SPINE Volume 29, Number 15, pp 1636–1641

The Flexion–Extension Profile of Lumbar Spine in 100 Healthy Volunteers

Kris W. N. Wong, PDPT, Mphil,* John C. Y. Leong, FRCS, FRCSE, FRACS,* and Man-kwong Chan, MBBS, FRCR,† K. D. K. Luk, FRCS, FHKAM (Ortho),* and W. W. Lu, PhD*

Study Design. Dynamic lumbar flexion–extension motions were assessed by an electrogoniometer and a videofluoroscopy unit simultaneously.

Objectives. The aims of this study were to assess the motion profile of lumbar spine in different genders and age groups and to assess their differences.

Summary of Backgrounds Data. The dynamic lumbar flexion–extension motions analysis method has been developed and validated. However, data profile of the spinal motions of healthy volunteers has not been established.

Methods. A total of 100 healthy volunteers, including 50 men and 50 women, were recruited. They were then divided into four equal groups, following their age ranges of 21 to 30 years, 31 to 40 years, 41 to 50 years, and 51 years and older. Lumbar flexion–extension motion was assessed with an electrogoniometer and videofluoroscopy simultaneously. Radiologic images of the lumbar spine were captured during flexion–extension in 10° intervals. Intervertebral flexion–extension (IVFE) of each vertebral level was calculated. The spinal motion of different genders was compared segment by segment with independent *t* test. The spinal motion of different age groups was compared with one-way analysis of variance.

Results. A linear-liked pattern of the IVFE curves was observed in different genders and age groups. No statistically significant difference in the pattern of motion was found between genders. However, statistically significant difference in the slope of IVFE curves was found at all lumbar levels in subjects whose age was 51 years or older ($P < 0.05$).

Conclusions. Assessment of motion profile was found to be helpful for the identification of spinal disorders in clinical practice. Because of the normal variation of spinal motion of subjects in different age ranges, interpretation of spinal motion disorders should be careful. Although the sample size in this study was limited, the database generated might be useful to assist the diagnosis of spinal “instability” in the future.

Key words: motion, lumbar spine, genders, age groups. **Spine 2004;29:1636–1641**

With the advancement of technology, assessment of the lumbar spinal motion is relatively accurate and reliable.[1–4] Following this research direction, the next target is to develop a normative database of lumbar spinal motion. This is because pathologic spinal motion can be identified only if “normal” spinal motion is defined.

Fitzgerald *et al*[5] probably were the pioneers in developing a database of “normal” lumbar spinal motion in 172 subjects. Using different measurement devices, studies of lumbar spinal motion in different scales have been reported recently.[6–8] Sullivan *et al*[9] even reported their “norm” of sagittal plane range of motion (ROM) in the lumbar spine with a sample size as large as 1126 healthy subjects.

Among these studies, merely anatomic ROM (ROM) of the whole lumbar spine was measured. However, it is well known that the value of ROM is limited. Ensink *et al*[10] showed that the ROM would vary significantly even within the same day. Another limitation of this assessment method is that the diagnostic power of ROM is insufficient. It is inadequate to assist surgeons to identify the specific problematic lumbar motion segment. This is particularly important for the operative management of patient with spinal disorders as all the surgical procedures are location specific. Therefore, it is necessary to develop a database of the segmental motion of the lumbar spine in the general population.

The aims of this study are to assess the motion profile of lumbar spine in different age groups and genders and to assess their differences.

Methods

Study Participants. It was designed to recruit four groups of healthy volunteers, Groups A to D, and the sample size of each group was 25. All of them denied having any history of back pain in the past 6 months. It was also designed to recruit nearly equal number of male and female subjects in each group. The age ranges of Groups A to D were fixed between 21 and 30 years, 31 and 40 years, 41 and 50 years, and those 51 years and older, respectively.

Procedures and Data Analysis. A lumbar spinal motion analysis system was developed using a spinal electrogoniometer, a videofluoroscopy (VF) unit, and a tailor-made image digitizing system (Figure 1). The spinal electrogoniometer was an in-house developed device comprised a series of metal link bars and three high-precision potentiometers installed at the movable joints of the link bars. The function of that was to assess the continuous anatomic motion of the lumbar spine at the sagittal plane. The analogue signals of the potentiometers were then digitized and stored at a portable computer by means of an analogue to digital conversion system, DataQ, and a data acquisition software, Windaq version 1.71, at a sampling rate

From the *Department of Orthopaedic Surgery, Queen Mary Hospital, University of Hong Kong, Pokfulum, Hong Kong; and †Radiology and Imaging, Queen Elizabeth Hospital, Kowloon, Hong Kong.
Acknowledgment date: May 27, 2003. First revision date: September 28, 2003. Acceptance date: September 29, 2003.
The manuscript submitted does not contain information about medical device(s)/drug(s).
No funds were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.
Address correspondence and reprint requests to Kris W. N. Wong, MPhil, Department of Physiotherapy, Queen Elizabeth Hospital, Kowloon, Hong Kong; E-mail: kriswong@hkusua.hku.hk

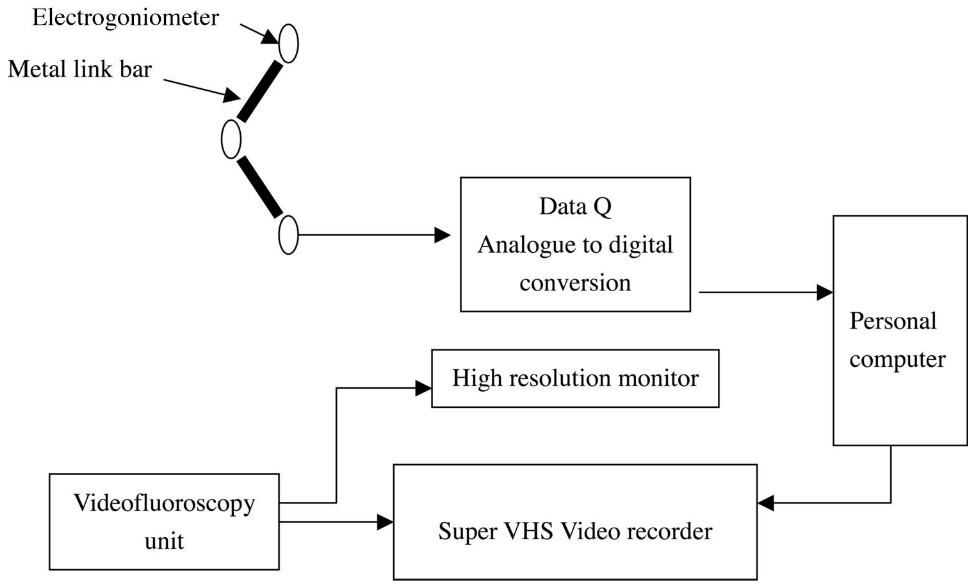

Figure 1. Schematic diagram of the lumbar spinal motion analysis system.

of 100 Hz. The VF used in this study was a standard clinical unit, manufactured by the General Electronic Ltd. The radiographic exposure factors of the unit, such as kilovoltage and milliampere second, were automatically regulated. During screening, the images were displayed with a high resolution monitor (1260 lines per second) and could be recorded with a super VHS video recorder. To assess the coherent motion of the lumbar spine in both the intervertebral and anatomic levels, synchronization of the video output signals of the VF and the spinal electrogoniometer data was designed. By using a connection cable, the computer was connected to an input socket of the video recorder. When the computer was triggered off to collect the spinal electrogoniometer data, the computer would immediately generate a signal and transmit to the video recorder, producing a blank screen in the recording. When the videotape was rewound and played back, the blank screen could be traced. This marked the commencement of the data collection in the electrogoniometer. As a result, the frame numbers of the radiographic images of the lumbar spine could be matched with the electrogoniometer data. For processing the radiographic images, the lumbar spinal motion were captured in every 10° intervals of flexion–extension of the lumbar spine, using a DC30+ monochrome frame grabber (Pinnacle systems, CA) and Adobe Premiere 4.2 computer software.

During the assessment, the subjects were asked to wear a harness at the upper back and another harness at the back of the pelvis. The electrogoniometer was then attached to these harnesses and connected to the computer. The subjects were instructed to stand upright between the image intensifier and the examination table (Figure 2). The intensifier was then positioned by the side of the subjects' backs. The lumbar spines were screened to confirm the correct focus of the image intensifier. The radiograph beam field of the VF unit was collimated to obtain optimal sharpness of the image. The magnification of the image intensifier was adjusted so that the size of the imaging field is large enough to view the whole lumbar spine.

Before actual screening, the subjects were allowed to practice the flexion–extension of the lumbar spine a few times with correction. The electrogoniometer and the video recorder were activated. The study participants were asked to perform flexion, extension, and return to the neutral position at their own speed three times with rest in between. To capture the whole lumbar spinal motion, the image intensifier was controlled by the radiologist and being moved along the lateral side of the back during image capturing while the subjects were performing lumbar flexion and extension. The anatomic motion of the lumbar spine was stored in the notebook computer while the images of the segmental spinal motion were recorded in an SVHS videotape.

The retrieved data then underwent distortion correction and analyzed by an in-house developed image analysis program, Dibview 4.0. During the image analysis, the program was run and the processed images of the subjects were displayed, frame by frame, on a high resolution monitor. By selecting the image that the spine was in the neutral position, the user was instructed by a dialogue box to draw straight lines along the four borders of each vertebral body, from L1 to L5 vertebrae, based on the method devised by Dvorák *et al.*[11] Having marked the borders of the vertebral bodies, the templates of each vertebra were generated. The position of each vertebra was denoted by the intersection points of the four lines. The coordinates of

Figure 2. Subject stands upright between the image intensifier and the examination table.

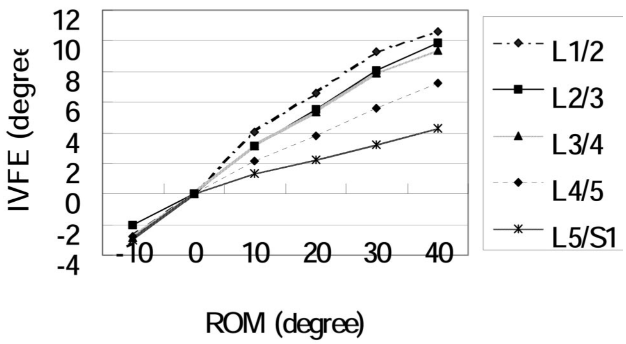

Figure 3. IVFE of lumbar spine in 100 healthy volunteers.

these points were calculated and saved into data files. The subsequent image in the next interval was retrieved and the templates of the vertebrae in the previous image were redisplayed in the monitor. The user was requested to drag the templates to overlap the corresponding vertebrae, by means of the computer pointing device. The new set of corresponding coordinates of the lumbar vertebrae were denoted and saved. The procedure was repeated for the rest of the captured images. The reliability, reproducibility, validity, and the inherent error measurements of the developed motion analysis system as well as the assessment procedure were detailed in our previous report.[12]

Following the analysis method devised by Dvorák *et al*[11] and Cholewicki *et al*,[13] the intervertebral flexion–extension (IVFE) between lumbar vertebrae was then calculated. Using the linear regression method, the change in IVFE throughout the assessment ROM that was defined as motion gradient, was calculated at each vertebral level and that in different gender and age groups. Comparison of the change in IVFE throughout the assessment ROM in different gender and age groups was performed with independent *t* test and one-way analysis of variance (ANOVA), respectively. For any statistically significant findings obtained in the ANOVA, Scheffé's *post hoc* tests were performed to identify the difference among the IVFE at each vertebral level. The level of significance was set at 0.05. A profile of normal spinal motion was established

■ Results

A total of 100 healthy volunteers participated in this study, including 50 men and 50 women. Their mean age was 39.2 years (range, 20–76 years). The number of the subject in Group A (range, 21–30 years), Group B (range, 31–40 years), Group C (range, 41–50 years), and Group D (51 years or older) were 30, 26, 21, and 23, respectively.

Lumbar Spinal Motion in 100 Healthy Volunteers

The average terminal flexion was 53.0° ± 10.2° while the average terminal extension was 23.4° ± 8.3°. As it was aimed to assess the spinal motion in a common ROM, analysis was performed between 40° of flexion and 10° of extension, in every 10° interval. The IVFE in each lumbar vertebral level is presented in Figure 3. In L1–L2, the IVFE increased steadily from 10° of extension to 40° of flexion. A linear-liked motion pattern of the IVFE curve was observed. The IVFE curve of L2–L3 aligned immediately next to L3–L4 and a linear-liked pattern of the curve was observed again. Similarly, the IVFE curve of L4–L5 and L5–S1 increased steadily from 10° of extension to 40° of flexion. Similar linear-liked pattern of the IVFE curve in different levels was identified. It was also found that the motion gradient (slope) of the IVFE curves decreased from L1–L2 to L5–S1 in descending order. However, in extension, the slope of the IVFE curves in different vertebral levels was found to be about the same, with an exception in L5–S1, which was relatively less steep than the rest. To test the fitness of using a straight-line model to present the IVFE curves, the results were assessed against general linear model followed by residual analysis. No statistically significant differences in the predicated values and residuals were found in any vertebral level. Therefore, the IVFE curves were assumed to be straight line in the rest of this report.

Lumbar Spinal Motion in Different Genders

The IVFE of the male and female study participants during flexion–extension in different ROM is summarized in Table 1. For the comparison of the spinal motion between male and female study participants, the assessment results were divided by genders. Using linear regression, the slopes of the IVFE curve at different levels were calculated. The slopes of the IVFE curves in each gender group were then compared with independent *t* test. Again, no statistical significant difference was found in either level between genders.

Lumbar Spinal Motion in Different Age Groups

The IVFE of different age groups were listed in Table 2. In 10° of extension, it was found that the IVFE generally

Table 1. Comparison of the IVFE in Different Genders

	L1–L2		L2–L3		L3–L4		L4–L5		L5–S1	
ROM	M	F	M	F	M	F	M	F	M	F
−10	−2.4 ± 1.1	−3.1 ± 1.2	−2.3 ± 1.1	−1.8 ± 1.0	−1.8 ± 0.7	−3.8 ± 0.9	−1.8 ± 1.0	−3.7 ± 1.0	−2.5 ± 0.8	−3.5 ± 1.1
0	0	0	0	0	0	0	0	0	0	0
10	3.4 ± 1.2	4.6 ± 1.7	3.4 ± 1.1	2.9 ± 1.0	2.9 ± 0.7	3.4 ± 0.7	2.0 ± 1.2	2.3 ± 0.8	1.5 ± 0.7	1.2 ± 0.5
20	6.1 ± 1.7	7.1 ± 1.9	5.9 ± 1.4	5.2 ± 1.1	5.2 ± 1.0	5.6 ± 0.9	3.9 ± 1.1	3.8 ± 0.8	2.4 ± 0.8	2.0 ± 0.7
30	8.8 ± 2.0	9.9 ± 2.3	8.6 ± 1.3	7.6 ± 1.3	7.6 ± 1.2	8.1 ± 1.3	5.7 ± 1.4	5.5 ± 0.9	3.7 ± 1.0	2.8 ± 1.1
40	10.0 ± 2.1	11.3 ± 2.4	10.6 ± 1.6	9.2 ± 1.7	9.2 ± 1.2	9.6 ± 1.6	7.5 ± 1.9	7.0 ± 1.6	4.5 ± 1.7	4.1 ± 1.5

Positive values indicate flexion, and negative values indicate extension.

Table 2. IVFE of the Lumbar Spine in Different Age Groups

ROM	Groups	L1–L2	L2–L3	L3–L4	L4–L5	L5–S1
−10	A	−2.6 ± 2.2	−2.5 ± 2.1	−1.8 ± 2.0	−1.3 ± 4.3	−2.4 ± 3.8
	B	−3.1 ± 2.0	−3.5 ± 1.9	−4.0 ± 1.7	−3.3 ± 2.0	−3.6 ± 2.3
	C	−2.8 ± 2.1	−3.5 ± 2.0	−2.9 ± 1.7	−4.2 ± 1.8	−2.8 ± 1.8
	D	−4.4 ± 2.4	−3.7 ± 2.1	−2.6 ± 1.7	−3.2 ± 2.4	−3.3 ± 1.9
0	A	0	0	0	0	0
	B	0	0	0	0	0
	C	0	0	0	0	0
	D	0	0	0	0	0
10	A	3.2 ± 2.7	2.8 ± 2.0	2.2 ± 1.4	1.6 ± 1.5	0.7 ± 1.3
	B	3.0 ± 2.4	2.8 ± 1.7	2.0 ± 1.3	1.3 ± 1.1	0.5 ± 0.6
	C	4.6 ± 2.0	4.3 ± 1.6	4.5 ± 1.0	1.3 ± 1.0	1.8 ± 0.9
	D	4.8 ± 2.7	4.5 ± 2.0	3.9 ± 1.3	2.7 ± 1.6	2.1 ± 1.0
20	A	5.5 ± 2.9	5.4 ± 2.1	4.4 ± 1.9	3.0 ± 1.8	1.1 ± 1.6
	B	5.8 ± 2.5	5.2 ± 1.8	3.8 ± 1.6	1.7 ± 1.6	1.2 ± 0.9
	C	6.7 ± 2.1	6.6 ± 1.4	6.2 ± 1.1	2.8 ± 1.0	2.0 ± 1.1
	D	7.9 ± 2.9	7.8 ± 2.4	6.7 ± 1.8	4.7 ± 1.8	3.8 ± 1.1
30	A	7.9 ± 3.3	7.6 ± 2.4	6.4 ± 2.4	4.3 ± 2.1	1.9 ± 2.1
	B	8.2 ± 3.0	7.4 ± 2.2	6.0 ± 1.9	3.2 ± 2.0	2.0 ± 1.0
	C	8.2 ± 2.6	8.0 ± 2.0	7.9 ± 1.3	4.5 ± 2.2	2.5 ± 1.0
	D	11.8 ± 3.0	11.7 ± 2.7	10.1 ± 2.1	6.4 ± 2.0	5.5 ± 1.6
40	A	10.0 ± 3.3	9.6 ± 2.7	8.2 ± 2.6	5.9 ± 2.6	2.8 ± 2.4
	B	10.2 ± 3.2	9.5 ± 2.5	8.2 ± 2.6	4.8 ± 2.3	3.2 ± 1.5
	C	8.5 ± 2.7	9.0 ± 2.2	8.1 ± 1.7	6.5 ± 2.4	2.5 ± 1.2
	D	13.7 ± 3.4	13.45 ± 2.6	11.9 ± 2.9	8.8 ± 2.4	7.3 ± 1.7

Positive values indicate flexion, and negative values indicate extension

increased from Group A To Group D in all spinal levels. Interestingly, similar pattern was also found throughout the flexion motion. As compared with extension motion, the differences in IVFE were found to be increased across Group A to Group D, from 10° to 40° of flexion.

At L1–L2 (Figure 4), the IVFE curve of Group D increased steadily from 10° of extension to 40° of flexion. As compared with Group D, the slopes of the IVFE curves of Groups A to C were found to be less steep. Using one-way ANOVA, the slopes of IVFE curves in different age groups were compared. A statistically significant difference in the slope was found in Group D among the other age groups ($P < 0.05$).

As compared among different spinal levels (Table 2), the IVFE gradually decreased from L1–L2 to L5–S1 in all the age groups. However, the IVFE curve of Group D was found to be different from the rest (Figures 5–8). The IVFE curves of Groups A, B, and C overlapped with each other while the slope of IVFE curves in Group D persisted to be larger than the other age groups. Similarly, using one-way ANOVA, the slopes of the IVFE curves among different age groups were repeatedly compared in L2–L3, L3–L4, L4–L5, and L5–S1, respectively. Statistically significant differences in the slope of Groups D were found in all levels ($P < 0.05$).

Discussion

Assessment of Lumbar Spinal Motion

It is generally thought that assessment of lumbar motion is helpful for the diagnosis of spinal disorders. For example, Bendo and Ong[14] showed that the dynamic motion of the lumbar spine could improve the accuracy in the diagnosis of lumbar spondylolisthesis. Fujiwara *et al*[15] investigated the effect of disc degeneration and facet joints osteoarthritis on the flexibility of the lumbar spine *in vitro*. They also investigated the stability of the lumbar

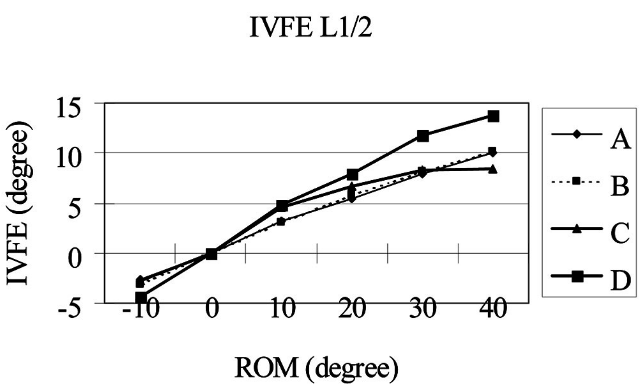

Figure 4. Comparison of the IVFE curves at L1–L2 in different age groups.

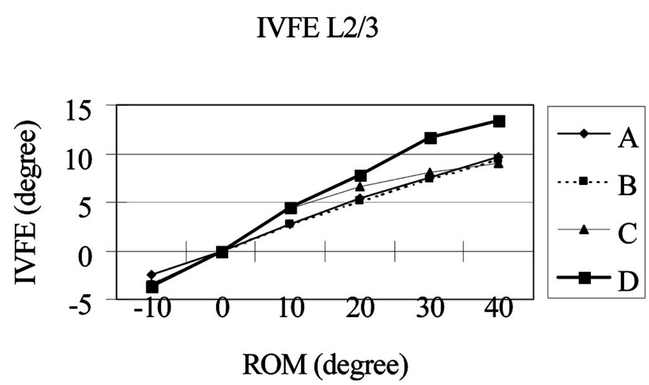

Figure 5. Comparison of the IVFE curves at L2–L3 in different age groups.

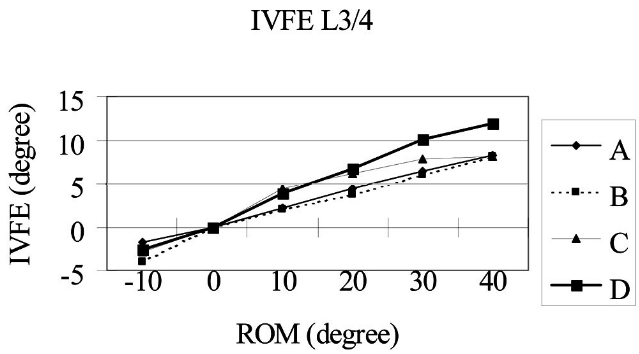

Figure 6. Comparison of the IVFE curves at L3–L4 in different age groups.

spine in 70 patients with radiologic signs of spinal degeneration. Their results showed that the kinematics of lumbar motion was closely related to the degree of spinal degeneration, which might help to explain the symptoms of the patients.

In relation to the assessment method of lumbar spinal motion, it was commonly performed by measuring either the anatomic or segmental motion of the lumbar spine.[2,15,16] However, the assessment methods varied from study to study.[17–19] In result, comparison of the database generated in previous studies[6–8] was not possible. Therefore, we proposed to standardize the assessment method by measuring the segmental motion of the lumbar spine at a number of common points of ROM.[12] Comparisons could be then made between individuals.

At most of the common assessment points of ROM (Figure 3), the IVFE decreased from L1–L2 to L5–S1. These results suggested that the flexibility of lumbar spine decreased generally from proximal to distal levels. Although this finding might not be able to apply to extension motion, based on the current results, it might at least explain the appearance of lumbar flexion initiating from upper segments to lower segments with phase lags in a recent report.[20] Lower segments of the lumbar spine had been suggested to be the key segments initiating extension.[21,22] However, our results showed that IVFE was about the same in different levels in extension. This implied that extension is evenly contributed by different

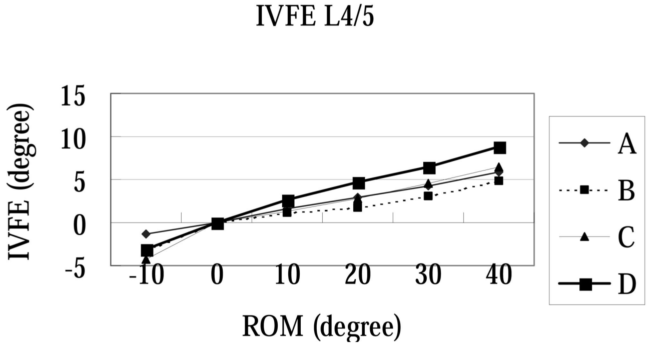

Figure 7. Comparison of the IVFE curves at L4–L5 in different age groups.

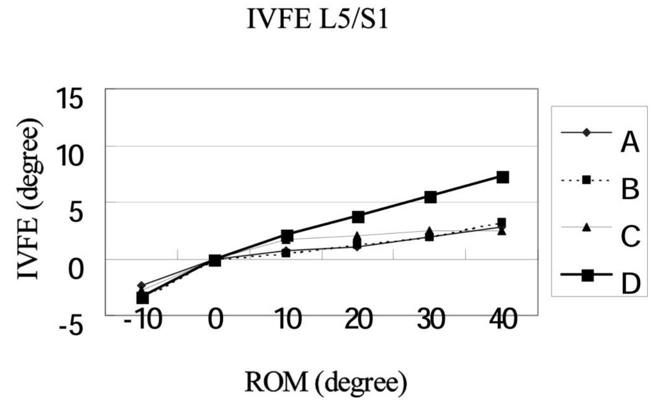

Figure 8. Comparison of the IVFE curves at L5–S1 in different age groups.

levels and the concavity of lumbar lordosis will increase steadily in extension. Our results also demonstrated that the segmental motion of lumbar spine was relatively linear in 10° of extension to 40° of flexion. This linear-liked motion pattern revealed that the lumbar vertebra moved in a sequential way and all the motion segments did contribute the lumbar physiologic ROM. It was important because detection of abnormal segmental motion in those pathologic spinal conditions could be made at any point of interest within the ROM. It might be useful to improve the clinical diagnosis of some spinal disorders, for example, "instability" of the spine in the future.

Lumbar Spinal Motion in Different Genders

In this study, the lumbar spine motion profile of the two genders was found to be similar. Dvorák *et al*[8] and Sullivan *et al*[9] assessed the ROM of the lumbar spine in 104 and 1,126 healthy subjects, respectively. No statistically significant difference in the terminal ROM was also found between the male and female study participants. Therefore, these results suggested that both the ROM and segmental lumbar spinal motion profile of the lumbar spine did not differ between the two genders.

Lumbar Spinal Motion in Different Age Groups

As statistical significant difference was found in the slope of IVFE curves of Group D compared with the other groups, it implied that attention should be paid to the interpretation of lumbar spinal motion. Previous studies showed that terminal physiologic ROM of the lumbar spine decreased as age increased.[5,8,9] Elderly subjects in our study (Group D, 51 years of age or older) showed a statistically significant decrease in physiologic ROM in both flexion and extension (Figure 9) but an increase in slope of the IVFE curve. Our results suggested that the segmental lumbar spinal motion profile did not change in the common ROM, 10° of extension to 40° of flexion, as age increased with the exception of the age exceeded 51 years. The result might imply that there was an increase in the stiffness of spine in elderly subjects. Mobility of the spine in the elderly was reduced. For the aging lumbar spine to achieve the same physiologic ROM, more inter-

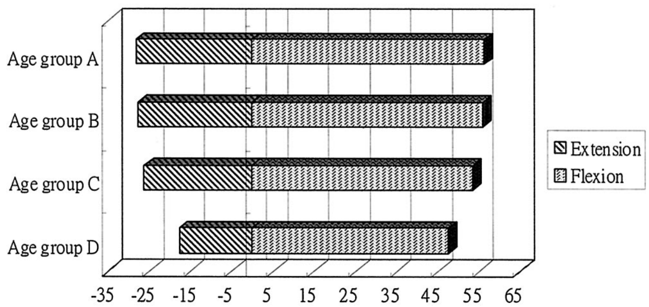

Figure 9. Decrease in physiologic ROM in both flexion and extension.

vertebral translation and rotation might be required in the older subjects. Our results stated that comparison of the mobility profile should be age specific. Interpretation of "spinal" instability should never be made without considering the age of the patients in the future.

■ Conclusion

Lumbar spinal motion profile was assessed in 100 healthy subjects. The proximal region of the lumbar spine was found to be more flexible than the distal region. A linear-liked motion was found in all the levels within the physiologic range of 10° of extension to 40° of flexion. No statistically significant difference in the motion profile was found between the two genders. However, the motion profile was found to be different in study participants between 21 and 50 years of age, as compared with that whose aged older than 51 years. Assessment of motion profile had shown to be potentially helpful for the identification of spinal disorders in clinical practice. Further research in the assessment of motion profile of patients with specific known diagnosis is encouraged. Although the number of subjects participated in this study is limited, our generated profile is useful to assist the diagnosis of spinal disorders, particularly when further data can be built on the current study.

■ Key Points

- Fluoroscopic measurement of lumbar intersegmental movement was conducted in healthy volunteers.
- A linear-like pattern of the IVFE curves was observed in different genders and age groups.
- The database generated is useful to assist the diagnosis of spinal instability in the future.

References

1. Rice J, Walsh M, Jenkinson A, et al. Measuring movement at the low back. *Clin Anat*. 2002;15:88–92.
2. Cooper R, Cardan C, Allen R. Computer visualisation of the moving human lumbar spine. *Comput Biol Med*. 2001;31:451–469.
3. Vogt L, Pfeifer K, Portscher M, et al. Influences of nonspecific low back pain on three-dimensional lumbar spine kinematics in locomotion. *Spine*. 2001;26:1910–1919.
4. Feipel V, De Mesmaeker T, Klein P, et al. Three-dimensional kinematics of the lumbar spine during treadmill walking at different speeds. *Eur Spine J*. 2001;10:16–22.
5. Fitzgerald GK, Wynveen KJ, Rheault W, et al. Objective assessment with establishment of normal values for lumbar spinal range of motion. *Phys Ther*. 1983;63:1776–1781.
6. Van Herp G, Rowe P, Salter P, et al. Three-dimensional lumbar spinal kinematics: a study of range of movement in 100 healthy subjects aged 20 to 60+ years. *Rheumatology (Oxford)*. 2000;39:1337–1340.
7. Troke M, Moore AP, Maillardet FJ, et al. A new, comprehensive normative database of lumbar spine ranges of motion. *Clin Rehabil*. 2001;15:371–379.
8. Dvorák J, Vajda EG, Grob D, et al. Normal motion of the lumbar spine as related to age and gender. *Eur Spine J*. 1995;4:18–23.
9. Sullivan MS, Dickinson CE, Troup JD. The influence of age and gender on lumbar spine sagittal plane range of motion: a study of 1126 healthy subjects. *Spine*. 1994;19:682–686.
10. Ensink FB, Saur PM, Frese K, et al. Lumbar range of motion: influence of time of day and individual factors on measurements. *Spine*. 1996;21:1339–1343.
11. Dvorák J, Panjabi MM, Novotny JE, et al. Clinical validation of functional flexion-extension roentgenograms of the lumbar spine. *Spine*. 1991;16:943–950.
12. Lee SW, Wong KWN, Chan MK, et al. Development and validation of a new technique for assessing lumbar spina motion. *Spine*. 2002;27:E215–E220.
13. Cholewicki J, McGill SM, Wells RP, et al. Method for measuring vertebral kinematics from videofluoroscopy. *Clin Biomech*. 1991;6:73–78.
14. Bendo JA, Ong B. Importance of correlating static and dynamic imaging studies in diagnosing degenerative lumbar spondylolisthesis. *Am J Orthop*. 2001;30:247–250.
15. Fujiwara A, Lim TH, An HS, et al. The effect of disc degeneration and facet joint osteoarthritis on the segmental flexibility of the lumbar spine. *Spine*. 2000;25:3036–3044.
16. McGregor AH, Cattermole HR, Hughes SP. Global spinal motion in subjects with lumbar spondylolysis and spondylolisthesis: does the grade or type of slip affect global spinal motion? *Spine*. 2001;26:282–286.
17. Bull AM, McGregor AH. Measuring spinal motion in rowers: the use of an electromagnetic device. *Clin Biomech*. 2000;15:772–776.
18. Takayanagi K, Takahashi K, Yamagata M, et al. Using cineradiography for continuous dynamic-motion analysis of the lumbar spine. *Spine*. 2001;26:1858–1865.
19. Edmondston SJ, Song S, Bricknell RV, et al. MRI evaluation of lumbar spine flexion and extension in asymptomatic individuals. *Man Ther*. 2000;5:158–164.
20. Coates JE, McGregor AH, Beith ID, et al. The influence of initial resting posture on range of motion of the lumbar spine. *Man Ther*. 2001;6:139–144.
21. Kanayama M, Abumi K, Kaneda K, et al. Phase lag of the intersegmental motion in flexion-extension of the lumbar and lumbosacral spine: an in vivo study. *Spine*. 1996;21:1416–1422.
22. Harada M, Abumi K, Ito M, et al. Cineradiographic motion analysis of normal lumbar spine during forward and backward flexion. *Spine*. 2000;25:1932–1937.