Measurement of compression and shear forces in the lumbar intervertebral disk LS/S1: Comparison using a static kinematical model and a frame structure model

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Measurement of compression and shear forces in the lumbar intervertebral disk L5/S1 : Comparison using a static kinematical model and a frame structure model

Shibata Katsuyuki

ABSTRACT

The purpose of this study was to clarify the difference in the compression force in the lumbar intervertebral disk L5/S1 between a static kinematical model and a frame structure model using the muscular moment arm measured by MRI. The subjects were 8 healthy male students who had had no lumbago, and gave consent. Methods : The experiments were performed by 2 methods using a static kinematical model or a frame structure model. In the static kinematical model, the compression force was measured by back lift and leg lift methods with a weight of 0, 10, or 20kg placed in the container. In the frame structure model, the compression force was measured with variable physical parameters, such as lifting weight, muscular traction, and intra-abdominal pressure (IAP). Results : The compression force in the lumbar region determined using the static kinematical model was slightly increased by increasing the load weight. There was no significant difference in the compression force between the back lift and leg lift methods, but the difference in the shear force was significant between the 2 methods. The compression force in the lumbar region determined using the frame structure model, which was closely correlated with that determined using the static kinematical model (R^2=0.92), was significantly increased by increasing the load weight. In the frame structure model, the compression force could be measured by simulation under different conditions of the lumbosacral angle, load weight, and IAP. Thus, these findings have implications for the biomechanical evaluation of the manual materials handling tasks.

KEY WORDS

Lifting movement, Lumbar intervertebral disk, Compression force, Shear force, Intra-abdominal pressure

Introduction

With regard to the measurement of the compression force in the lumbar intervertebral disk L5/S1 (compression force), Morris et al[1]. calculated the compression force using a static kinematical model in 1961, and Chaffin et al[2]. developed a static kinetic model in 1983. McGill et al[3]. introduced a dynamic kinetic model using superficial electromyograms and video recording, and Marras et al[4]. developed EMG-assisted model using a lumbar motion monit in 1993. Among epidemiological studies[5,6] in t manufacturing and industrial field, Anderson[7] ı ported that activities with compression force of 3,4 N caused low back diseases (LBD) at a rate of 40' and Chaffin[6]reported that the incidence of LBD activities with compression force of 4,500 N w

Department of Occupational Therapy, School of Health Sciences, Faculty of medicine, Kanazawa University (Director : Prof.Ikuta M.)

10%. It is difficult to perform invasive measurement of the compression force clinically or while working for the evaluation of load in the lumbar region. Therefore, estimation of the compression force in the lumbar region using a theoretical model with parameters, such as morphological measurements, working posture, and the direction and height of operation, has been common. In some studies[8-13] reported that intra-abdominal pressure (IAP) is a defense mechanism of the spine against compression force loaded on the dorsolumbar region caused by lifting heavy substances, but it has also been reported that there are no effects of IAP[14-18]. The purpose of this study was to clarify the difference in the compression force between a static kinematical model and a frame structure model using parameters measured by MRI, and to evaluate the function of IAP that removes the compression force in the lumbar region using a frame structure model of the body trunk.

Subjects

The subjects were 8 healthy males who had had no lumbago, and gave consent to this study. The mean age was 22.2±2.5 (SD) years, the mean height 172.0±4.3 (SD) cm, the mean body weight 61.4±6.1 (SD) kg, the mean length of the upper limb 74.6±4.4 (SD) cm, and the mean length of the lower limb 78.8 ±3.0 (SD) cm.

Methods

1. Experiments

The experiments were performed using 2 models. In the static kinematical model, the compression force in the lumbar region was determined while the subject was lifting a container from the floor up to the height of the hip by the following 6 methods. The subject lifted a load weight of 0, 10, or 20kg placed in the container, weighing 0.45kg, while extending the hip joints and knee joints (leg lift) or while extending the body trunk (back lift). In the frame structure model, the compression force was measured by changing the muscular traction of the body trunk, IAP, and the lumbosacral angle in the lumbar region.

Measurement apparatus

a. Analysis of the movement

The movement of weight lifting was imaged using 2 video cameras (SONY Inc., DXC-200), and recorded with a two-dimensional image analysis apparatus (Bertec Inc. Winanalyze, ver 4.1). The markers were applied to 13 sites, consisting of 1 site of the container and 12 sites on the right side of the subject body, which were the earhole, C7 processus sipnosus, Th7.8 processus sipnosus, spina illiaca anterior superior, spina illiaca anterior inferior, trochanter major, knee joint, malleolus lateralis, caput ossis metatarsalis, acromion, elbow joint, and hand joint. The articular angles in the cervical and thoracic regions and the angles of the hip joint, knee joint, and foot joint were determined using angles formed between the extensions made by connecting markers (Fig. 1).

b. Measurement of the muscular moment arm by MRI

Transverse section of the lumbar region of the L1-S1 intervertebral disks was performed using a magnetic resonance imaging (MRI) apparatus (1.5-T superconducting, Signa, GE Yokogawa Medical Systems) in the radiotherapy department of Kanazawa University Hospital. Imaging was performed with the subject in a supine position, with the knees extended and both upper limbs attached to each body side. The upper boundary, center, and lower boundary of the vertebral corpus of the lumbar vertebrae 1, 2, 3, 4, and 5 (L1-5) were imaged 11 slices (Fig. 2a). The moment arm was determined on the images of the center of the vertebral corpus of L1, L3, and L5 using image processing and analysis software with NIH image. The center of the vertebral corpus of L1, L3, and L5 on the transverse plane of the body trunk was regarded as the standard point, and the lengths of the erector spine muscles and rectus abdominal muscles were determined in the anteroposterior direction and the transverse direction.

c. Estimation of the compression force in the lumbar intervertebral disk using the static kinematical model

The compression force in the lumbar region was determined using parameters, such as morphological measurements, working posture, the center of mass,

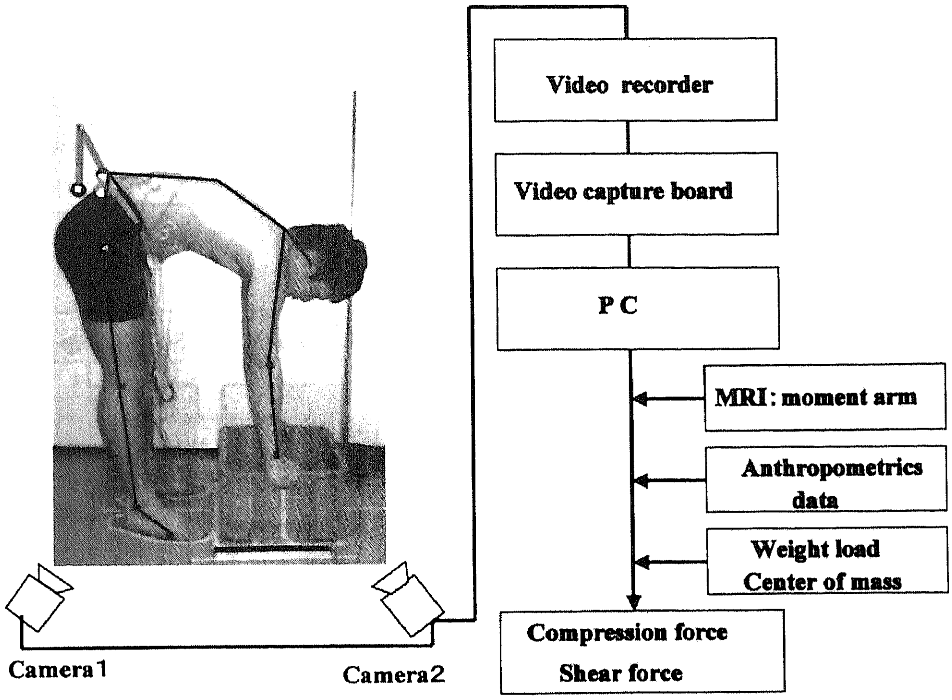


Fig 1. Block diagram of the measurement systems using the static kinematical model

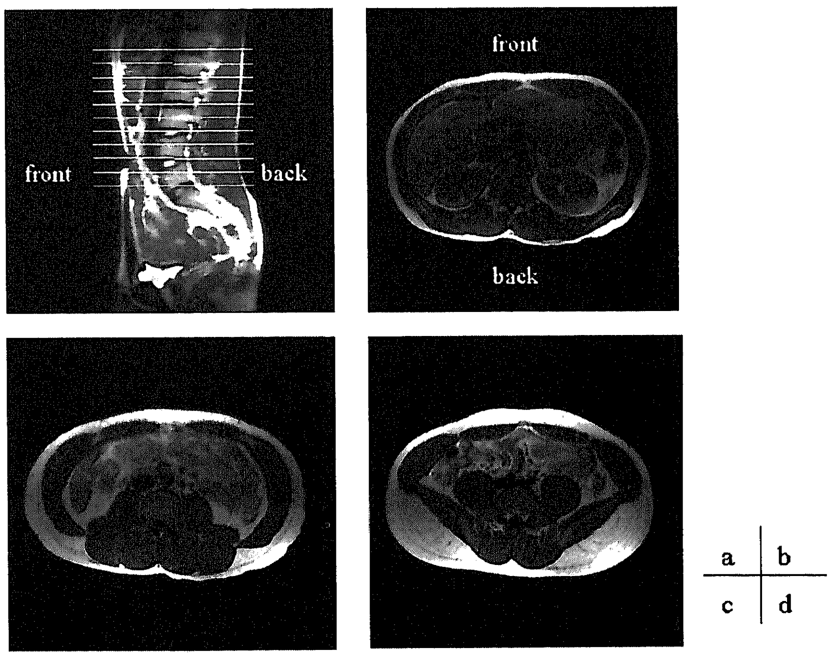


Fig 2. Measurement sites in the lumbar region by MRI
(a) Left profile (b) L1 level (c) L3 level (d) L5 level

and muscular moment arm of the subject during the back lift and leg lift.

The torque around the lumbar intervertebral disk L5/S1, shown as the product of the weight of the upper body trunk and its moment arm and the product of the lifted substance weight and its moment arm, was calculated using the following equation ($M_{L5/S1}$=a × mg × body weight+b × mg × load)[1-3]. a : moment-arms for center of upper body weight. b : moment-arms for weight load. IAP was calculated

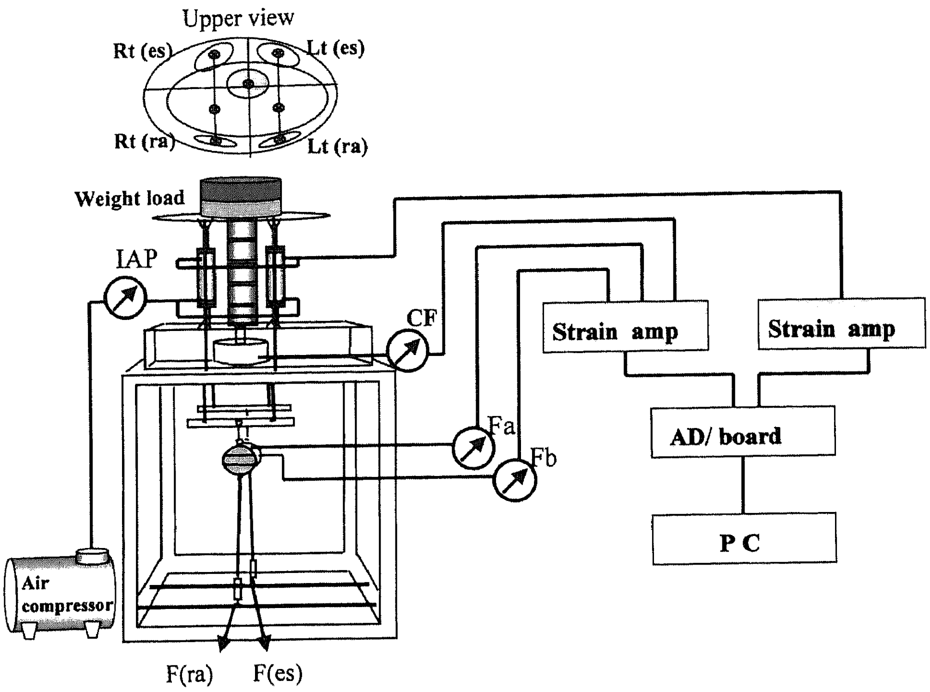


Fig 3. Outline of experiments using the frame structure model
Lt (ra) : Traction position of the Lt.rectus abdominal muscle,
Rt (ra) : Traction position of the Rt.rectus abdominal muscle,
Lt (es) : Traction position of the Lt.erector spinae muscles,
Rt (es) : Traction position of the Rt.erector spinae muscles,
Weight load: The weight simulated the weight of the upper body and weight load of lifting,
F (ra) : Traction force of the rectus abdominal muscles,
F (es) : Traction force of the erector spinae muscles,
Fa: The vector of Lt (ra) and Rt (ra),
Fb: The vector of Lt (es) and Rt (es),
IAP: intra-abdominal pressure;IAP simulated with air compressor
CF: compression force of vertebral disk L5/S1,

using Fisher's estimation equation, IAP=$M_{L5/S1}\times(0.067+0.082\times\sin(\theta)\times10^{-4}$. θ ; hip flexion angle.[1-3]. The compression force (CF) in the intervertebral disk L5/S1 was determined by dividing by the moment arm of the erector spine muscles measured by MRI using the following equation ; $F_{(CF)}$=a × (mg × body weight)+b × (mg × load)-D(Fa)/Erec.spin. mg × load ; weight of the load in the hands. Fa ; IAP(Pa) × area of diaphragm (D) by MRI. Erec. Spine ; moment-arms of erector spine by MRI.

d. Estimation of the compression force using the lumbar frame structure model

The lumbar frame structure model was produced by determining the arrangement of the lumbar intervertebral corpora and muscles based on the muscular moment arm of the subject measured by MRI (Fig. 3.Upper view). A load cell (KYOWA Inc.RCD-200K) for loading was placed on the bottom of the frame structure model for the measurement of compression force. Above the load cell, 5 columns equivalent to the intervertebral corpora were piled up, which could be bent by the lumbosacral angle. The load weight in the frame structure model was 1/10 of the sum of the weight of the upper body trunk and the load weight for lifting. The weight of the load cell (KYOWA Inc. LTZ-50KA) for traction was 1/10 of the calculated strengths of the erector spine muscles and rectus abdominal muscles. Pressurization with 1/10 of the IAP determined using the theoretical model was performed using the air cylinders (CKD Inc. SCM-20D50). In the frame structure model, the

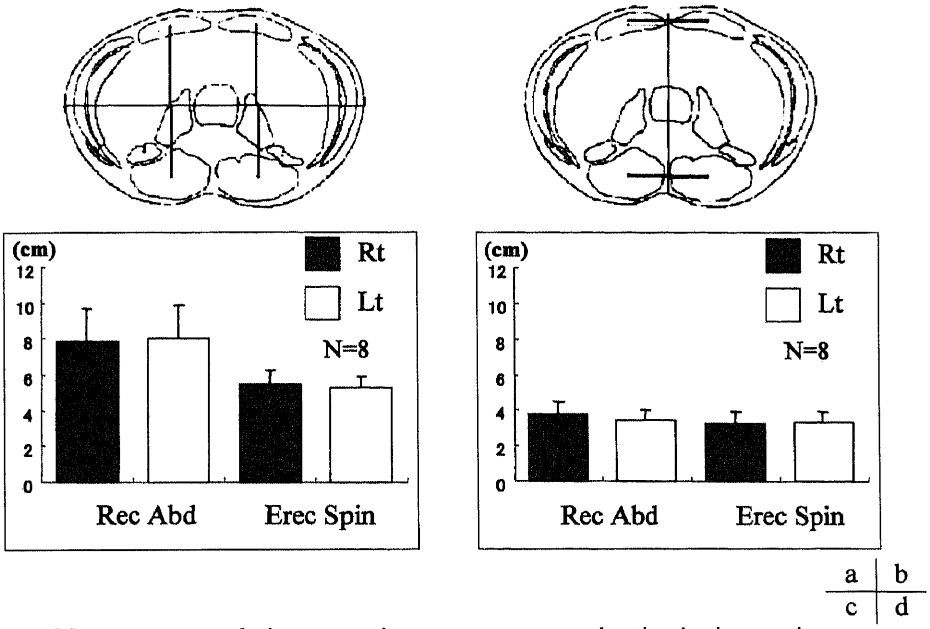


Fig 4. Measurement of the muscular moment arms in the body trunk
(a) Sagittal plane moment arms at the L3 level
(b) Coronal plane moment arms at the L3 level
(c) Mean of the Sagittal plane moment arms from L1 to L5 level
(d) Mean of the Coronal plane moment arms from L1 to L5 level
The moment arms at each vertebral level were determined by coordinates of muscle centroid and the vertebral body centroid

downward traction force of the bilateral erector spine muscles and rectus abdominal muscles, and the IAP that reduces load by pulling up from the pelvic bottom, were amplified by a dynamic distortion amplifier, and measured by inputting into a personal computer via an AD board (AD Instrument Inc. Mac Lab.8S) (Fig. 3).

Statistical analysis

The mean compression force and standard deviation determined in each model were analyzed under each condition by the multiple comparison method. The comparisons of experiments were performed by Bonferroni's method, and a value of $p<0.05$ was regarded as significant.

Results

a. Measurement of parameters in the abdomen by MRI

As the moment arms of the rectus abdominal muscles and erector spine muscles, the means of the moment arms measured at L1, L3, and L5 were determined. The moment arm of the rectus abdominal muscles was 7.9 ± 1.8cm (SD) on the sagittal plane and 3.6 ± 0.7 (SD) cm on the coronal plane. The moment arm of the erector spine muscles was 5.4 ± 0.7 (SD) cm on the sagittal plane and 3.3 ± 0.6 (SD) cm on the coronal plane (Fig. 4).

b. Determination of the compression force in the lumbar region using the static kinematical model

There was no difference in the compression force in the lumbar region between the back lift and leg lift methods. The compression force was slightly increased by increasing the load weight. Table 1 shows the mean compression force on the lumbus during lifting the container from the floor to the height of the hip. There were significant differences in the mean compression force caused by the back lift and leg lift methods between 0kg and 10kg and between 0kg and 20kg ($p<0.05$). On the other hand there was a significant difference in the shear force between the back lift and leg lift methods. The shear force was slightly increased by increasing the load weight, and the differences were significant with each load weight between the 2 methods (Table 1).

Table 1. Means of the compression force and shear force on the L5/S1 in the static kinematical model

N=8

	Compression force						
Weight load	Back lift (N)			Leg lift (N)			Back lift vs Leg lift
0 kg	1275.1 (367.7)			1176.9 (257.7)			NS
		*			*		
10 kg	2075.3 (489.1)		*	2071.2 (430.5)		*	NS
20 kg	2673.7 (702.0)			2586.5 (530.4)			NS

	Shear force						
Weight load	Back lift (N)			Leg lift (N)			Back lift vs Leg lift
0 kg	269.5 (26.1)			215.8 (24.0)			*
		*			*		
10 kg	364.7 (27.2)		**	296.4 (27.6)		**	**
		*			*		
20 kg	464.5 (28.2)			378.9 (29.2)			**

Parenthesis; SD * P<0.05 ** P<0.01

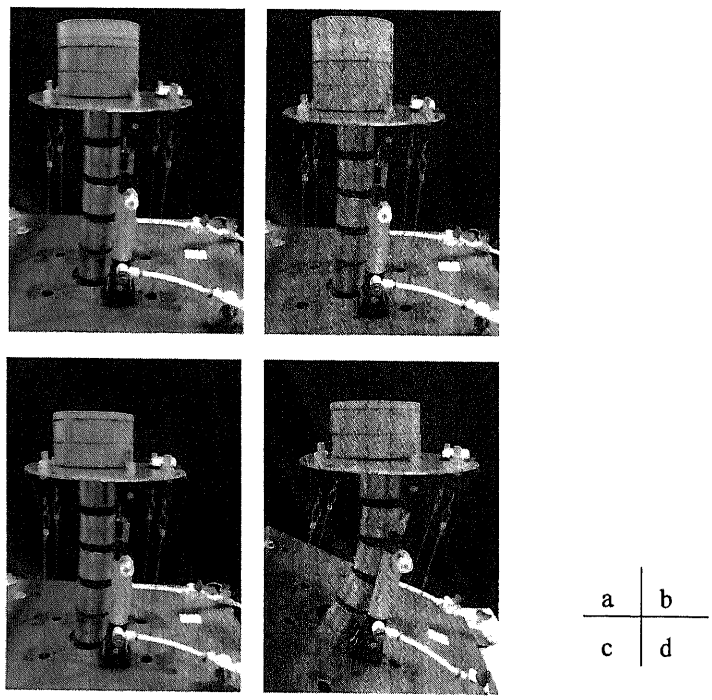


Fig 5. Measurement of the compression force at different weight loads and lumbosacral angle in the frame structure model
(a) Condition: Lumbosacral angle 0°, (Weight of the upper bodytrunk+10kg)×1/10
(b) Condition: Lumbosacral angle 0°, (Weight of the upper bodytrunk+20kg)×1/10
(c) Condition: Lumbosacral angle 0°, Weight of the upper body trunk×1/10
(d) Condition: Lumbosacral angle: 30°, Weight of the upper body trunk×1/10

Table 2. Means of the compression force on the L5/S1 in the frame structure model

N=8

Weight load	Compression force: Non IAP			Compression force: IAP			Non IAP vs IAP
0 kg	920.0 (160.2)	** (0 vs 10 kg)	** (0 vs 20 kg)	786.3 (137.6)	** (0 vs 10 kg)	** (0 vs 20 kg)	NS
10 kg	1557.5 (216.6)	* (10 vs 20 kg)		1328.8 (161.7)	* (10 vs 20 kg)		NS
20 kg	2003.8 (220.6)			1643.8 (167.2)			*

Weight load	Compression force: Lumbosacral angle 0 °			Compression force: Lumbosacral angle 30°			0° vs 30°
0 kg	786.3 (137.6)	* (0 vs 10 kg)	* (0 vs 20 kg)	672.5 (75.0)	* (0 vs 10 kg)	* (0 vs 20 kg)	NS
10 kg	1328.7 (161.7)	ns (10 vs 20 kg)		1272.5 (219.2)	ns (10 vs 20 kg)		NS
20 kg	1643.7 (167.2)			1500 (249.1)			NS

Parenthesis; SD   * P<0.05   ** P<0.01

c. Measurement of the compression force in the frame structure model (Fig. 5)

In the frame structure model, the compression force was measured by loading the muscular strength in the body trunk and IAP determined in the static kinematical model. The compression force by loading a weight of 0kg was 920±160.2 N by traction alone (non-IAP) and 786.3±137.6 N by addition of IAP (IAP), showing reduction by 21%. The compression force by loading a weight of 10kg was 1,557.5± 216.7 N by non-IAP and 1,328.8±161.7 N by IAP, showing reduction by 20%. The compression force by loading a weight of 20kg was 2,003.8±220.6 N by non-IAP and 1,643.8±167.2 N by IAP, of which the reduction was 24%. There was a significant difference in the compression force at 20kg weight load between non-IAP and IAP ($p<0.05$) (Table 2).

To examine the difference in the compression force between lumbosacral angles, the compression force was measured at a lumbosacral angle of 0° and 30° in the frame structure model, as shown in Fig. 5, c, d. The compression force was lower at a lumbosacral angle of 30° than at a lumbosacral angle of 0°, of which the reduction was 15% with a load weight of 0kg, 4.3% with a load weight of 10kg, and 8.8% with a load weight of 20kg. However, there were no significant differences in the compression force between the lumbosacral angles of 0° and 30° (Table 2).

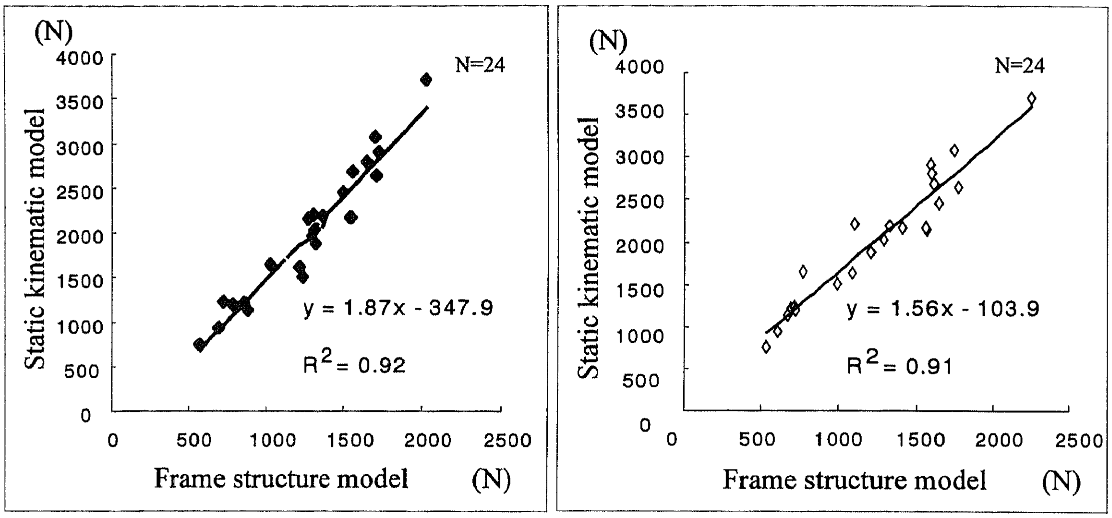
d. Comparison of the compression force in the static kinematical model and the frame structure model

Fig. 6 shows the correlation between the static kinematical model and the frame structure model. At a lumbosacral angle of 0°, the relationship could be expressed as a linear regression equation, $y=1.87X-347.9$, ($R^2=0.92$), indicating a close correlation. At a lumbosacral angle of 30°, the regression equation was $y=1.55X-103.9$ ($R^2=0.91$), indicating a close correlation.

Discussion

1. Compression force in the static kinematical model

To calculate the compression force in the lumbar region, the product of the weight of the upper body trunk and its moment arm and the product of the



a | b

Fig 6. Comparison of the compression force in the static kinematical model and the frame structure model
(a) Lumbosacral angle:0° (b) Lumbosacral angle:30°
($P<0.05$,by the simple linear regression test)

lifted load weight[1,2,13,15] and its moment arm[12,15,19-21], the torque around the intervertebral disk L5/S1, are required[1-3].The force against the torque is induced by afferent activity of bilateral erector spine muscles, and the force pulling the body trunk upward and backward is added to the lumbar region as high compression force. Therefore, the muscular moment arm and load weight are important parameters in the static kinematical model[1,3,12,27]. In past studies using the static kinematical model, the moment arm of the erector spine muscles often being between approximately 5.0 and 7.0cm[6,15,20,21]. In the present study, since the muscular moment arm of each subject was measured by MRI, and used for the measurement, the compression force could be determined with the anatomical characteristics of each subject. The measurement of the moment arm by MRI was performed in the supine position. To determine the moment arm more accurately, it was considered necessary to correct the moment arm by accurate measurement of the rotational axis of the lumbar vertebrae and the central line of muscular mass against gravity[12]. However, there were no differences in the data between this study and past studies[20,21]. Threrfore, the validity of the static kinamatic model was proved from this study.

The compression force in the lumbar region caused by lifting a heavy substance was slightly increased by increasing the load weight. There were significant differences in the compression force between the load weights of 0kg and 10kg and between the load weights of 0kg and 20kg ($p<0.05$). However, there was no difference in the compression force between the back lift and leg lift methods. The shear force was slightly increased by increasing the load weight, and the difference in the shear force was significant between the back lift and leg lift methods. The lumbosacral angle was increased together with increases in the angle of pelvic procurvation during the back lift period[12], and the shear force induced in the intervertebral disk L5/S1 may have been increased. The moment arm from the center of mass to the container was decreased with increases in the load weight during the leg lift period, and the container was lifted by pulling it to the front of the body trunk. The leg lift method reduced mechanical disadvantages, indicating that this method with reduced compression force in the lumbar region is useful[15,25]. The IAP was significantly higher with the back lift method than with the leg lift method. The elevation of IAP against the strong bending moment suppressed the bending force of the body trunk induced by the back lift method, suggesting that the elevated IAP contributed to the inflexibility of the spine[12, 13, 27, 28].

2. Compression force in the frame structure model

Among past studies[1-4, 15, 16, 22, 26, 31] using biodynamic model, Cholewickl[24] produced a two-dimensional pendulum model, and determined the energy using a coil spring as the muscular strength of the body trunk and an air cylinder as IAP. Granata[23] calculated the compression force as the resultant force of muscular potentials determined from the cross-sectional area and moment arm of 12 bilateral muscles in the body trunk using a three-dimensional double pendulum model. In the present study, we determined the muscular strength of the bilateral erector spine muscles and rectus abdominal muscles and the increase in IAP based on the moment arm of the subjects measured by MRI, and the compression force in the lumbar region using a three-dimensional frame structure model. Since the compression force determined using the frame structure model produced in this study was closely correlated with that determined using the static kinematical model, it was confirmed that the compression force in the lumbar region was estimated by changing the load weight, IAP addition, and lumbosacral angle. A static kinematic model and a frame structure model showed high correlation (R^2 =0.91,0.92). But the need examined even if trunk lateral muscle in the direction of coronal is added to raise correlation more was suggested. In the future, we will study the method for the measurement of compression force using a frame structure model, to which activities of the internal and external abdominal oblique muscles are added as the supplementary traction force, because these muscles arranged in the oblique direction have large moment arms in the lateral direction[19].

3. Function of IAP for the removal of the compression force in the lumbar region

Morris[1] reported that IAP presses the thorax upward, and reduces the compression force on the lumbar vertebral corpora by increasing the extension force of the lumbar vertebral corpora in the major axis direction. However, Nachemson[9] reported that strong activities of the muscles of the abdominal wall are required for the elevation of IAP by increasing abdominal pressure, and that the activities of the abdominal muscles increase the compression force in the lumbar vertebrae via the thoracic and pelvic bottoms.

Morris[1] and Chaffin et al[2]. reported that the reduction rate of the compression force by IAP was 10-15% in the static kinematical model. In the present study, the reduction rate of the compression force by IAP induced using 2 air cylinders in the frame structure model was 8.5%, which agreed well with that in past studies[10, 15, 17].

In past in vivo studies, McGill[15] measured pressure in the abdominal wall by inserting a sensor from the oral cavity, and reported that the IAP was increased by 100-150mmHg during the weight-lifting period. Maeda et al[17]. reported that a sensor indwelled in the rectum demonstrated 50-60mmHg elevation. Hodges[10] indicated that IAP below 100mmHg was generally insufficient, less than 5-6% of the level that would be necessary for the reduction of compression force. In the present study, 230-420mmHg IAP was added in the frame structure model. If such a level of pressure is added, it is difficult to increase IAP and maintain its high level for a long time because the abdominal arteries are compressed. Therefore, IAP may be effective in instantaneous lifting movement alone[11, 12, 28-31].

In the frame structure model, the pressurization by the air cylinders, by which IAP function was simulated, demonstrated not only load-reducing function but also enhancement of the physiological procurvation of the lumbar vertebral corpora. Actual IAP supports a load weight in the abdominal whole. A system to disperse isn't taking a load weight into consideration with this experiment system. In the future, It will have the need that the system which the compression force to disperse around the lumbar region. This suggested that the IAP elevation suppressed the bending moment in the front of the body trunk mass inclined at the lumbosacral angle, and increased the spinal safety and inflexibility[29-31].

Conclusions

We studied the movement of weight lifting (0, 10, 20kg) from the floor by back lift and leg lift methods with 8 healthy male subjects. The compression forces in the lumbar region determined using the static kinematical model and frame structure model were compared.

1. The anatomical parameters measured by MRI were used for the determination of the compression force in the static kinematical model.
2. The compression force was slightly increased by increasing the load weight. The shear force was significantly higher by the back lift method than by the leg lift method.
3. The frame structure model was produced based on the anatomical parameters. The compression force was significantly increased by increasing the load weight.
4. In the frame structure model, the compression force in the lumbar region could be measured by simulation under different conditions of the lumbosacral angle, load weight, and IAP.

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腰部椎間板 L5／S1内の圧迫力とせん断力の計測
静的力学モデルと骨格構造モデルによる比較

柴田　克之

要　旨

本実験の目的は，L5／S1 椎間板内の圧迫力を，MRI で計測した各被験者の筋モーメントアームを用いて，静的力学モデルと，骨格構造モデルによる圧迫力の差異を明示することである。対象は８名の健常男性であり，過去に腰痛の既往の無く，本実験の主旨に同意した学生であった。方法：本実験は静的力学モデルと骨格構造モデルを用いた２つの実験からなる。静的力学モデルは，コンテナの持ち上げ方 back lift と leg lift の２条件，持ち上げるコンテナの重量負荷を，０kg，10kg，20kgの３条件で行い，腰部圧迫力を計測した。一方，骨格構造モデルは，持ち上げる重量，筋による牽引力，腹腔内圧などの物理的なパラメータを可変させて，圧迫力を計測した。結果：静的力学モデルで算出した腰部圧迫力は，負荷重量の増加に伴い圧迫力は漸増した。圧迫力は back lift と leg lift の２群間に有意差はなかった。せん断力は back lift と leg lift の２群間で有意差を示した。骨格構造モデルで計測した圧迫力は，静的力学モデルで算出した圧迫力と高い相関（R^2=0.92）を示し，負荷重量の増大に伴い，圧迫力は有意に漸増した。骨格構造モデルは，腰仙角，負荷重量，IAP 加圧などの条件を任意に可変して，異なる負荷条件での圧迫力を模擬的に計測することができた。取り扱う重量物の持ち上げ課題に対して生体力学的な評価として明示することができた。