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Calculation of Intervertebral Disc Pressure in the Thoracic and Lumbar Spine in Elderly Women with Kyphosis Using a Novel Musculoskeletal Model with Isolated Thoracic Vertebrae and Rib Cage

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Abstract

Background: Degeneration of the intervertebral disc is one of the causes of kyphosis. Several biomechanical studies have investigated the mechanisms of development of spinal deformity using simulation models. Realistic musculoskeletal models are helpful for investigating the pathophysiology and changes in internal forces in patients with kyphosis. However, the association between intervertebral disc pressure and kyphosis has not been fully elucidated to date. **Purpose:** To calculate intervertebral disc pressure in elderly women with kyphosis using a novel and precise thoracolumbar three-dimensional musculoskeletal model. **Materials and Method:** Ten female patients with a mean age of 80.0 ± 6.5 years who visited our hospital for medical examination of osteoporosis were included. The subjects were divided into the normal and kyphosis groups depending on their sagittal vertical axis. Intervertebral disc pressures in the thoracic and lumbar spines of subjects were analyzed by inverse dynamics analysis using a novel three-dimensional musculoskeletal model, and were compared between the groups. **Result:** Significant differences in lumbar lordosis (LL) were observed between the two groups. Furthermore, the kyphosis group was older and shorter. In the kyphosis group, the upper thoracic vertebrae (T1 - T6) showed significantly higher intervertebral pressure than the normal group. **Conclusion:** Intervertebral disc pressure in the thoracic and lumbar spines of patients with spinal deformities was evaluated using a novel thoracolumbar three-dimensional musculoskeletal model. Using this novel model with separated thoracic spine and modified muscle path reflecting actual physiological curvature, disc pressure closer to the realistic condition was obtained. Intervertebral disc pressure in the upper thoracic spine in the kyphosis group was significantly increased compared with that in the normal group. Moreover, intervertebral disc pressures in the upper thoracic spine correlated negatively with LL.

Keywords

Intervertebral Disc Pressure, Three-Dimensional Musculoskeletal Model, Adult Spinal Deformity, Anybody Modeling System

1. Introduction

Kyphosis progresses with advancing age [1], and has been found to be associated with multiple health-related problems, including back pain [2], imbalance, a tendency to fall [3] [4] [5], gastroesophageal disorders [6], multifaceted disorders such as mental depression [7], and decrease in health-related quality of life [8]. The possible causes of kyphosis are degeneration of intervertebral discs, development of vertebral fractures, and decrease in trunk muscle strength [9]. Hence, it is important to understand the mechanical behavior of the intervertebral disc as a part of the entire spinal column in order to understand the etiology of spinal deformity. However, the mechanisms of progression of kyphosis other than due to the development of vertebral fractures are still unclear.

Several biomechanical studies have used simulation models to investigate the mechanisms of the development of spinal deformity [10] [11] [12]. Most of these studies focused mainly on vertebral body stress rather than intervertebral disc pressure. *In vitro* studies using human or animal cadavers have evaluated the internal forces in vertebral bodies and intervertebral discs [13] [14] [15] [16]. Disc pressure has also been measured *in vivo* during various movements and lifting operations, by inserting a pressure sensor inside the intervertebral disc [17] [18] [19] [20]. However, the *in vivo* procedures are basically invasive, especially for healthy subjects. Besides, the majority of these studies were performed mainly on the lumbar spine. Therefore, evaluation of intervertebral disc pressure of the entire spinal column, to determine how kyphosis occurs and progresses, is necessary. Realistic musculoskeletal models might be helpful for investigating the pathophysiology and changes in internal forces in patients with kyphosis.

Recently, several biomechanical studies using a musculoskeletal model of the entire spine, including the rib cage or whole body, have been developed [10] [21] [22] [23] [24]. We also developed a novel musculoskeletal model of the entire spinal column, which was modified from the original model for the lumbar spine, which included the thoracic cage as one rigid body [23]. The predicted intervertebral disc pressure of the spinal column as a whole with this model was validated to show the accuracy of measurements including the thoracic spine. Since previous studies using a musculoskeletal model for the whole spine focused on the development of vertebral fractures [10] [25] or the effect of various movements on disc pressure [22], the association between intervertebral disc pressure and kyphosis has not been fully elucidated to date. The purpose of this study was to calculate intervertebral disc pressure in elderly women with kyphosis using a novel thoracolumbar three-dimensional musculoskeletal model.

2. Materials and Methods

2.1. Participants

Ten female participants with osteoporosis were recruited from among post-menopausal women who visited our outpatient clinic for the purpose of medical examination of osteoporosis. Participants were included on the basis that they had been diagnosed with primary osteoporosis requiring treatment. All participants were housewives without experiences of heavy work, and were ambulatorywithout any complaints of back pain. Individuals with histories of spinal surgery, vertebroplasty/kyphoplasty, and multiple vertebral fractures (≥2) were excluded. The ethics committee of our institute approved this study protocol.

2.2. Imaging

Lateral radiographs of the whole spine, including the pelvis, with both hands placed on the clavicle, were taken in the relaxed standing position. The following parameters were measured on the radiographs: sagittal vertical axis (SVA: Horizontal distance from the C7 plumb line originating at the middle of the C7 vertebral body to the posterior superior endplate of S1), lumbar lordosis (LL: Cobb angle from the upper endplate of L1 to the lower endplate of S1), and thoracic kyphosis (TK: Cobb angle from the upper endplate of T4 to the lower endplate of T12).

2.3. Biomechanical Model

The novel thoracolumbar spine model used in this study was constructed with the commercially available AnyBody Modeling System software (AMS. V.6.0.5.4379) (AnyBody Technology, Alborg, Denmark) [23]. The original model was constructed based on a generic lumbar spine model [26], although the thorax was constructed as one rigid unit. In the novel model, the thorax was divided into 33 parts, including 12 thoracic vertebrae, 10 pairs of articulated ribs, and the sternum. Trunk muscles, including 15 individual muscles and 328 fascicles, were newly defined. The origin and insertion points of the muscles and muscle cross sections were decided based on magnetic resonance imaging (MRI) data [27]. The muscle path were determined using a previously described wrapping method [28] that follows the geometric shape of the figure. The model was previously validated for accuracy of the predicted intervertebral disc pressure using inverse dynamics analysis [23], and was shown to accurately predict intervertebral disc pressure in comparison with previous *in vivo* data [17] [18] [29]. The constructed model is shown in **Figure 1**.

2.4. Input of Vertebral Geometry

The vertebral centroid was determined to be located at the intersection of the diagonal lines of the quadrilateral formed by each vertebral body in lateral standing radiographs. Next, the centroids of vertebral bodies from C7 to S1 were plotted on the x-axis and y-axis directions in the sagittal plane (**Figure 2**). Body weight and height for each patient were input into the model.

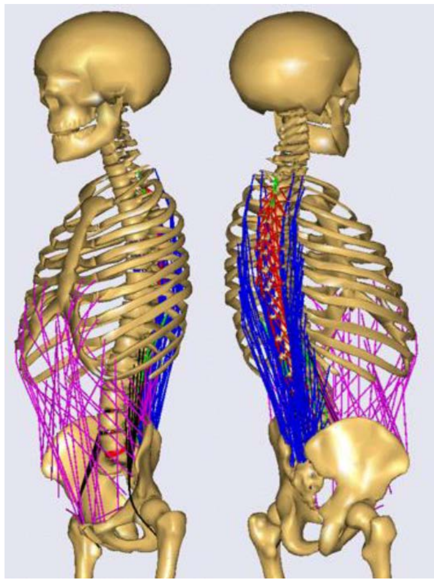

Figure 1. Overview of the novel musculoskeletal spine model. The thorax in the novel model was divided into separated thoracic vertebrae, articulated ribs, and the sternum. The origin and insertion points of the muscle path and muscle cross section were decided based on MRI data. The muscle paths were determined using the wrapping method.

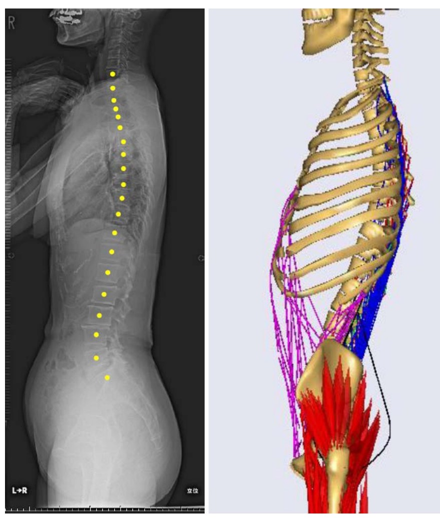

Figure 2. The centroids of vertebral bodies measured from lateral standing radiographs were plotted in the x-axis and y-axis directions in the sagittal plane.

2.5. Conditions for Calculation of Intervertebral Disc Pressure

The patients were asked to stand still with their hands on their clavicles, and the pelvis and sacrum were fixed in the sagittal plane using three-dimensional coordinates. In each subject, inverse dynamics analysis was performed in the model to estimate joint movement and muscle tension, and intervertebral disc compression force was calculated from these values. Intervertebral disc compression force was converted to intervertebral disc pressure by substituting the correction factor of a previously reported equation [30].

2.6. Statistical Analysis

Statistical analyses were performed with SPSS® software version 24 (IBM Corp., Armonk, NY, USA). The correlation coefficient between spinal column alignment, intervertebral disc pressure, and height and weight was analyzed with Pearson's test. Comparisons between the two groups were made using the unpaired test. A P-value of < 0.05 was considered statistically significant.

3. Results

Demographic data for all the patients are presented in **Table 1**. The average age

Table 1. Demographic data of the study subjects (n = 10).

Variables	Values (mean ± SD)
Age (years)	80.0 ± 6.5
Height (cm)	147.0 ± 7.1
Weight (kg)	44.5 ± 9.2
TK (˚)	38.0 ± 9.9
LL (˚)	42.0 ± 13.2
SVA (mm)	38.5 ± 19.1
T1-2 (N)	34.0 ± 20.3
T2-3 (N)	31.9 ± 23.2
T3-4 (N)	46.8 ± 38.0
T4-5 (N)	68.7 ± 42.7
T5-6 (N)	84.8 ± 51.0
T6-7 (N)	104.3 ± 58.2
T7-8 (N)	131.0 ± 58.8
T8-9 (N)	146.5 ± 62.4
T9-10 (N)	186.6 ± 67.0
T10-11 (N)	273.2 ± 84.1
T11-12 (N)	314.1 ± 85.1
T12-L1 (N)	330.0 ± 90.4
L1-2 (N)	353.2 ± 77.0
L2-3 (N)	362.0 ± 89.5
L3-4 (N)	321.9 ± 88.3
L4-5 (N)	422.6 ± 96.3
L5-S (N)	493.2 ± 96.9

TK: thoracic kyphosis (˚), LL: lumbar lordosis (˚), SVA: sagittal vertical axis (mm), The values for the individual spinal levels denote indicate intervertebral disc pressure (N: Newton).

of the patients was 80.0 ± 6.5 years. The spinopelvic parameters indicated moderate deterioration of alignment. One vertebral fracture each was seen in four of the study subjects. The calculated intervertebral disc pressure at each spinal level increased in a caudal direction.

The patients were divided into two groups based on SVA. Patients with an SVA of more than 40 mm were defined as the kyphosis group, and those in whom SVA was less than 40 mm as the normal group [31]. Significant differences in LL were observed between the two groups. Furthermore, the kyphosis group was older and shorter (**Table 2**).

In the kyphosis group, the disc spaces between the upper thoracic vertebrae of T1-2, T2-3, T3-4, T4-5 and T5-6 showed significantly higher intervertebral pressures than the normal group (**Figure 3**).

Correlation coefficients between intervertebral disc pressure and sagittal spinal alignment are presented in **Table 3**. Intervertebral disc pressures significantly positively correlated with SVA from T1-2 to T6-7, and negatively correlated with LL from T3-4 to T5-6. Both findings were mainly found in the upper thoracic vertebrae.

4. Discussion

This study examined intervertebral disc pressure of the entire spine, including the thoracic and lumbar spine, and evaluated the effect of kyphosis on intervertebral disc pressure using a novel musculoskeletal model developed at our institution [23]. One of the characteristics of this new model is that the thoracic cage, which was originally a rigid structure in a previous model [26], was divided into 12 vertebrae, 10 pairs of articulated ribs, and the sternum. In addition, geometric muscle structures were constructed based on our own precise anatomical data obtained using computed tomography and MRI [27]. Initially, the pathways of the muscles were defined as straight lines between the origin and insertion of the muscle. However, since the actual muscles of the trunk often turn around bony structures or soft tissues, the muscle paths were re-constructed using a wrapping method, which reproduces the muscle path, closely reflecting actual physiological curvature around the underlying bony structures and soft tissues [28]. Then, intervertebral disc pressures that were calculated with this model under several

Table 2. Comparison of spinopelvic parameters between the two groups.

	SVA ≥ 40˚ (n = 4)	SVA < 40 ˚ (n = 6)	p value
Age (years)	85.5 ± 2.8	77.0 ± 6.1	0.05
Height (kg)	141.5 ± 3.0	152.0 ± 5.3	0.01
Weight (cm)	38.0 ± 2.2	52.5 ± 7.0	0.01
TK (˚)	38.5 ± 8.1	33.0 ± 10.9	Ns
LL (˚)	31.0 ± 3.6	42.0 ± 11.4	0.02

SVA: sagittal vertical axis (mm), TK: thoracic kyphosis (˚), LL: lumbar lordosis (˚).

Table 3. Pearson's correlation coefficients between intervertebral disc pressure and sagittal parameters.

	SVA	TK	LL
T1-2	0.70*	0.27	−0.44
T2-3	0.69*	0.13	−0.55
T3-4	0.70*	0.08	−0.61*
T4-5	0.70*	−0.60	−0.63*
T5-6	0.69*	−0.27	−0.61*
T6-7	0.64*	−0.06	−0.58
T7-8	0.61	−0.12	−0.49
T8-9	0.59	−0.15	−0.45
T9-10	0.56	−0.17	−0.39
T10-11	0.53	−0.24	−0.38
T11-12	0.52	−0.17	−0.37
T12-L1	0.48	−0.22	−0.31
L1-2	0.29	−0.21	−0.05
L2-3	0.48	−0.23	−0.24
L3-4	0.27	−0.20	0.00
L4-5	0.28	−0.01	−0.03
L5-S	0.34	−0.24	−0.12

SVA: sagittal vertical axis (mm), TK: thoracic kyphosis (˚), LL: lumbar lordosis (˚), (*$p < 0.05$).

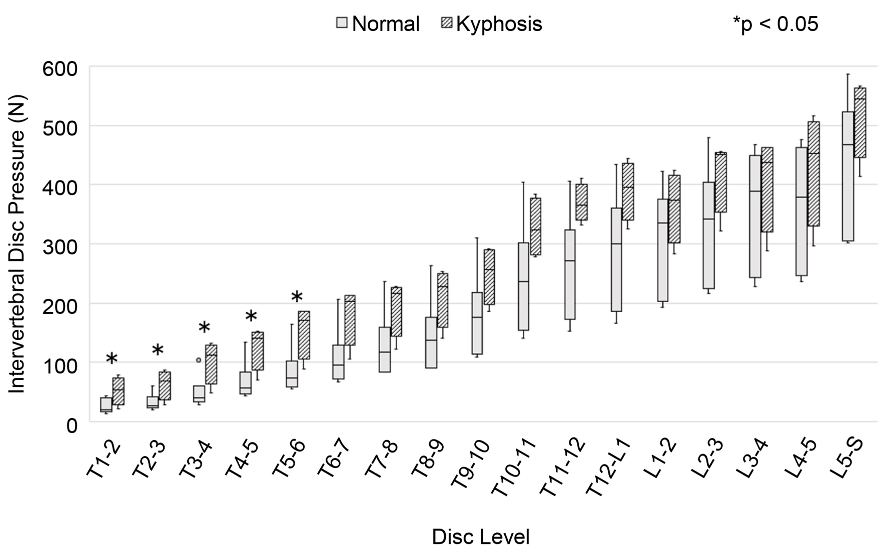

Figure 3. Comparison of intervertebral disc pressure between the groups.

conditions of daily activities were validated and demonstrated to accurately predict the load [23]. Therefore, the results obtained in this study are considered realistic and reliable for estimating intervertebral disc pressure under various conditions of spinal alignment, including kyphosis.

Biomechanical studies evaluating the internal forces in the intervertebral disc are mostly performed for the lumbar spine, with measurements performed *in vivo*, using cadaver studies, or by model simulation. Numerous cadaver studies have been conducted on the load and kinematics of vertebral bodies or intervertebral discs [13] [14] [15] [16] [32]. Brown *et al.* reported the effect of functional spinal unit instability on lumbar disc degeneration using cadavers [13]. Anderson *et al.* investigated intervertebral disc pressures of the thoracic spine and demonstrated the effect of the rib cage and follower load [15]. Liebsch *et al.* also showed the effect of follower load on the motion of the thoracic spine using an entire rib cage specimen, trying to simulate physiological loading conditions [32]. Although these *in vitro* studies using cadavers demonstrated accurate measurement of disc pressure and kinematic data, the cadaveric spine does not completely reflect *in vivo* conditions in terms of the effects of muscle tone or intra-thoracic and abdominal pressure. Besides, *in vitro* cadaver studies are generally performed with isolated thoracic spines with or without rib cages.

Several reports have described measurement of changes in *in vivo* forces due to postural changes by a method involving actual insertion of a pressure sensor in the intervertebral disc [17] [18] [19] [20]. Nachemson *et al.* first reported intervertebral disc pressure in various postures, such as standing, sitting and supine positions, in 1964 [20]. Wilke *et al.* measured the intervertebral disc pressure in daily life in various sitting postures and with lifting of heavy weights [19] [29]. Sato *et al.* reported that the internal disc pressure in degenerated L4-5 discs was significantly reduced compared with that of normal discs [17]. Polga *et al.* measured intervertebral disc pressure in the thoracic vertebrae and showed that changes in the lumbar spine with posture differed from those previously reported, depending on the posture [18]. These *in vivo* studies are considerably important to understand the fundamental mechanisms of the intact spine. However, these experiments are increasingly difficult to reproduce due to their invasiveness for healthy subjects and the associated ethical issues. Therefore, a validated musculoskeletal model comparable to these previous studies is helpful to expand opportunities for investigation of the biomechanical behavior of the complete spine. The model employed in the present study was compared with these previous *in vivo* data [17] [18] [20], which showed that the predicted value with this model showed significant correlation with the literature value [23]. Further, while the results of intervertebral disc pressure in the validation study were calculated for healthy subjects, the present results demonstrated the value in patients with kyphosis for the first time.

As a less invasive strategy for assessment of intervertebral disc dynamics, analyses using a finite element model or musculoskeletal models are being actively developed. A majority of the studies on intervertebral discs were conducted on the lumbar spine [33] [34] [35] [36]. Few studies investigated the whole spine to determine the association between kyphosis and spinal loads in vertebral bodies and intervertebral discs [10] [12] [37]. Okamoto *et al.* constructed a kyphosis model with vertebral fractures, and concluded that presence of a pre-existing vertebral fracture causes an increase in stress on adjacent vertebrae [10]. Briggs *et al.* reported the effects of increased kyphosis on the loading profile of the thoracolumbar spine by constructing a two-dimensional biomechanical model using the radiographic data from patients with kyphosis, and concluded that increases in thoracic kyphosis were associated with significantly higher multi-segmental spinal load and trunk muscle forces in the upright stance [12]. Ignasiak *et al.* investigated the effects of muscle aging and sarcopenia on spinal load using generic AnyBody musculoskeletal multibody modeling, which was similar to our original model [24]. In their study which highlighted the effect of muscle or sarcopenia, forward flexion of the whole spine was simulated to observe changes in spinal load. The conclusion from these previous studies was that kyphosis increases intervertebral load, moving it in a more cranial direction, which was a similar trend to the results of the present study. In addition, these previous musculoskeletal models used geometric data from a single typical human body, while the present study used the data from 10 subjects with different spinal alignments and input the data in the model. Therefore, this study might be the introduction of patient specific biomechanical evaluation before treatment in patients with kyphosis.

There are several limitations to this study. First, the number of subjects was small. Since this study demonstrated preliminary results, further research would be expected based on the findings from this study. Second, the data were obtained only in the standing position without any movement. However, the results can serve as the basis for future study of whole thoracic and lumbar spine under dynamic conditions in patients with kyphosis. Third, in this analysis, coronal deformity and pelvic alignment were not considered. Sagittal spinopelvic alignment is a significant factor when considering the relationship between the health-related quality of life and spinal alignment in adult patients with spinal deformity [31] [38]. Further, pelvic tilt and lower limb compensation are very important in spinal alignment studies. However, this study focused on establishing a simple method to evaluate the effect of progression of kyphosis with the position of the pelvis fixed. Since this model has a three-dimensional structure, it might be possible to evaluate pelvic and coronal alignment and the connection with the lower limbs in future studies.

5. Conclusion

Intervertebral disc pressure in the thoracic and lumbar spines of patients with spinal deformities was evaluated using a novel three-dimensional thoracolumbar musculoskeletal model. Using this novel model with separated thoracic spine and modified muscle path reflecting actual physiological curvature, disc pressure closer to the realistic condition was obtained. Intervertebral disc pressure in the upper thoracic spine in the kyphosis group was significantly higher than that in the normal group. Moreover, intervertebral disc pressure correlated negatively with LL in the upper thoracic spine.

Ethical Considerations

The ethics committee of our institute approved the study protocol. All subjects provided written informed consent before participating in this study.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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