Age-related degenerative changes and sex-specific differences in osseous anatomy and intervertebral disc height of the thoracolumbar spine

Masaaki Machino, MD[1)2)]; Hiroaki Nakashima, MD, PhD[1)2)]; Keigo Ito, MD, PhD[2)]; Yoshito Katayama, MD, PhD[2)]; Tomohiro Matsumoto, MD, PhD[2)]; Mikito Tsushima, MD[2)]; Kei Ando, MD, PhD[1)]; Kazuyoshi Kobayashi, MD, PhD[1)]; Shiro Imagama, MD, PhD[1)]

1) Department of Orthopedic Surgery, Nagoya University Graduate School of Medicine, Nagoya, Japan
2) Department of Orthopedic Surgery, Chubu Rosai Hospital, Japan Organization of Occupational Health and Safety, Nagoya, Japan

Address for correspondence and reprints:

Masaaki Machino, MD (corresponding author)

Department of Orthopaedic Surgery, Nagoya University Graduate School of Medicine

65, Tsurumai, Showa-ku, Nagoya, Aichi, 466-8550, Japan

Phone: +81-52-741-2111

Fax: +81-52-744-2260

E-mail: mmachino@med.nagoya-u.ac.jp

ABSTRACT

The aim of this study was to determine age-related changes and sex-specific differences in sagittal alignment, range of motion (ROM), and intervertebral disc height of the thoracolumbar spine in healthy subjects. Lateral neutral and flexion–extension radiographs of the thoracolumbar spine of 627 asymptomatic subjects (307 males and 320 females; average age, 49.6 ± 16.5 years) were evaluated. We included at least 50 males and 50 females in each decade of life between the 20s and the 70s. Intervertebral disc height from T10/T11 to L5/S1, local lordotic alignment, and ROM from T10–T11 to L5–S1 were measured. T10–L2 kyphosis and T12–S1 lordosis as well as flexion, extension, and total ROM were measured. T10–L2 kyphosis did not markedly change with age in subjects of either sex but a sudden increase was noted in the 70s females. T12–S1 lordosis increased with age in both sexes, except the 70s. Flexion, extension, and total ROM at T10–L2 and T12–S1 decreased with age in most subjects. The levels from L3–L4 to L5–S1 were conspicuous as mobile segments. Intervertebral disc height gradually increased from T10/T11 to L4/L5; the shortest was at T10/T11 and the longest at L3/L4 or L4/L5 in all subjects. Age-related decreases in intervertebral disc height were most prominent at L4/L5 in middle-aged and elderly individuals of both sexes. Normative values of sagittal alignment, ROM, and intervertebral disc height at each segmental level were established in both sexes and all age groups in healthy subjects.

Key words: thoracolumbar and lumbar spine; alignment; range of motion; healthy subjects; age-related and gender differences

INTRODUCTION

Adequate range of motion (ROM) of the lumbar spine is required to perform various activities of daily living smoothly [1,2]. Degenerative changes such as spondylosis can decrease lumbar ROM and limit the ability to perform these activities. Surgical treatments for lumbar disorders are designed to reestablish normal alignment, reduce neurologic symptoms, and reduce low back pain (LBP). Posterior lumbar interbody fusion is considered the gold standard procedure for treating single-level degenerative disc disease. More recently, lateral lumbar interbody fusion (LLIF) is being increasingly used as an alternative intervention [3,4]. However, surgical procedures involving spinal fusion result in limited lumbar ROM [5,6]. To maintain ROM, motion-preserving techniques such as artificial disc replacement (ACR) can be used as an alternative to conventional fusion [7,8].

Recently, several researchers have emphasized the importance of sagittal spinal alignment and have attempted to establish normal alignment and dynamic motion parameters of the lumbar spine using plain radiographs in healthy subjects [9-13]. Although intervertebral disc height and local segmental lumbar ROM are estimated to decrease with age-related degeneration, there are few studies that have measured sagittal segmental parameters in a large age- and sex-balanced cohort [14,15]. Such extensive data would enable individualized treatment based on the patient’s age and sex. However, to the best of our knowledge, no reports have summarized anatomical age-related intervertebral disc height and segmental ROM changes in the thoracolumbar spine or examined sex-specific differences.

Therefore, we conducted a large sex- and age-balanced cohort study of normal thoracolumbar spine alignment in 627 asymptomatic volunteers using plain radiography. The aim of this cross-sectional study was to determine age-related changes and sex-specific differences in sagittal alignment, ROM, intervertebral disc height, vertebral body shape, and intervertebral disc shape of the thoracolumbar spine.

MATERIALS AND METHODS

Study Population

Healthy Japanese volunteers were recruited after the study purpose was officially announced, and approval was obtained from the institutional review board of Chubu Rosai Hospital (IRB approval no., 2009-2). Written informed consent was obtained from all subjects. The exclusion criteria included sensory or motor symptoms such as numbness, clumsiness, weakness, and gait disturbance; severe LBP; history of spinal trauma or congenital spinal deformity; history of brain or spinal surgery; and neurological diseases such as cerebral ischemic disease and neuropathy. Pregnant females, individuals receiving worker's compensation or presenting with symptoms after a motor vehicle accident, and those in whom sagittal radiograph parameters were difficult to examine because of lumbosacral transitional anomalies or spinal malformations were excluded. Finally, 627 asymptomatic subjects (307 males and 320 females; mean age, 49.6 ± 16.5 years) with appropriate imaging results were enrolled; at least 50 subjects from each sex were included in the following age groups: 20–29, 30–39, 40–49, 50–59, 60–69, and 70–79 years (Table 1).

Lateral neutral and flexion–extension thoracolumbar radiographs were obtained with the subject in the recumbent position. The vertebral body height at each vertebral level (from T10 to L5) and intervertebral disc height at each disc level (from T10/T11 to L5/S1) were measured. At each segmental level (from T10–T11 to L5–S1), local lordotic alignment and local ROM were calculated. In addition, thoracolumbar kyphotic alignment (T10–L2 kyphosis), lumbar lordotic alignment (T12–S1 lordosis), flexion, extension, and total ROM were measured (Figure 1). All the images were transferred to a computer in Digital Imaging and Communications in Medicine format. Each parameter was measured by experienced radiation technologists under the supervision of a certified spine surgeon using Osiris 4 imaging software (Icestar Media Ltd, Essex, UK) as described previously

[16-18].

To assess vertebral body and intervertebral disc shape, the anterior and posterior heights of the vertebral bodies and intervertebral discs were measured at each level in the lateral view, and anterior–posterior height ratios were calculated. The anterior–posterior ratio in vertebral body height was defined as the ratio of the vertebral body height at the posterior wall to that at the anterior wall and was calculated from T10 to L5. Vertebral body shape was determined using the following formula: [(vertebral body height at the posterior wall) / (vertebral body height at the anterior wall) × 100%]. Values of <100% indicated lordotic vertebral body shape, whereas those of >100% indicated kyphotic shape. The anterior–posterior ratio in intervertebral disc height was defined as the ratio of the intervertebral disc height at the posterior edge to that at the anterior edge and was calculated from T10/T11 to L5/S1. Intervertebral disc shape was calculated using the following formula: [(intervertebral disc height at the posterior edge) / (intervertebral disc height at the anterior edge) × 100%]. Values <100% indicated lordotic intervertebral disc shape, whereas those >100% indicated kyphotic shape.

Statistical Analysis

Data were analyzed using SPSS software version 27.0 (IBM Corp., Armonk, NY, USA). All values were expressed as mean ± standard deviation. The Mann–Whitney U-test was used for nonparametric analysis of differences between males and females. $p < 0.05$ was considered statistically significant.

RESULTS

Patient characteristics, including height, weight, and body mass index, are shown in Table 1. Body height tended to decrease with increasing age (Table 1).

Vertebral body height at the center gradually increased from T10 to L4; the shortest height was at T10 and the longest at L3 or L4 in all age groups and both sexes. The vertebral body heights were lower in females than in males in all age groups. The height at the center slightly decreased with increasing age at most vertebral levels (Supplemental Table 1).

The intervertebral disc height at the center gradually increased from T10/T11 to L4/L5; the shortest was at T10/T11 and the longest at L3/L4 or L4/L5 in all age groups and both sexes. The disc heights were lower in females than in males. Age-related decreases in disc height were most prominent at L4/L5 in middle-aged and elderly individuals in both sexes. The intervertebral disc height at L4/L5 was 11.4 ± 2.0mm in males and 10.3 ± 1.7mm in females aged 20–29 years, but narrowed to 9.8 ± 3.3mm in males and 9.3 ± 2.3mm in females aged 70–79 years. Remarkably, in the thoracolumbar region from T11/T12 to L1/L2, intervertebral disc height increased gradually with increasing age in both sexes. Unexpectedly, the intervertebral disc height at other levels did not change with age in either sex (Table 2).

Local lordotic alignment at each segmental level gradually increased from L2–L3 to L5–S1: the largest was at L5–S1 in all age groups in both sexes (19.9 ± 5.3° in males and 19.2 ± 6.9° in females aged 40–49 years). Lumbar lordosis occurred most frequently in the lower lumbar region from L4 to S1. Local alignment showed kyphosis in the thoracolumbar region from T11–T12 to L1–L2; other regions showed lordosis. Local lordotic alignment in the lumbar region was higher in females than in males, except at L5–S1. Progression of local kyphosis because of age-related degenerative change was confirmed in the thoracolumbar region from T11–T12 to T12–L1 in middle-aged and elderly females. Although local lordotic alignment increased slightly with increasing age in both sexes, a sudden decrease in local lordotic alignment in the lumbar region was observed in subjects aged 70–79 years (Table 3).

Local ROM at each segmental level gradually increased from T10–T11 to L4–L5; the smallest was at T10–T11 (2.9 ± 2.3° in males and 3.1 ± 2.1° in females aged 40–49 years) and the largest at L4–L5 (12.7 ± 4.6° in males and 14.4 ± 4.9° in females aged 40–49 years) in most subjects. Local ROM was larger in females than in males. The L3–L4 to L5–S1 levels were conspicuous as mobile segments, with larger local ROM than other levels. Local ROM decreased with increasing age at all segmental levels and in both sexes. In particular, the decrease in local ROM with increasing age was most prominent from L3–L4 to L5–S1 in both sexes (Table 4).

Flexion ROM, extension ROM, and total ROM at T10–L2 decreased with increasing age in most subjects (Table 5). Among middle-aged and elderly individuals, ROM was larger in females than in males, although the difference was not significant (Figure 2). Kyphosis at T10–L2 was significantly smaller in females than in males, except in subjects aged 70–79 years. Thoracolumbar kyphosis did not markedly change with age in either males or females, but a sudden increase was noted in females aged 70–79 years (Figure 2).

Flexion ROM, extension ROM, and total ROM at T12–S1 decreased with increasing age in both sexes (Table 5). Age-related decrease in ROM was more prominent in extension than in flexion in both sexes. Extension ROM did not significantly differ between males and females. Total ROM was significantly larger in females than in males in subjects aged 30–59 years (Figure 3). Lordosis at T12–S1 increased with age in both sexes, except in subjects aged 70–79 years. Lumbar lordosis was significantly larger in females than in males in subjects aged 30–69 years. A sudden decrease in lumbar lordosis was noted in females aged 70–79 years (Figure 3).

The anterior–posterior ratio in vertebral body height at each vertebral level did not substantially change with age in either sex (Supplemental Table 2). The most kyphotic vertebra in all age groups was L1 in males and T12 in females. The vertebral body was kyphotic in the thoracolumbar region from T11 to L2; the L5 vertebra was lordotic. The anterior–posterior ratio in vertebral body height from T11 to L3 or L4 was significantly lower in females than in males (Figure 4).

The anterior–posterior ratio in intervertebral disc height in the lumbar region slightly decreased in middle-aged and elderly individuals in both sexes (Supplemental Table 3). The anterior–posterior ratio was higher in females than in males at all levels in most subjects and gradually decreased from T10/T11 to L5/S1 in females. The intervertebral disc at L5/S1 was most lordotic in all age groups and both sexes (Figure 5).

DISCUSSION

To the best of our knowledge, this large cross-sectional study is the first to determine age-related changes and sex-specific differences in sagittal alignment, ROM, intervertebral disc height, vertebral body shape, and intervertebral disc shape of the thoracolumbar spine. The aging process involves disc and vertebral degeneration, which potentially affects the lumbar sagittal profile, alignment, and ROM. These effects can be radiographically confirmed. Plain radiography using anteroposterior, lateral, and lateral flexion–extension views remains fundamental in the diagnosis of lumbar spinal disorders. These views allow judgment of lumbar ROM, alignment, intervertebral disc height, and instability.

This study showed that thoracolumbar kyphosis did not considerably change with increasing age in either sex, but a sudden increase was observed in females aged 70–79 years. Lordosis at T12–S1 increased with age in both sexes, except in subjects aged 70–79 years. Flexion ROM, extension ROM, and total ROM at T10–L2 and T12–S1 decreased with increasing age in most subjects. Local ROM decreased with increasing age at all segmental levels and in both sexes.

Our main finding was that the anterior–posterior ratio in vertebral body height at each level did not markedly change with age in either sex. Furthermore, the vertebral body was kyphotic in the thoracolumbar region from T11 to L2, whereas the L5 vertebra was lordotic. The anterior–posterior ratio in intervertebral disc height in the lumbar region marginally decreased in middle-aged and elderly individuals in both sexes. This ratio gradually decreased from T10/T11 to L5/S1 in females. The L5/S1 intervertebral disc was the most lordotic disc in all age groups and both sexes. We speculate that age-related progression of lordosis in the lumbar spine is caused by increasing lordosis of the intervertebral disc.

Asai et al. determined the normal values of lumbar sagittal alignment to clarify the effect of age-related changes using large, community-based cohorts and found that lumbar lordosis decreased in females aged 70–79 years [11]. Two large cohort studies of elderly Japanese volunteers aged over 50 years indicated differences in age-related spinal sagittal alignment between males and females and showed that the onset of pelvic retroversion was at an earlier age in females [19,20]. This change in pelvic alignment may be associated with a history of childbirth and/or pregnancy. Lower lumbar lordosis also tended to worsen earlier in females than in males. However, lumbar and pelvic alignment changes did not develop in males until the age of 79 years [19].

Spinal sagittal alignment plays an essential role in pain and disability and influences health-related quality of life in patients with adult spinal deformity [5,21]. Glassman et al. concluded that the restoration of ‘a more normal sagittal balance’ is the critical goal of any reconstructive spinal surgery [22]. However, the definition of what distinguishes normal from pathologic spinal alignment remains unclear. In spinal deformity surgery, lumbar lordosis is the only parameter that can be manipulated and therefore is crucial.

The standard values for sagittal alignment changed with patient age in the present study. In particular, lumbar lordosis suddenly decreased in subjects aged 60–69 years to those aged 70–79 years. However, when performing reconstructive lumbar surgery, it is still controversial to use the standard alignment of all age groups or average alignment based on age as a surgical goal. Moreover, lumbar lordosis occurred most frequently in the lower lumbar region (L4–S1) in our study. Therefore, more lordosis in the lower lumbar levels should be achieved in spinal reconstruction surgery.

We used recumbent radiographs to evaluate thoracolumbar sagittal alignment because of their ease in evaluating flexion and extension ROM. Lumbar spine ROM naturally decreases with age and flexion ROM is less affected by age than extension ROM [1,15]. In our study, total ROM decreased linearly with age and the highest reduction was observed in extension ROM. In general, older females demonstrated more thoracic kyphosis than males [14]. As age-related spinal degeneration progresses, spinal flexibility decreases and spinal compensatory mechanisms are lost [5,6]. In our study, L3–L4 to L5–S1 were conspicuous as mobile segments, exhibiting larger ROM than other levels. In addition, loss of local ROM with increasing age was most prominent at these same levels in both sexes. In fusion surgery for lumbar disc disorders, we should pay attention to the motion preservation levels.

In our study, intervertebral disc height at the center gradually increased from T10/T11 to L4/L5; the shortest was at T10/T11 and the longest at L3/L4 or L4/L5 in all decades and both sexes. Age-related degenerative disc height loss was most prominent at L4/L5 in middle-aged and elderly individuals of both sexes. As the number of disc surgeries performed, such as LLIF and ACR, increases in the future, these results will serve as useful baseline information for clinicians planning surgical intervention. Elderly subjects may require special surgical consideration owing to their differences from younger subjects.

This study has certain limitations. First, flexion–extension radiographs were obtained in the recumbent position because it was easier for the radiation technologist to control film positioning and obtain adequate radiographs. Second, measurements were performed only once because the number of specific measurements and subjects were large. However, these measurements were performed by well-experienced radiation technologists with knowledge of spinal osseous anatomy. Furthermore, previous studies have shown that intra- and interobserver intraclass correlation coefficients for radiographic measurements are high with good reproducibility [20]. Therefore, our data set was sufficiently large for most evaluations [15]. Third, the limitation of radiographs is that it is associated with radiation exposure. Plain radiography images were obtained for the purpose of research in all subjects. The study was approved by our Institutional Review Board and written informed consent was obtained from each subject prior to examination and study participation. Fourth, all subjects were Japanese; therefore, our results may not be applicable to subjects belonging to other racial and ethnic groups. Despite these limitations, to the best of our knowledge, this cross-sectional study is the largest of its kind. Moreover, all subjects were evaluated using the same imaging modality.

Age-related changes in sagittal alignment of the thoracolumbar spine are gaining more importance than ever owing to the increasing number of reconstructive surgeries conducted for lumbar disc disorders. A long-term follow-up study is needed to understand natural changes in thoracolumbar spine alignment and ROM over time. However, it is impractical to observe age-related changes over a subject's entire life span. Therefore, a large-scale cross-sectional observational study can be conducted as a substitute for longitudinal analysis. In our study, we enrolled 627 asymptomatic volunteers, and at least 50 subjects belonging to each sex were included in each age group. This is one of the largest cohort studies on thoracolumbar alignment and ROM, with a sex ratio of almost 1:1. The large sample size and balanced sex and age distribution of the study population contribute to the reliability of our results.

CONCLUSION

This study established normative values of thoracolumbar sagittal alignment, ROM, and intervertebral disc height at each segmental level based on sex and age in a large cohort of healthy subjects. These data can provide standard values for understanding the natural course of thoracolumbar spine aging and assist surgical planning in clinical practice.

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The study does not contain information about medical device(s)/drug(s).

The Institutional Review Board in our institution approved this study, and written informed consent was obtained from all subjects before study participation.

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FIGURE LEGENDS

Figure 1

Measurement of each parameter on neutral and flexion–extension views.

a: Vertebral body height at the center

b: Vertebral body height at the anterior wall

c: Vertebral body height at the posterior wall

d: Intervertebral disc height at the center

e: Intervertebral disc height at the anterior edge

f: Intervertebral disc height at the posterior edge

A: Lumbar lordotic alignment during flexion

α: Local segmental alignment at each level during flexion

B: Lumbar lordotic alignment during extension

β: Local segmental alignment at each level during extension

Figure 2

Flexion, extension, total range of motion, and kyphotic alignment at T10–L2.

Figure 3

Flexion, extension, total range of motion, and lordotic alignment at T12–S1.

Values are expressed as means ± standard deviation. *p < 0.05; **p < 0.01

Figure 4

Anterior–posterior ratio in the vertebral body height at each vertebral level.

[(c / b) × 100] in Figure 1.

Values are expressed as means ± standard deviation. *p < 0.05; **p < 0.01; ***p < 0.0001

Figure 5

Anterior–posterior ratio in the intervertebral disc height at each disc level.

[(f / e) × 100] in Figure 1.

Values are expressed as means ± standard deviation. *p < 0.05; **p < 0.01; ***p < 0.0001

Figure 1

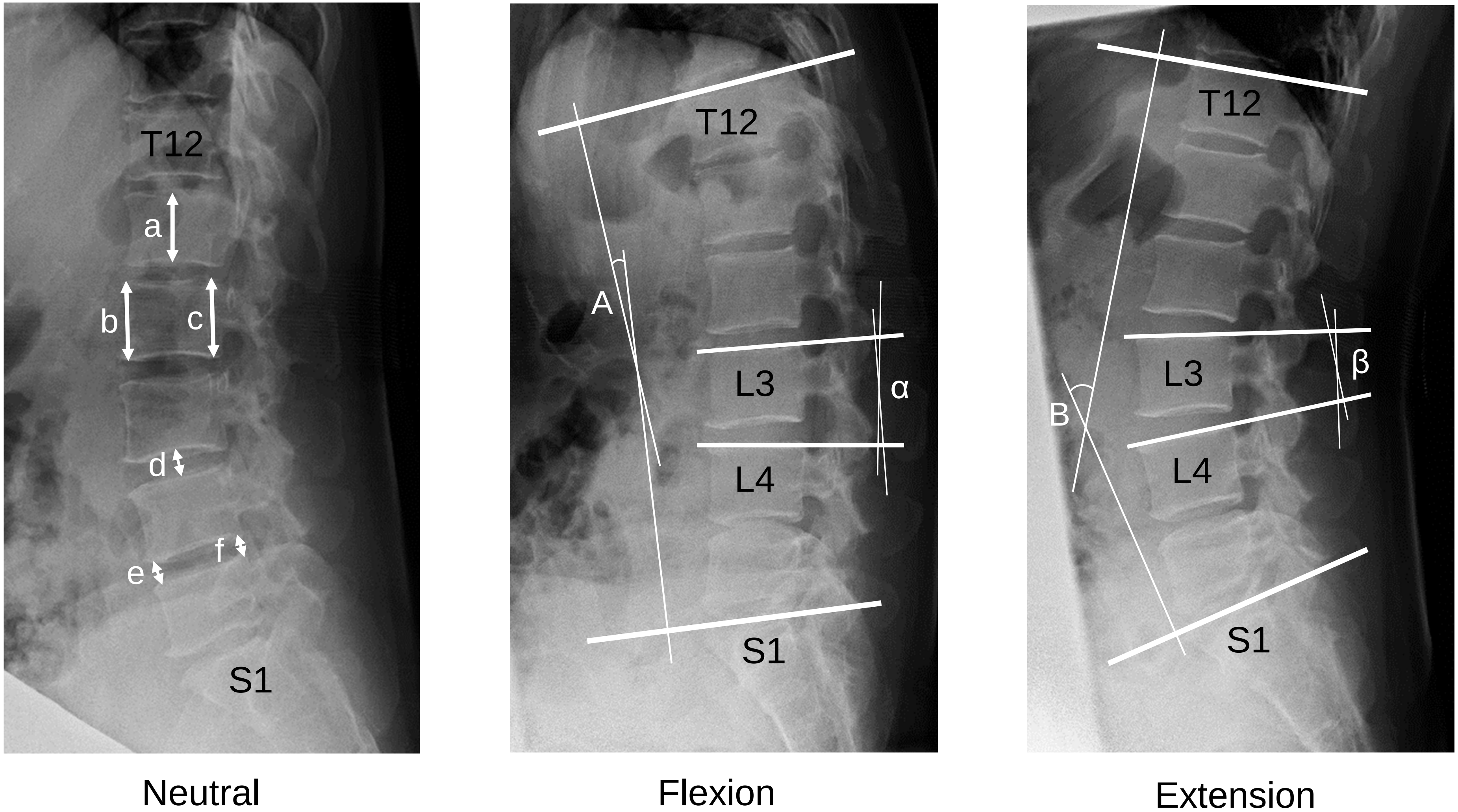

T12
a
b
c
d
e
f
S1
Neutral
T12
A
L3
α
L4
S1
Flexion
T12
B
L3
β
L4
S1
Extension

Figure 2

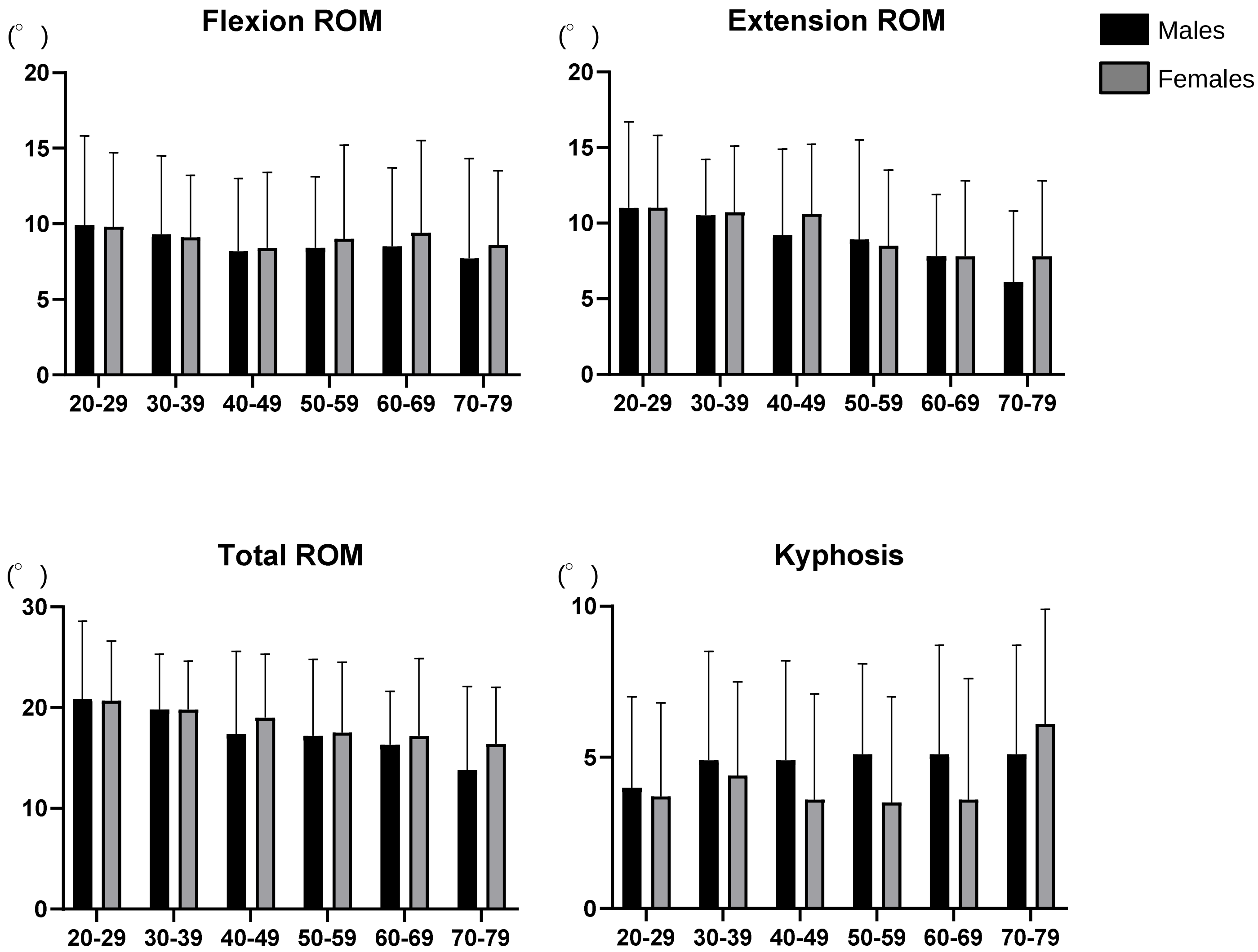
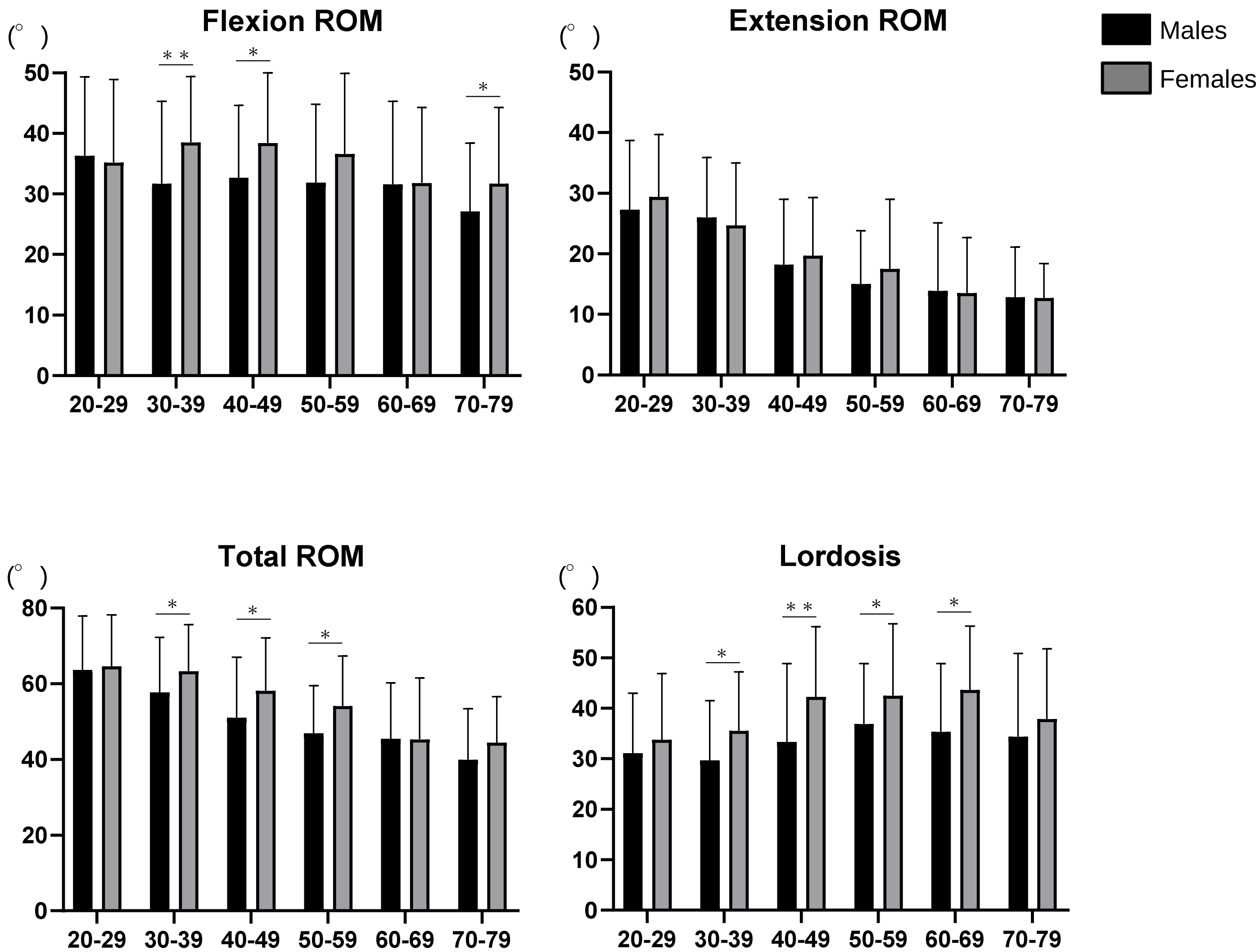

Flexion ROM
Extension ROM
Total ROM
Kyphosis
(°)
Males
Females
20-29
30-39
40-49
50-59
60-69
70-79

Figure 3



Flexion ROM
(°)
50
40
30
20
10
0
* *
*
*
20-29
30-39
40-49
50-59
60-69
70-79
Extension ROM
(°)
50
40
30
20
10
0
20-29
30-39
40-49
50-59
60-69
70-79
Males
Females
Total ROM
(°)
80
60
40
20
0
*
*
*
20-29
30-39
40-49
50-59
60-69
70-79
Lordosis
(°)
60
50
40
30
20
10
0
*
* *
*
*
20-29
30-39
40-49
50-59
60-69
70-79

Figure 4

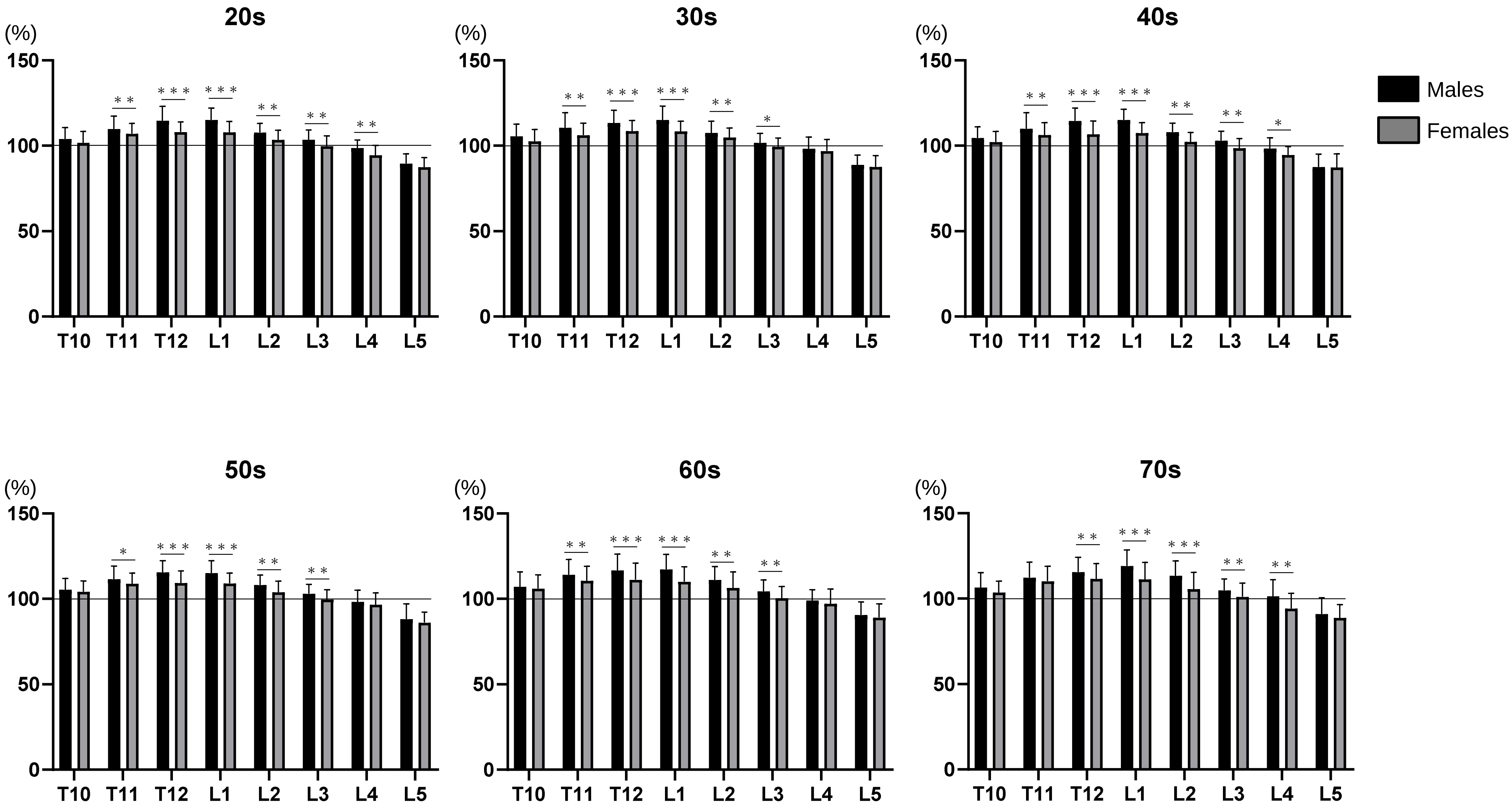
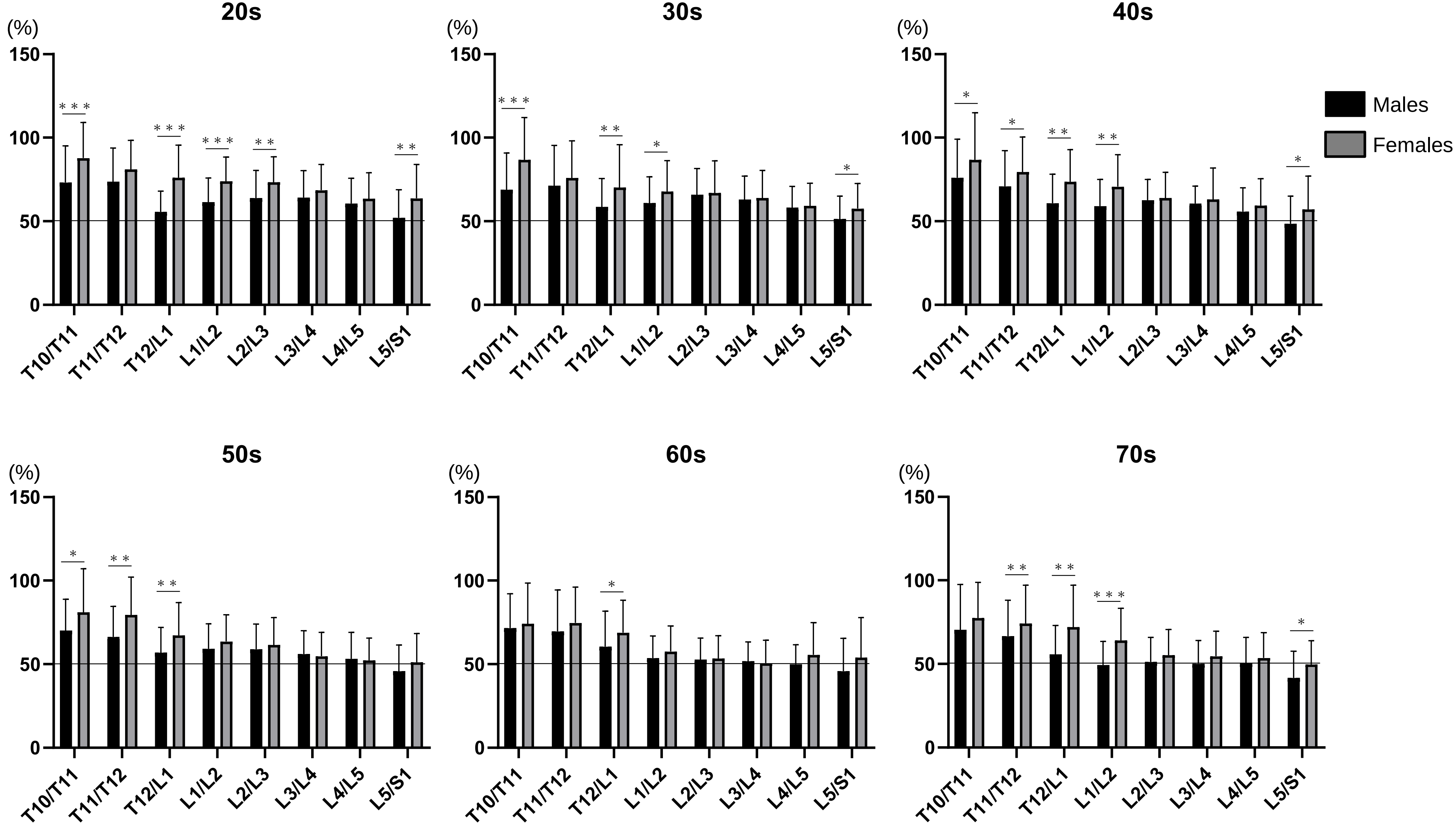

20s
30s
40s
50s
60s
70s
(%)
150
100
50
0
T10
T11
T12
L1
L2
L3
L4
L5
Males
Females

Figure 5



20s
30s
40s
50s
60s
70s
(%)
150
100
50
0
T10/T11
T11/T12
T12/L1
L1/L2
L2/L3
L3/L4
L4/L5
L5/S1
Males
Females

Table 1.
Demographics of healthy subjects at present study

Age (years)		Males	Females
20–29	Number	50	52
	Age (years)	26.0 ± 2.3	25.0 ± 2.7
	Body height (cm)	171.3 ± 6.3	158.8 ± 5.5
	Body weight (kg)	65.1 ± 9.9	51.3 ± 5.6
	BMI (kg/m^2)	22.2 ± 2.9	20.4 ± 1.8
30–39	Number	51	50
	Age (years)	35.0 ± 3.0	35.0 ± 3.0
	Body height (cm)	170.4 ± 6.0	159.1 ± 6.5
	Body weight (kg)	67.2 ± 10.9	52.5 ± 7.3
	BMI (kg/m^2)	23.1 ± 3.2	20.7 ± 2.6
40–49	Number	50	57
	Age (years)	44.5 ± 3.1	44.8 ± 3.0
	Body height (cm)	172.9 ± 5.1	156.4 ± 5.7
	Body weight (kg)	71.7 ± 13.5	54.2 ± 8.8
	BMI (kg/m^2)	23.9 ± 4.4	22.2 ± 3.7
50–59	Number	56	51
	Age (years)	54.2 ± 2.7	53.7 ± 2.5
	Body height (cm)	168.3 ± 5.8	156.4 ± 4.9
	Body weight (kg)	68.5 ± 9.6	54.8 ± 9.5
	BMI (kg/m^2)	24.1 ± 3.1	22.4 ± 3.9
60–69	Number	50	60
	Age (years)	64.5 ± 2.9	64.7 ± 3.1
	Body height (cm)	166.1 ± 6.1	154.5 ± 5.5
	Body weight (kg)	63.8 ± 7.5	52.3 ± 7.7
	BMI (kg/m^2)	23.1 ± 2.3	21.9 ± 3.2
70–79	Number	50	50
	Age (years)	73.3 ± 2.6	73.2 ± 2.6
	Body height (cm)	165.4 ± 5.8	151.9 ± 4.7
	Body weight (kg)	64.0 ± 6.8	51.5 ± 7.2
	BMI (kg/m^2)	23.5 ± 2.5	22.3 ± 2.8
Total	Number	307	320
	Age (years)	49.7 ± 16.4	49.6 ± 16.7
	Body height (cm)	169.1 ± 6.4	156.1 ± 6.0
	Body weight (kg)	66.7 ± 10.2	52.8 ± 7.9
	BMI (kg/m^2)	23.3 ± 3.2	21.7 ± 3.2

Values given are mean ± standard deviation (SD) unless otherwise specified.
BMI indicates body mass index.

Table 2.
Intervertebral disc height at the center at each disc level (mm)

Age (years)		20–29	30–39	40–49	50–59	60–69	70–79	Total
Males	T10/T11	6.6 ± 1.0	7.0 ± 1.3	6.7 ± 1.3	6.7 ± 1.5	7.3 ± 1.3	6.9 ± 1.4	6.9 ± 1.3
	T11/T12	7.2 ± 1.1	7.2 ± 1.2	7.5 ± 1.3	7.6 ± 1.3	8.0 ± 1.8	7.7 ± 1.2	7.5 ± 1.3
	T12/L1	7.6 ± 1.0	8.1 ± 1.1	8.2 ± 1.5	8.4 ± 1.2	8.8 ± 1.3	8.8 ± 1.4	8.3 ± 1.3
	L1/L2	9.0 ± 1.4	9.2 ± 1.2	9.5 ± 1.8	9.4 ± 1.6	10.2 ± 1.8	9.9 ± 2.1	9.6 ± 1.7
	L2/L3	10.5 ± 1.6	11.0 ± 1.5	11.2 ± 1.8	11.2 ± 1.7	10.9 ± 2.1	10.2 ± 2.6	10.8 ± 1.9
	L3/L4	11.1 ± 1.7	11.6 ± 1.7	11.8 ± 1.9	11.3 ± 1.6	11.3 ± 2.2	10.7 ± 2.4	11.3 ± 1.9
	L4/L5	11.4 ± 2.0	11.8 ± 1.5	11.5 ± 2.5	10.7 ± 2.3	10.0 ± 3.1	9.8 ± 3.3	11.0 ± 2.6
	L5/S1	9.8 ± 2.5	9.6 ± 2.2	10.2 ± 2.6	9.8 ± 3.0	9.5 ± 3.2	9.2 ± 3.1	9.8 ± 2.8
Age (years)		20–29	30–39	40–49	50–59	60–69	70–79	Total
Females	T10/T11	5.9 ± 1.0	6.2 ± 1.2	6.1 ± 1.3	6.0 ± 1.0	6.4 ± 1.3	6.1 ± 1.3	6.1 ± 1.2
	T11/T12	6.3 ± 1.0	7.0 ± 1.1	6.9 ± 1.5	6.7 ± 1.1	7.0 ± 1.3	6.9 ± 1.7	6.8 ± 1.3
	T12/L1	6.6 ± 1.1	7.3 ± 1.0	7.1 ± 1.3	7.5 ± 1.3	7.9 ± 1.2	7.9 ± 1.3	7.4 ± 1.3
	L1/L2	7.8 ± 1.4	8.3 ± 1.3	8.6 ± 1.6	8.9 ± 1.3	9.3 ± 1.7	8.9 ± 1.7	8.6 ± 1.6
	L2/L3	9.3 ± 1.4	9.7 ± 1.8	9.7 ± 1.5	9.7 ± 1.7	9.8 ± 2.1	9.7 ± 2.2	9.7 ± 1.8
	L3/L4	10.1 ± 1.6	10.5 ± 1.9	10.0 ± 1.9	10.1 ± 2.0	10.0 ± 2.2	10.1 ± 2.2	10.1 ± 2.0
	L4/L5	10.3 ± 1.7	10.5 ± 1.9	10.0 ± 1.9	9.4 ± 2.2	9.3 ± 2.7	9.3 ± 2.3	9.9 ± 2.2
	L5/S1	9.0 ± 1.8	8.9 ± 2.0	9.3 ± 2.7	8.4 ± 2.3	9.0 ± 3.3	9.0 ± 2.4	9.0 ± 2.6

Values given are mean ± standard deviation (SD) unless otherwise specified.

Table 3.
Local lordotic alignment at each segmental level (degree)

Age (years)		20–29	30–39	40–49	50–59	60–69	70–79	Total
Males	T10–T11	1.0 ± 2.7	0.7 ± 2.3	0.2 ± 2.4	0.1 ± 2.0	0.5 ± 2.4	-0.1 ± 2.4	0.4 ± 2.4
	T11–T12	-1.4 ± 3.2	-1.9 ± 2.8	-1.3 ± 2.7	-2.2 ± 2.7	-2.1 ± 3.2	-1.3 ± 2.8	-1.7 ± 2.9
	T12–L1	-1.9 ± 2.9	-2.0 ± 3.0	-2.4 ± 3.1	-1.9 ± 3.0	-2.5 ± 3.1	-1.5 ± 3.2	-2.0 ± 3.0
	L1–L2	-1.8 ± 2.6	-2.1 ± 3.0	-1.5 ± 3.4	-0.7 ± 2.9	-0.8 ± 4.2	-1.8 ± 4.3	-1.4 ± 3.5
	L2–L3	2.2 ± 2.9	1.6 ± 3.5	2.5 ± 3.5	2.9 ± 3.5	3.6 ± 3.5	1.9 ± 4.1	2.4 ± 3.5
	L3–L4	4.7 ± 3.3	6.0 ± 3.6	6.7 ± 3.7	7.4 ± 3.6	7.5 ± 3.9	6.8 ± 4.3	6.5 ± 3.8
	L4–L5	9.4 ± 3.4	9.9 ± 4.4	10.4 ± 4.4	11.0 ± 4.3	11.5 ± 5.0	9.9 ± 4.3	10.4 ± 4.4
	L5–S1	18.9 ± 6.5	17.7 ± 3.9	19.9 ± 5.3	19.2 ± 5.7	20.1 ± 6.8	20.9 ± 5.5	19.4 ± 5.8
Age (years)		20–29	30–39	40–49	50–59	60–69	70–79	Total
Females	T10–T11	-0.1 ± 2.1	-0.1 ± 2.2	-0.1 ± 2.6	0.4 ± 2.2	-0.5± 2.8	-0.5 ± 2.4	-0.2 ± 2.4
	T11–T12	-1.1 ± 2.4	-1.6 ± 3.1	-1.8 ± 2.7	-2.3 ± 3.5	-2.4 ± 3.4	-2.5 ± 3.3	-2.0 ± 3.1
	T12–L1	-1.9 ± 2.6	-1.6 ± 3.3	-1.3 ± 3.3	-1.5 ± 3.4	-2.7 ± 5.6	-2.5 ± 3.8	-1.9 ± 3.8
	L1–L2	-1.2 ± 3.3	-1.0 ± 2.9	-0.1 ± 3.3	1.0 ± 3.5	0.9 ± 4.1	-0.9 ± 4.4	-0.2 ± 3.7
	L2–L3	2.2 ± 4.0	2.5 ± 3.4	4.6 ± 4.5	5.0 ± 4.6	5.0 ± 4.5	3.6 ± 4.6	3.9 ± 4.4
	L3–L4	6.6 ± 3.7	7.7 ± 3.2	8.7 ± 3.7	8.6 ± 4.1	9.7 ± 4.6	7.7 ± 5.3	8.2 ± 4.3
	L4–L5	11.0 ± 4.4	10.6 ± 4.3	12.8 ± 4.0	11.9 ± 4.2	11.2 ± 4.6	10.0 ± 6.8	11.3 ± 4.8
	L5–S1	17.3 ± 5.9	17.5 ± 5.2	19.2 ± 6.9	18.7 ± 7.1	19.2 ± 7.2	19.2 ± 8.7	18.5 ± 6.9

Values given are mean ± standard deviation (SD) unless otherwise specified.

Table 4.
Local range of motion at each segmental level (degree)

Age (years)		20–29	30–39	40–49	50–59	60–69	70–79	Total
Males	T10–T11	3.1 ± 2.8	3.0 ± 2.2	2.9 ± 2.3	2.4 ± 1.8	3.3 ± 2.4	2.2 ± 1.9	2.8 ± 2.3
	T11–T12	4.7 ± 3.0	4.5 ± 2.4	3.9 ± 2.5	4.1 ± 2.2	3.8 ± 2.8	3.1 ± 2.3	4.0 ± 2.6
	T12–L1	5.3 ± 3.3	5.4 ± 2.6	4.2 ± 3.0	4.7 ± 2.8	4.8 ± 2.8	4.4 ± 2.8	4.8 ± 2.9
	L1–L2	7.9 ± 3.3	7.6 ± 2.9	6.6 ± 3.5	6.3 ± 3.2	7.3 ± 4.0	6.0 ± 3.0	6.9 ± 3.4
	L2–L3	10.8 ± 3.5	9.2 ± 3.6	8.0 ± 3.3	7.9 ± 3.4	8.1 ± 3.5	7.2 ± 3.5	8.6 ± 3.6
	L3–L4	11.3 ± 4.3	10.8 ± 3.2	9.9 ± 3.3	9.7 ± 4.0	9.6 ± 3.9	7.2 ± 3.8	9.8 ± 4.0
	L4–L5	13.4 ± 4.4	13.8 ± 5.7	12.7 ± 4.6	11.9 ± 4.7	11.4 ± 4.0	9.5 ± 4.1	12.1 ± 4.7
	L5–S1	14.4 ± 6.4	12.1 ± 7.8	12.0 ± 7.4	10.9 ± 5.9	9.7 ± 5.6	8.3 ± 4.7	11.3 ± 6.6
Age (years)		20–29	30–39	40–49	50–59	60–69	70–79	Total
Females	T10–T11	2.9 ± 1.9	3.0 ± 2.4	3.1 ± 2.1	2.8 ± 1.9	3.0 ± 1.9	2.5 ± 2.2	2.9 ± 2.1
	T11–T12	4.7 ± 2.8	3.9 ± 2.9	4.6 ± 2.7	3.8 ± 2.8	4.1 ± 2.6	4.2 ± 2.9	4.2 ± 2.8
	T12–L1	5.5 ± 3.0	4.8 ± 3.0	4.6 ± 3.1	6.4 ± 3.0	4.4 ± 2.7	4.7 ± 3.8	5.1 ± 3.2
	L1–L2	8.1 ± 3.3	8.5 ± 3.9	7.5 ± 3.5	7.4 ± 3.2	6.6 ± 3.7	7.0 ± 4.5	7.5 ± 3.7
	L2–L3	10.8 ± 4.0	10.0 ± 3.6	10.2 ± 3.4	9.1 ± 4.4	8.5 ± 3.4	7.6 ± 3.2	9.4 ± 3.8
	L3–L4	12.2 ± 3.7	11.5 ± 3.8	10.9 ± 4.0	9.7 ± 5.2	8.9 ± 4.5	9.4 ± 3.2	10.4 ± 4.3
	L4–L5	16.1 ± 4.6	15.0 ± 4.9	14.4 ± 4.9	13.2 ± 5.0	10.3 ± 5.7	10.1 ± 5.8	13.2 ± 5.6
	L5–S1	13.5 ± 6.2	13.1 ± 5.5	12.4 ± 6.3	10.2 ± 6.6	11.1 ± 7.0	9.8 ± 5.0	12.3 ± 6.9

Values given are mean ± standard deviation (SD) unless otherwise specified.

Table 5.
Flexion, extension, total ROM, and alignment in thoracolumbar and lumbar region (degree)

Kyphotic alignment at T10–L2 level								
Age (years)		20–29	30–39	40–49	50–59	60–69	70–79	Total
Males	Flexion	9.9 ± 5.9	9.3 ± 5.2	8.2 ± 4.8	8.4 ± 4.7	8.5 ± 5.2	7.7 ± 6.6	8.7 ± 5.4
	Extension	11.0 ± 5.7	10.5 ± 3.7	9.2 ± 5.7	8.9 ± 6.6	7.8 ± 4.1	6.1 ± 4.7	8.9 ± 5.4
	Total ROM	20.9 ± 7.7	19.8 ± 5.5	17.4 ± 8.2	17.2 ± 7.6	16.3 ± 5.3	13.8 ± 8.3	17.6 ± 7.5
	Kyphosis	4.0 ± 3.0	4.9 ± 3.6	4.9 ± 3.3	5.1 ± 3.0	5.1 ± 3.6	5.1 ± 3.6	4.9 ± 6.7
Age (years)		20–29	30–39	40–49	50–59	60–69	70–79	Total
Females	Flexion	9.8 ± 4.9	9.1 ± 4.1	8.4 ± 5.0	9.0 ± 6.2	9.4 ± 6.1	8.6 ± 4.9	9.2 ± 5.3
	Extension	11.0 ± 4.8	10.7 ± 4.4	10.6 ± 4.6	8.5 ± 5.0	7.8 ± 5.0	7.8 ± 5.0	9.3 ± 5.0
	Total ROM	20.7 ± 5.9	19.8 ± 4.8	19.0 ± 6.3	17.5 ± 7.0	17.2 ± 7.7	16.4 ± 5.6	18.5 ± 6.5
	Kyphosis	3.7 ± 3.1	4.4 ± 3.1	3.6 ± 3.5	3.5 ± 3.5	3.6 ± 4.0	6.1 ± 3.8	4.1 ± 7.6
Lordotic alignment at T12–S1 level								
Age (years)		20–29	30–39	40–49	50–59	60–69	70–79	Total
Males	Flexion	36.3 ± 13.0	31.7 ± 13.6	32.7 ± 11.9	31.9 ± 12.9	31.6 ± 13.7	27.1 ± 11.3	32.0 ± 13.0
	Extension	27.3 ± 11.4	26.0 ± 9.9	18.2 ± 10.8	15.0 ± 8.8	13.9 ± 11.2	12.8 ± 8.3	20.2 ± 11.4
	Total ROM	63.6 ± 14.3	57.7 ± 14.5	51.0 ± 16.0	46.9 ± 12.6	45.5 ± 14.7	39.9 ± 13.5	52.2 ± 16.0
	Lordosis	31.1 ± 11.9	29.7 ± 11.8	33.4 ± 15.5	36.9 ± 12.0	35.4 ± 13.5	34.4 ± 16.5	33.9 ± 13.8
Age (years)		20–29	30–39	40–49	50–59	60–69	70–79	Total
Females	Flexion	35.2 ± 13.7	38.5 ± 10.9	38.4 ± 11.6	36.6 ± 13.3	31.8 ± 12.5	31.7 ± 12.6	35.3 ± 13.1
	Extension	29.4 ± 10.3	24.7 ± 10.3	19.7 ± 9.6	17.5 ± 11.5	13.5 ± 9.2	12.7 ± 5.7	19.7 ± 11.2
	Total ROM	64.6 ± 13.6	63.3 ± 12.3	58.1 ± 14.0	54.1 ± 13.2	45.3 ± 16.3	44.4 ± 12.2	55.1 ± 15.8
	Lordosis	33.8 ± 13.1	35.5 ± 11.7	42.3 ± 13.9	42.5 ± 14.3	43.6 ± 12.7	37.9 ± 13.9	39.4 ± 13.7

Values given are mean ± standard deviation (SD) unless otherwise specified.
ROM indicates range of motion.

Supplemental Table 1.
Vertebral body height at the center at each vertebral level (mm)

Age (years)		20–29	30–39	40–49	50–59	60–69	70–79	Total
Males	T10	26.4 ± 1.9	26.3 ± 2.0	26.6 ± 1.8	26.2 ± 2.0	25.6 ± 1.7	25.9 ± 1.7	26.2 ± 1.9
	T11	28.1 ± 2.0	28.2 ± 1.8	28.0 ± 2.0	27.6 ± 1.9	27.3 ± 1.6	27.3 ± 1.8	27.7 ± 1.9
	T12	30.0 ± 2.1	30.6 ± 1.8	30.1 ± 2.2	29.5 ± 1.8	29.1 ± 1.7	29.3 ± 1.8	29.8 ± 2.0
	L1	31.8 ± 2.0	32.1 ± 1.7	32.1 ± 1.9	31.5 ± 1.9	30.7 ± 1.6	30.8 ± 2.2	31.5 ± 2.0
	L2	32.4 ± 1.8	32.7 ± 1.6	33.0 ± 2.1	31.9 ± 2.1	31.1 ± 1.8	32.1 ± 2.5	32.2 ± 2.1
	L3	32.8 ± 1.8	33.2 ± 1.8	33.3 ± 2.3	32.6 ± 2.4	31.9 ± 2.1	32.2 ± 2.3	32.7 ± 2.2
	L4	33.2 ± 1.7	33.6 ± 1.6	33.5 ± 2.5	32.7 ± 2.5	31.9 ± 2.6	32.3 ± 2.7	32.9 ± 2.4
	L5	32.5 ± 2.3	33.3 ± 2.1	32.3 ± 3.0	31.9 ± 3.1	31.0 ± 2.6	31.6 ± 2.6	32.1 ± 2.7
Age (years)		20–29	30–39	40–49	50–59	60–69	70–79	Total
Females	T10	23.7 ± 2.1	23.2 ± 1.5	24.2 ± 1.9	23.9 ± 2.3	23.6 ± 2.3	22.7 ± 1.9	23.6 ± 2.1
	T11	25.4 ± 2.2	24.9 ± 1.6	25.5 ± 2.1	25.1 ± 1.5	25.0 ± 1.9	24.5 ± 2.1	25.1 ± 1.9
	T12	27.8 ± 2.2	27.2 ± 1.8	27.6 ± 2.0	27.4 ± 1.5	26.9 ± 2.5	26.3 ± 2.9	27.2 ± 2.2
	L1	29.8 ± 2.1	29.5 ± 1.6	29.8 ± 1.8	29.1 ± 1.8	28.6 ± 2.1	27.7 ± 3.0	29.1 ± 2.2
	L2	30.7 ± 2.2	30.8 ± 2.1	30.8 ± 2.1	30.3 ± 2.0	29.6 ± 2.3	28.3 ± 3.3	30.1 ± 2.5
	L3	31.6 ± 2.2	31.5 ± 2.2	31.1 ± 1.8	31.1 ± 2.0	30.7 ± 2.4	29.4 ± 2.8	30.9 ± 2.3
	L4	31.7 ± 2.3	31.6 ± 2.1	31.9 ± 1.9	31.1 ± 2.1	30.5 ± 2.6	29.3 ± 2.8	31.0 ± 2.5
	L5	30.8 ± 2.5	30.7 ± 2.2	30.3 ± 4.6	30.6 ± 2.3	29.4 ± 3.0	28.7 ± 2.7	30.1 ± 3.1

Values given are mean ± standard deviation (SD) unless otherwise specified.

Supplemental Table 2.
Anterior–posterior ratio in the vertebral body height at each vertebral level (%)

Age (years)		20–29	30–39	40–49	50–59	60–69	70–79	Total
Males	T10	103.9 ± 6.8	105.6 ± 7.1	104.6 ± 6.4	105.3 ± 6.6	107.0 ± 8.8	106.5 ± 8.7	105.5 ± 7.5
	T11	109.8 ± 7.5	110.6 ± 8.8	109.9 ± 9.4	111.6 ± 7.6	114.0 ± 9.1	112.2 ± 9.2	111.4 ± 8.7
	T12	114.7 ± 8.4	113.3 ± 7.5	114.6 ± 7.5	115.4 ± 7.0	116.7 ± 9.5	115.5 ± 8.7	115.1 ± 8.3
	L1	115.1 ± 7.0	115.0 ± 8.2	115.0 ± 6.4	115.0 ± 7.4	117.2 ± 8.8	119.1 ± 9.5	116.0 ± 8.5
	L2	107.7 ± 5.4	107.6 ± 6.8	107.9 ± 5.4	108.0 ± 5.9	111.0 ± 7.9	113.3 ± 8.7	109.2 ± 7.1
	L3	103.6 ± 5.7	101.7 ± 5.6	102.9 ± 5.7	102.9 ± 5.7	104.4 ± 6.6	104.8 ± 6.8	103.4 ± 6.1
	L4	98.7 ± 4.7	98.3 ± 6.8	98.4 ± 6.3	98.2 ± 6.8	99.0 ± 6.4	101.4 ± 9.6	99.0 ± 7.0
	L5	89.5 ± 5.8	88.8 ± 5.8	87.6 ± 7.6	88.1 ± 8.9	90.5 ± 7.8	90.9 ± 9.7	89.2 ± 7.8
Age (years)		20–29	30–39	40–49	50–59	60–69	70–79	Total
Females	T10	101.7 ± 6.7	102.5 ± 7.1	102.2 ± 6.2	104.2 ± 6.4	106.1 ± 7.9	103.6 ± 6.6	103.4 ± 7.0
	T11	107.0 ± 6.0	106.2 ± 7.1	106.3 ± 7.2	108.8 ± 6.2	110.6 ± 8.4	110.2 ± 8.7	108.2 ± 7.5
	T12	108.1 ± 5.8	108.5 ± 6.3	106.7 ± 7.8	109.3 ± 7.1	111.2 ± 9.7	111.5 ± 9.1	109.2 ± 8.7
	L1	107.8 ± 6.4	108.4 ± 6.0	107.4 ± 6.2	109.0 ± 6.0	110.0 ± 8.8	111.3 ± 9.9	109.0 ± 7.7
	L2	103.4 ± 5.7	104.8 ± 5.6	102.3 ± 5.5	103.8 ± 6.6	106.4 ± 9.4	105.6 ± 9.8	104.4 ± 8.6
	L3	99.7 ± 6.1	99.4 ± 5.1	98.6 ± 5.6	99.5 ± 5.9	100.4 ± 6.8	101.1 ± 8.0	99.8 ± 6.3
	L4	94.4 ± 5.9	96.9 ± 6.8	94.6 ± 5.0	96.5 ± 7.0	97.2 ± 8.6	94.2 ± 9.0	95.7 ± 7.4
	L5	87.4 ± 5.8	87.6 ± 6.7	87.3 ± 8.0	86.1 ± 6.2	89.1 ± 8.1	88.7 ± 7.9	88.0 ± 7.4

Values given are means ± standard deviation unless otherwise specified.

Supplemental Table 3.
Anterior–posterior ratio in the intervertebral disc height at each disc level (%)

Age (years)		20–29	30–39	40–49	50–59	60–69	70–79	Total
Males	T10/T11	73.2 ± 21.9	68.9 ± 21.9	76.0 ± 23.1	70.2 ± 18.6	71.6 ± 20.4	70.4 ± 27.1	71.7 ± 22.2
	T11/T12	73.7 ± 20.1	71.3 ± 24.1	70.8 ± 21.5	66.3 ± 18.3	69.5 ± 24.9	66.6 ± 21.6	69.6 ± 21.8
	T12/L1	55.5 ± 12.5	58.6 ± 16.9	60.7 ± 17.5	56.8 ± 15.2	60.4 ± 21.3	55.7 ± 17.4	58.0 ± 17.0
	L1/L2	61.4 ± 14.5	60.9 ± 15.7	59.0 ± 16.0	59.2 ± 15.0	53.5 ± 13.3	49.3 ± 14.1	57.3 ± 15.3
	L2/L3	63.9 ± 16.5	65.8 ± 15.7	62.5 ± 12.5	58.9 ± 15.1	52.7 ± 12.8	51.2 ± 14.7	59.2 ± 15.5
	L3/L4	64.2 ± 16.1	63.0 ± 14.1	60.5 ± 10.5	56.0 ± 14.1	51.7 ± 11.6	50.2 ± 14.1	57.6 ± 14.4
	L4/L5	60.5 ± 15.2	58.2 ± 12.7	55.8 ± 14.2	53.2 ± 15.8	49.9 ± 11.7	50.4 ± 15.5	54.6 ± 14.7
	L5/S1	52.1 ± 16.7	51.3 ± 13.8	48.4 ± 16.6	45.7 ± 15.7	45.8 ± 19.6	41.7 ± 16.0	47.5 ± 16.7
Age (years)		20–29	30–39	40–49	50–59	60–69	70–79	Total
Females	T10/T11	87.8 ± 21.2	86.7 ± 25.3	86.7 ± 28.2	81.1 ± 25.9	74.2 ± 24.4	77.4 ± 21.4	82.2 ± 24.9
	T11/T12	81.0 ± 17.4	75.9 ± 22.1	79.4 ± 21.0	79.4 ± 22.6	74.7 ± 21.4	74.2 ± 22.8	79.0 ± 22.2
	T12/L1	76.0 ± 19.6	70.2 ± 25.6	73.5 ± 19.3	67.2 ± 19.6	68.8 ± 19.5	72.1 ± 25.1	71.3 ± 21.5
	L1/L2	73.9 ± 14.5	67.8 ± 18.5	70.7 ± 19.1	63.5 ± 16.0	57.6 ± 15.3	64.1 ± 19.2	66.1 ± 17.9
	L2/L3	73.3 ± 15.3	66.9 ± 19.3	63.9 ± 15.4	61.4 ± 16.4	53.3 ± 13.7	55.2 ± 15.3	62.2 ± 17.2
	L3/L4	68.6 ± 15.5	63.9 ± 16.5	63.1 ± 18.7	54.7 ± 14.4	50.6 ± 13.7	54.6 ± 15.0	59.1 ± 16.8
	L4/L5	63.4 ± 15.5	59.2 ± 13.5	59.3 ± 16.1	52.2 ± 13.3	55.5 ± 19.3	53.6 ± 15.1	57.3 ± 16.1
	L5/S1	63.7 ± 20.2	57.6 ± 14.9	57.7 ± 20.0	51.1 ± 17.2	53.9 ± 23.9	49.7 ± 14.2	55.6 ± 19.4

Values given are means ± standard deviation unless otherwise specified.