centroids in the input and base ROIs, the double vertebral body outline was reduced to a single outline by tracing the outer parts only (Fig. 4). The centroid of S1 did not need to be determined because linear motion L5/S was defined as centroid displacement L5 with respect to a matched sacrum.

Analytical methods were conducted to compute angular motion and linear displacement in three steps. The first step reduced the two outlines of the matched base and input ROIs, as shown for L4 in Fig. 3, to a single outline by tracing their outer parts only. The image data within this new outline were represented by $m(i,j)$.

The second step computed the centroid of $m(i,j)$ by using:

$$c = \frac{\sum_i x_i m(i,j)}{\sum_{i,j} m(i,j)} \quad (1)$$

where (i,j) represents the row (i) and column (j), respectively, and x_i is a vector representing the i -axis of the image data. The new outline and the centroid (c) are depicted in Fig. 4.

The third step included the projections of the centroid (c) onto the top and left edges of the flexion and extension images, respectively, as shown in Fig. 5. Their distances ($x_{flexion}, y_{flexion}, x_{extension}, y_{extension}$) were then measured in number of pixels.

Angular motion was calculated by using the trigonometry equation:

$$\alpha = \arccos\left(\frac{x_{flexion}}{x_{extension}}\right) \quad [\text{degrees}] \quad (2)$$

Linear centroid displacement in pixels was computed by applying the Euclidean distance:

Fig. 4 The two outlines (grey lines) of the matched vertebral body image L4 have been reduced to a single outline (black line) by tracing their outer parts only. The centroid of the image data within this outer edge is computed with Equation 1, and shown as a black dot

Fig. 5 The centroid is projected onto the left and top edges of the matched flexion (*dotted lines*) and extension (*interrupted lines*) images, respectively. Angle (α) indicates degree of angular motion L4/L5. Linear centroid displacement is calculated using the Euclidean distance given in Equation 3

$$D_p = \sqrt{(x_{flexion} - x_{extension})^2 + (y_{flexion} - y_{extension})^2} \text{ [pixels]} \quad (3)$$

Linear centroid displacement in mm was calculated by using Equation 3:

$$D_{mm} = \frac{D_p \times p}{M_R} \text{ [mm]} \quad (4)$$

where p is the pixel size, and M_R the radiological magnification.

According to the DICOM Reader the digital lumbar spine images always had a pixel size (p) of 0.17 mm.

Radiological magnification (M_R) was read from the ruler, vertically fixed over the spinous processes of the patient's back during radiography.

Statistical methods

In the analysis, patients and lumbar levels were considered independent with respect to measurement error. The measurements by each of the three observers were described by the mean of the five angle measurements and its corresponding SD.

Comparison of angle measurement error between the image registration method and the manual superimposition method was obtained by calculating the pooled SD and its 95% confidence interval, using the chi-squared distribution with 100 degrees of freedom. Actual pairs of SDs for each patient and each lumbar level were plotted, and the Wilcoxon signed ranks test was used to test whether measurement error between methods was different.

Results

Table 1 presents the mean and SD of all measurements of angular motion for experts A and B using the image registration method. Single investigation measuring time for each expert (A and B) ranged from 2 to 3 min. Pooled SD with 95% confidence interval was calculated as 0.44 (0.39–0.51) for expert A and 0.48 (0.42–0.56) for expert B.

Table 2 presents the mean and SD of all measurements of angular motion according to the method of Begg and Falconer [1] by one experienced radiologist. Measuring time ranged from 3 to 6 min. Pooled SD with 95% confidence interval was calculated as 1.54 (1.35–1.78).

Fig. 6 shows the SDs of pairs of angular motion measurements. The Wilcoxon signed ranks test provided a p -value < 0.001 for both comparisons (expert A versus manual superimposition method: $z = -4.11$, and expert B versus manual superimposition method: $z = 4.19$).

Table 3 shows the mean and SD of all measurements of linear flexion-extension motion by means of image registration. The values were obtained together with the values of angular flexion-extension motion, shown in Table 1. Linear displacement was computed in pixels, but has been converted into mm with the help of Equation 3.

Table 4 presents centroid displacement (in mm) per degree of angular motion, calculated for examiners A and B by dividing the mean values of Table 3 by the mean values of Table 1.

Fig. 6 Representation of the SDs of pairs of measurements. The Wilcoxon signed ranks test provided a p -value < 0.001 for both comparisons (expert A versus manual superimposition method: $z = -4.11$, and expert B versus manual superimposition method: $z = 4.19$). The diagonal line represents the situation where SDs of both measurements are equal

Discussion

Compared with the manual superimposition method, the image registration method proves to have greater precision and convenience. The only required user intervention is import of the digital radiographic images into the computer program, and placement of a guiding cross on each of the six vertebral bodies L1–S in flexion and extension (Fig. 2). After this intervention the computer automatically produces segmental angular motion and linear displacement. The length of a single investigation varies between 2 and 3 min.

Measurement error of the image registration method is significantly smaller than that of the manual superimposition method. There was no overlap between the 95% confidence intervals of the pooled SDs of experts A and B using the image registration method and the 95%

Table 4 Mean linear centroid displacement (mm) per degree of angular motion

Level	Patient									
	I		II		III		IV		V	
	A	B	A	B	A	B	A	B	A	B
L1/2	0.33	0.36	0.31	0.32	0.33	0.35	0.35	0.31	0.32	0.33
L2/3	0.30	0.31	0.28	0.29	0.29	0.28	0.32	0.32	0.30	0.29
L3/4	0.35	0.34	0.33	0.32	0.34	0.32	0.35	0.36	0.28	0.29
L4/5	0.33	0.32	0.31	0.33	0.34	0.31	0.29	0.28	0.34	0.33
L5/S1	0.35	0.40	0.31	0.31	0.32	0.35	0.33	0.32	0.32	0.31

confidence interval of the pooled SDs of the manual superimposition method. Comparison of Tables 1 and 2 shows that the mean values of repeated manual measurement approach those obtained by the image registration method. This is an indication that the image registration values reflect reality and are not subject to system error.

Frobin et al. [4] developed a precision method, which is not based on superimposition but on comparison of identical landmarks and lines drawn on the flexion and extension films, allowing calculation of both angular and linear motion. Its precision is higher than that of the manual superimposition method, but the necessity of drawing strictly defined lines and calculating angular and linear motion from differences in line angulation and line length makes the method of Frobin et al. very time-consuming and hence less suitable for routine practice.

The image registration method measures linear centroid displacement in pixels, which was converted into mm by correcting for pixel size and radiological magnification (Equation 3). As Table 4 shows, mean centroid displacement per degree of angular motion ranges from 0.28 mm to 0.40 mm. Linear displacement per degree of angular motion may facilitate judgement whether a given extent of displacement is normal or not [3]. Fig. 7 demonstrates that once degree of angular motion and extent of centroid displacement is known the instantaneous centre of motion (ICM) can be constructed.

The lumbar spine was chosen to apply the principles of image registration because of its relatively simple radiological anatomy and the relatively large size of the lumbar vertebral bodies. Further research will have to decide whether the image registration method will yield comparable accuracy in measurement of degree and extent of motion of the cervical spine, the craniovertebral region and other joints.

Conclusion

For many years, radiographs of the lumbar spine in flexion and extension have served all over the world to detect abnormal segmental mobility and vertebral instability. Theoretically they allow quantification of degree of angular rotation and extent of linear displacement in each of the lumbar motion segments, but in clinical practice this possibility is hardly exploited because the available methods are either not reliable enough or too time-consuming.

Fig. 7 The ICM is found on the mid-perpendicular of the actual linear displacement line D , connecting the centroid of the upper vertebral body in flexion (C_F) with the centroid of the upper vertebral body in extension (C_E). The ICM is found by giving the angle α the value of the actual flexion-extension angle of rotation

It is hoped that the here described more accurate and more convenient method of measurement of segmental vertebral motion by means of image registration will renew interest in diagnosis of abnormal segmental mobility and vertebral instability.

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