Relationship between Upper Body Posture Angle and Vertebral Body Posture Angle in Lateral Flexion and Rotation Posture

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Abstract Lumbar loading causes increased intervertebral pressure and is an important factor in low back pain. However, it is difficult to quantitatively judge the actions that affect lumbar load and the magnitude of lumbar load increase. Low back pain occurs not only in the workplace but also during activities of daily living. Therefore, it is necessary to investigate the factors inducing low back pain by measuring movements in various planes and determining the magnitude of the lumbar load. Accordingly, the lumbar spine should be examined during various movements. Several studies have examined vertebral bodies in the anteflexion posture. However, the relationship between body flexion angle and vertebral body angle during lateral flexion and rotation remains unknown. In this study, we proposed an estimation method for changes in vertebral body angle during lateral flexion and rotation in the lumbosacral region using a wearable sensor system we previously developed. The accuracy of the proposed estimation method was evaluated and demonstrated using X-ray images.

Keywords: low back pain, lumbosacral alignment, lumbar load, X-ray image.

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1. Introduction
The lifetime prevalence of low back pain in Japan is said to be 80%, and the incidence of low back pain in the Japanese population is over 10%. Therefore, the guidelines for preventing low back pain in Japan were revised in 2013 [1]. In these guidelines, the lifting load limit for a single person is defined, and load on the lower back due to lifting is recognized as a problem. Low back pain is a global problem that is not limited to Japan. Guidelines for back pain are also published in the United States [2] and the European Union [3]. However, it is still difficult to identify the factors involved in low back pain, and 80% of low back pain is non-specific low back pain. There are many causes of low back pain, and there are various approaches to clarifying the cause. However, many studies of lumbar load have focused on increased intradiscal pressure [4–6].

The shape of the intervertebral disc between vertebral bodies is known to change during anteflexion, thereby changing the shape of the entire spinal column [7]. The relationship between lumbar spine alignment and the compression force on the intervertebral disc depends on the geometrical characteristics such as position and posture (i.e., alignment), of each vertebra in the lumbar spine and sacrum. Nachemson found that pressure on the lumbar spine changes with postural changes [8].

Many studies have noninvasively measured information inside the body. For example, motion capture has been used to estimate intervertebral disc load by capturing changes between vertebral bodies because of the close distance between the vertebrae and the body surface [9]. Motion capture has also been used to construct individual hand models [10]. Furthermore, design support software has been used for reducing the load on the lumbar spine and calculating the load by video recording postural movements [11]. Similar to these studies, video recording has been combined with a three-dimensional (3D) motion analysis device such as motion capture to estimate measurements inside the body. However, these methods are restricted in terms of measurement space, so they are not easy to perform in practice. We previously
investigated internal information by examining changes in the shape of the skin during anterior-posterior bending using a wearable sensor system that measures lumbar spine alignment to estimate lumbar load [12, 13]. To use this system regardless of the physique of the person being measured, we analyzed anatomical changes in the shape of the epidermis and the size of the lumbosacral region according to physique and posture. In the lumbar region, in addition to ante/flexion and retro/flexion, lateral flexion and rotation can be performed. Therefore, it is necessary to construct a system to measure lumbar load considering lumbar spine alignment during lateral flexion and rotation. Although there are few studies of lumbar posture during lateral/flexion and rotation, analyses of vertebral posture in healthy adults have shown a range of joint movements during exercise [14]. However, the ratio of the lumbar postural angle to the upper body postural angle during lateral flexion and rotation has not been presented in detail. In addition, it has been reported that rotational motion is a factor for chronic transformation of low back pain [15], with an increased risk of 1.51 to 2.28 [16]. Therefore, it is necessary to measure the lumbar spine posture of lateral flexion and rotation during movement.

In this study, we aimed to develop a non-invasive and accurate method to measure lumbosacral alignment in lateral flexion and rotation. The relationship between each vertebral body and the epidermis changes depending on body size, type, and posture. We analyzed X-ray images and proposed a method for estimating changes in vertebral body angles during lateral flexion and rotation. The accuracy of the proposed method was evaluated using X-ray imaging.

2. Wearable sensor system for lumbosacral alignment estimation

The spine supports the trunk of the human body and comprises 24 articulating vertebrae and 9 fused vertebrae that together form the cervical spine, thoracic (T) spine, lumbar (L) spine, sacrum (S), and coccyx. A method has previously been developed for estimating internal skeletal information from external information, specifically, a noninvasive method for estimating the hip joint center position by using X-ray images as true values [18]. In this study, we applied a similar method to measure lumbar spine alignment by observing the shape of the skin in the lumbar region. Although a small layer of fat is present between the spinous processes of the spinal column and the dorsal epidermis, changes in the spinous processes can still be observed from the epidermis. We also previously found a relationship between the epidermis and vertebral bodies from X-ray images during muscular pretensioning [13, 19]. Thus, we estimated the lumbar spine alignment assuming that the shape of the epidermis (skin line) is equivalent to the smoothed curve connecting the vertebral centroids of the lumbar spine (spine line).

Figure 1 shows the wearable sensor system for estimating lumbosacral alignment. The system comprising 4 sets of curvature sensors and 2 inertial measurement units was developed based on X-ray image analysis. Details of the wearable sensor system have been presented elsewhere [19, 20]. The spine line is a curve connecting point b0 to point b6. The norm for each intervertebral distance is retained during the lumbosacral alignment estimation.

3D motion of the spine is commonly known, and the range of joint motion has been investigated [14]. However, the method to obtain the postural angle of each vertebral body from upper body postural angle measurements has not been generalized. The lumbosacral spine alignment estimation employs a stacked algorithm, which requires knowledge of each vertebral posture. Therefore, it is necessary to calculate the lateral flexion and rotation angles of each vertebral posture using the upper body IMU sensor, which can calculate the upper body posture angles. The next section describes the method for estimating each vertebral body postural angle in lateral flexion and rotational motion from the upper body postural angle that can be measured from an inertial measurement unit attached to a wearable sensor system.

3. Determining changes in lumbosacral alignment by lateral flexion and rotation

We estimated lumbosacral alignment by focusing on motion in the sagittal plane. The lumbar spine is able to perform lateral flexion and rotation in addition to ante/flexion and retro/flexion. In everyday life, the human body flexes and rotates laterally, although to a lesser extent than ante/flexion and retro/flexion. Therefore, it is neces-
necessary to estimate lumbar spine alignment for movements other than anteflexion and retroflexion. However, the relationship between the posture angle of the lumbar spine during lateral flexion and rotation and the posture angle of the upper body is unknown. This relationship can be clarified by X-ray image analysis. For this reason, data are acquired using an experimental environment that allows simultaneous measurement of 3D motion and X-ray images, as shown in Fig. 2. In this paper, we consider that the upper body posture angle can be obtained from upper body inertial measurement unit data. In addition, we assume that the T12 vertebral body posture angle can be calculated from the upper body posture angle and that the sacrum posture angle and the S1 sacral posture angle can also be calculated.

3.1 Determining vertebral body angle during lateral flexion and rotation on X-ray images

Lumbosacral vertebral alignment during lateral flexion and rotation was measured using X-ray imaging and a 3D measurement system (MAC3D motion capture system). X-ray images were taken from the posteroanterior and lateral views in the standing posture and from the posteroanterior view in the lateral flexion and rotation postures. The X-ray images of one subject are shown in Fig. 3. X-ray imaging was performed under the guidance of a physician and was approved by the Ethics Review Committee of Hokkaido University.

The center of gravity positions including $b_i$ of the T12 vertebral body, L1 to L5 vertebral bodies, and S1 sacrum were determined from the X-ray images. We analyzed the relationship between each posture and each vertebral center of gravity position from the extracted data. The center of gravity position of the S1 sacrum was $b_0$, and that for the T12 vertebral body was $b_6$. An example of determining the vertebral center of gravity is

![Fig. 2 Experimental environment for simultaneous 3D measurement and X-ray imaging.](image1)

![Fig. 3 X-ray images of one subject.](image2)
shown in Fig. 4. As shown in Fig. 4, the point at the intersection of the epidermis with the parallel line from the vertebral body weight center $b_i$ was defined as $S_i$ and extracted from the X-ray images. $S_i$ is a point on the surface. The upper body posture angle on the epidermis was measured by a 3D measurement system. Markers were placed on the epidermis of the T12 and S1 projections. The posture angle was calculated using Cortex (MotionAnalysis).

The vertebral body angles during lateral flexion $\theta_i$ and those during lateral rotation $\phi_i$ were determined from the vertebral center of gravity position. Each vertebral body angle during lateral flexion $\theta_i$ was extracted and calculated from the position change in the vertebral body center of gravity position between the standing posture $b_i'$ and the lateral flexion posture $b_i$. It was assumed that the pelvis and sacrum do not change due to postural changes. Therefore, $\theta_0$ was 0 deg. Each vertebral body lateral flexion angle $\theta_i$ was calculated using eq. (1), with the S1 sacral center of gravity position $b_0$ of each posture as the origin.

$$
\theta_i = \cos^{-1}\left(\frac{(b_i - b_0) \cdot (b_i' - b_0')}{|b_i - b_0||b_i' - b_0'|}\right)
$$

(1)

Each vertebral body angle during rotation $\phi_i$ was calculated from changes in the vertebral body center of gravity position.

The distance between the vertebral center of gravity and the epidermis $d_i$ was obtained for each vertebral body using measurements from the lateral X-ray image in the standing posture:

$$
d_i = \sqrt{(b_i - s_i)^2 + (b_i - s_i')^2}
$$

(2)

Then, $\phi_i$ was calculated using $d_i$ and each vertebral body center of gravity position $b_i$ measured on postero-anterior X-ray images, assuming that $\phi_i$ was small in eq. (3):

$$
\phi_i = \sin\left[\frac{\sqrt{((b_i - b_i')^2 + (b_i - b_i')^2)}}{d_i}\right]
\approx \frac{\sqrt{(b_i - b_i')^2 + (b_i - b_i')^2}}{d_i}
$$

(3)

We assumed that there was no correlation between lateral flexion and rotation.

### 3.2 Estimation method for vertebral body angle during lateral flexion and rotation

The X-ray images referred to in the previous section were obtained for 15 men and 15 women (mean age 44.8 years, standard deviation [SD] 13.6). Mean height was 165.3 cm (SD 8.6) and mean weight was 64.7 kg (SD 16.9). We excluded 5 subjects who showed a tendency toward scoliosis, and hence analyzed the distribution of the posture angle of each vertebral body from the data of the remaining 25 subjects. The relationship between the upper body posture angle $\theta_T$ and each vertebral body angle during lateral flexion is shown in Fig. 5.

The results of linear approximation are also shown in Fig. 5. The parameters and correlation coefficients of the linear approximation equation are shown in Table 1. The correlation coefficients increased from the lower to upper lumbar spine. Slope $\alpha_{\theta_0}$ was also observed to increase from the lower to upper lumbar spine. A low correlation coefficient was found for the L5 vertebra angle during lateral flexion $\theta_1$ and no change in angle was observed even with changes of body posture angle.

The relationship between the upper body posture angle $\theta_T$ and each vertebral body angle during rotation $\phi_i$ is shown in Fig. 6. The results of linear approximation are also shown in this figure. The parameters and correlation coefficients of the linear approximation equation are shown in Table 2. The correlation coefficient tended to increase from the lower to upper lumbar spine. Slope $\alpha_{\phi_0}$ was also observed to increase from the lower to upper lumbar spine. The rotation angle was small, hence we judged that the low correlation in the lower lumbar spine did not pose a problem for use in this research.

From these results, it was possible to estimate the vertebral body angle during lateral flexion and rotation from the body posture angle. Therefore, assuming that lateral flexion and rotation were independent events, the estimation formula was defined accordingly:

$$
\begin{bmatrix}
\theta_T \\
\phi_1 \\
\end{bmatrix} =
\begin{bmatrix}
\alpha_{\theta_0} & 0 \\
0 & \alpha_{\phi_0}
\end{bmatrix}
\begin{bmatrix}
\theta_T \\
\phi_T
\end{bmatrix}
$$

(4)

The upper body posture angle ($\theta_T$, $\phi_T$) shown here can be measured from a wearable sensor system, and...
each lumbar posture can be estimated using eq. (5).

\[ q(t) = Aqq(t - 1) + (1 - A)q_a \]  

(5)

$q_g$ is the quaternion obtained from the gyro sensor and $q_a$ is the quaternion obtained from the accelerometer. $A$ is the coefficient of the interpolation filter, which is usually set to about 0.9. The calculation of each quaternion is based on a previous report [20].

4. **Evaluating vertebral body angle during lateral flexion and rotation**

Vertebral body angles were estimated from the body posture angles using the linear and quadratic curve approximation equations. To evaluate the results obtained, we compared them with the true values using the following formula:

- \[ E_{\theta} = \frac{1}{N} \sum_{j=1}^{N} \left| \frac{\theta_j - \hat{\theta}_j}{\theta_T} \right| \]  

(6)

- \[ E_{\phi} = \frac{1}{N} \sum_{j=1}^{N} \left| \frac{\phi_j - \hat{\phi}_j}{\phi_T} \right| \]  

(7)

To evaluate the estimated results, the body position angles were compared using equally divided values of the upper body posture angles. Multiple divided vertebral posture angles from the upper body posture angle were used for comparison because equal division has the lowest calculation cost. This method is referred to as an even division method. The number of subjects ($N$) was 25 and the average error value across all subjects was evaluated.

5. **Results and Discussion**

The evaluation results are shown in Figs. 7 and 8. For the lateral flexion angle of each lumbosacral vertebral body, we were able to decrease the estimation error by an average of 44.0% compared with the even division method. The lateral flexion angle of each vertebral body from T12 to L4 could be determined according to the upper body posture angle using the proposed method. The
one-sided t-test showed significant differences ($p < 0.01$) from L1 to L4. Thus, the estimation of the vertebral body angle in the upper body during lateral flexion was deemed sufficiently effective. For the L5 vertebral body angle $\theta_1$, there was no difference from the average value. This is because, as described previously, this lower vertebral body is considered to move only marginally in lateral flexion. For rotation angle, the estimation error was reduced by 58.0% on average compared with the even division method. One-sided t-test showed significant differences ($p < 0.01$) from L1 to L5, indicating that estimation in the lumbar spine was sufficiently effective.

From these results, it can be seen that the estimation accuracy is low in the case of $\phi_1$, $\theta_1$. Previous studies [14] have shown that side flexion and rotational movements

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**Table 2** Parameters for $\phi_i$ of linear approximation equation and correlating value.

| $\phi_i$ | $\alpha_{\phi_i}$ | $R$   |
|---------|----------------|------|
| $\phi_1$   | 0.592   | 0.0  |
| $\phi_2$   | 0.624   | 0.366|
| $\phi_3$   | 0.671   | 0.541|
| $\phi_4$   | 0.764   | 0.789|
| $\phi_5$   | 0.862   | 0.936|

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![Fig. 6](image_url) Relationship between $\phi_T$ and $\phi_i$.

![Fig. 7](image_url) Estimation results of the average error $E_{\theta_i}$.

![Fig. 8](image_url) Estimation results of the average error $E_{\phi_i}$. 

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result in little to no rotation angle between the lumbar vertebrae, hence the angle to be estimated is small. Another reason was that although the subjects were instructed to perform postural changes without moving the pelvis during the experiment, the reference pelvic upper surface angle may have changed. Future analyses will have to take the pelvic upper surface into account.

It can be seen from the coefficients (α<sub>0</sub> and α<sub>θ</sub>) that the vertebrae in the lumbar region do not rotate evenly during lateral flexion and rotation. Therefore, a method for externally estimating the posture angle of the lumbar spine is necessary. In the future, individual differences in vertebral body angles during lateral flexion and rotation should be considered. Thus, it is necessary to analyze correlation with parameters such as body surface area when performing posture angle correction to account for individual differences. In addition, lumbosacral spine alignment should be estimated by examining actual movement as measured by the sensor system compared with X-ray images. This estimation would require corrections only for elements affected by individual differences. We previously proposed a method for estimating lumbar load during motion with an unknown external load by measuring back muscle strength with a muscle stiffness sensor [21]. It is also necessary to analyze and evaluate lumbar load in 3D motion. In addition, by considering human anatomy, we hope to improve the accuracy of our proposed method and aim to develop an easy-to-use device that can be applied in the real world.

6. Conclusion

We aimed to estimate alignment of the lumbosacral region by analyzing vertebral body angles and body posture angles in 3D using a wearable sensor system during lateral flexion and rotation. The lumbosacral vertebral alignment at the time of lateral flexion and rotation posture was measured and analyzed using X-ray imaging and three-dimensional measuring system. We analyzed the distribution of the posture angle of each vertebral body from the data of 25 persons (5 were excluded because they showed a tendency toward scoliosis). From the results of our analysis, we proposed a method to estimate the angle of each lumbar vertebra from the angle of the upper body. The accuracy of the proposed estimation method was evaluated and shown to be effective by comparison with X-ray images.

In the further work, we will develop a 3D lumbosacral alignment estimation, and will evaluate the method using a 3D model.

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