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CONSTRUCTION AND VALIDATION OF A NOVEL THREE-DIMENSIONAL TRUNK MUSCULOSKELETAL MODEL

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Abstract
Studies of internal biological forces during motion using musculoskeletal models have mainly focused on the extremities. Few reports have examined internal biological forces in spine motion using a trunk model. The aim of this study was to analyze detailed three-dimensional motion of healthy adults using a novel trunk model, and estimate internal biological forces in a standing position. We constructed a three-dimensional trunk musculoskeletal model. Dimensions of the vertebrae, other segments such as upper or lower extremities and muscles were based on a 31-year-old healthy man. Joint angle data for trunk and extremities kinematics were obtained from a standing position using a three-dimensional motion analysis system. To analyze motion of the spine in detail, we applied markers to three different places in each vertebral body from C7 to L5. Flexion moments accorded with spinal curvature at the apex of curvature of the thoracic spine at T8-9. Mean intradiscal pressure calculated from muscle strength was 802.9 N. The thoracolumbar three-dimensional trunk musculoskeletal model generated in the present study could potentially be used to analyze spinal moment and trunk muscle strength during static and dynamic motions.

Key words : Three-dimensional trunk musculoskeletal model, spinal moment, intradiscal pressure

Introduction

In recent years, advances in biomedical engineering have enabled motion analysis of activities such as standing and walking[1-3)]. Internal biological forces, such as muscle force and joint loading, are almost impossible to measure actually. Thus, inverse dynamics techniques using musculoskeletal models have generally been used to calculate internal biological forces[4-6)].

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Studies of internal biological forces during motion using musculoskeletal models have mainly focused on the extremities[7-9)]. Few reports have described internal biological force in spine motion using trunk models. This is because musculoskeletal models of the trunk are difficult to study *in vivo* compared to the extremities of the human body because of the large number of facet joints, muscles, ligaments, and disks[10)]. Most studies have provided descriptions of muscle structures without precise data on factors, such as fiber length, muscle length, cross-sectional areas, moment arms and forces[11)], in thoracic spine. As a result, a standard trunk musculoskeletal model has not yet been established. Some lumbar models are available to analyze internal forces[4,12,13)], but few reports have described thoracolumbar models, because the thoracic structure is complex. Briggs *et al.*[14] reported a thoracolumbar musculoskeletal model using data from two-dimensional radiography, resulting in a relatively simple model.

In the present study, we constructed a novel three-dimensional trunk musculoskeletal model that included thoracolumbar facet joints using data from computed tomography (CT) and magnetic resonance imaging (MRI). The validation of this model used the calculated intradiscal pressure for the L4/5 disk according to previous reports[13]. Characteristics of the model are as follows. First, the thoracolumbar structure was modeled in detail (i.e., skeleton, muscle paths and muscle cross-sectional areas) from CT and MRI data. Second, to calculate internal biological forces more accurately than previous models, new factors were included in this model, such as intra-abdominal pressure and physiological trunk range of motion. Third, this trunk musculoskeletal model is able to analyze dynamic motion. The aim of this study was to analyze detailed three-dimensional motion in healthy adults using this model, and to estimate internal biological forces, including spinal moment and muscle strength in a standing position.

Materials and Methods

Construction of the three-dimensional trunk musculoskeletal model

1) Skeletal model

The trunk skeletal model was designed with the skull, upper extremities including the scapula and clavicle, seven cervical vertebrae (C1-C7), twelve thoracic vertebrae (T1-T12), five lumbar vertebrae (L1-L5), pelvis, lower extremities and ribs. We focused on the trunk skeletal model in the whole body skeletal models. According to Ishikawa's method[16], the anatomy of the body was determined from actual CT images from one healthy volunteer. The dimensions of the vertebrae and other segments were based on data from a 31-year-old healthy man (height, 1.74 m; weight, 78.5 kg), after obtaining informed consent. We extracted the skeletal area from CT data, and made a three-dimensional form of a skeleton using Mimics software (Materialise, Leuven, Belgium). We then input the three-dimensional skeletal

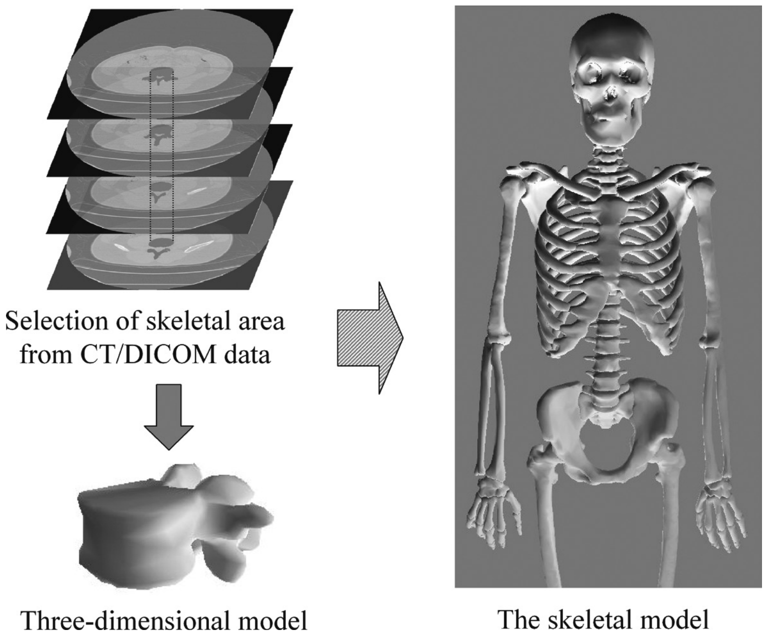
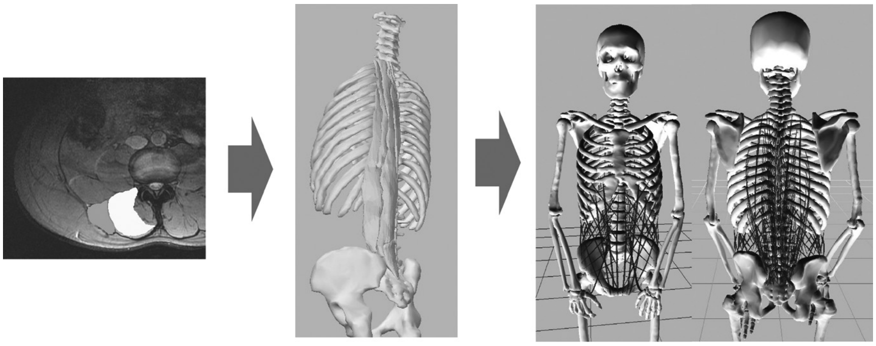


Fig. 1. The skeletal model was designed with vertebrae and other segments. The skeletal area was extracted from CT/DICOM data. The three-dimensional skeletal model (i.e., vertebrae, rib, pelvis, etc.) was reconstructed from the extracted area.



A) MRI data B) Reconstruction of muscles C) Musculoskeletal model

Fig. 2. The musculoskeletal model. A) Muscle area was extracted from MRI data. B) The muscle model was reconstructed from MRI data using Mimics software. The reconstruction methods allowed analysis of muscle cross-sectional area and muscle paths. C) The musculoskeletal model for the whole body was reconstructed using EICAS software.

form into the Equivalent Impedance Characteristics Analysis System (EICAS) (Toyota Central R&D Labs, Nagoya, Japan) and configured the skeletal model (Fig. 1).

2) Muscles

Muscles were modeled using the muscle path as close to the real muscle as possible. No reports have shown any cross-sectional areas or accurate motions of all the muscles related to the spine, including the deep muscles. Therefore, according to Blemker's report[17], the structure of these muscles was constructed from MRI data of the same subject (a 31-year-old man) from whom the skeletal model was made. Attachment sites of muscle were made according to previous reports[4,11,18-20]. We extracted the cross-sectional area and muscle path based on MRI data using Mimics software, then input the data into EICAS to make the three-dimensional spinal musculoskeletal model (Fig. 2). We designed muscle components to have a contractile element. Our model included abdominal muscles (rectus abdominal muscles, internal oblique muscles, external oblique muscles, and quadratus lumborum muscles), short dorsal muscles (interspinales muscles, intertransversarii muscles), transversospinales muscles (semispinalis thoracis muscles, multifidus muscles, and rotator muscles), erector spinae muscles (iliocostalis lumborum/thoracis muscles, longissimus thoracis muscles and spinalis muscles) and psoas major muscles (Table 1). Reproducing the transverse abdominal muscle into the musculoskeletal model was impossible, due to no effects agonist the gravity, so we reproduced the trunk muscle group except for the transverse abdominal muscle. The human trunk consists of numerous muscles with a complex morphology. Thus, each anatomical muscle has to be divided into several functional fascicles in order to mimic the diverse mechanical functions of the

Table 1. Modeled muscles

Erector spinae muscles	
	Iliocostalis thoracis muscles
	Iliocostalis lumborum muscles
	Longissimus thoracis muscles
	Spinalis muscles
Transversospinales muscles	
	Semispinalis thoracis muscles
	Multifidus muscles
	Rotator muscles
Short dorsal muscles	
	Interspinales muscles
	Intertransversarii muscles
Abdominal muscles	
	Rectus abdominal muscles
	Internal oblique muscles
	External oblique muscles
	Quadratus lumborum muscles
Psoas major muscles	

real muscle[11,13]. In particular, many muscles have multiple attachments, such as the multifidus muscle, so we elaborated the distributions of muscle paths according to component muscle fibers and reproduced these distributions. For example, the multifidus muscle was divided into 19 fascicles[13]. In total, all trunk muscles were classified into 328 fascicles. To successfully reproduce muscle paths, we used the wrapping method[8,21] included in the spatial muscle path. The wrapping method is used to connect the starting point of the muscle with the end, in the shortest possible route along a geometric pattern. In this model, we placed ellipsoidal bodies based on three-dimensional pattern data obtained from MRI. This model was able to change the physical parameters of bones and muscles.

3) Intra-abdominal pressure

Intra-abdominal pressure is generated by muscle tension in contraction of the abdominal wall, diaphragm and pelvic floor muscles, and plays a functional role with the spine. Morris reported[22] that temporary increases in intra-abdominal pressure provide anterior protection for the spine[23,24], and decrease pressing strength in a vertical-axis direction on the intervertebral disks[25]. We set the intra-abdominal pressure value for this model at 30 mmHg[26,27], as the mean value for a normal subject. However, intra-abdominal pressure cannot be reproduced by the musculoskeletal model. We therefore set it as an external force that was then applied to the spine. According to the methods described by Mens[27], external force was set as the area calculated from intra-abdominal pressure and MRI cross-sectional imaging.

4) Spinal mobility

Spinal mobility is determined by the influences of bone shape and soft tissues (e.g., ligaments). For this model, we took X-ray images from the sagittal plane in positions of maximum flexion and maximum extension of the trunk, and measured spinal mobility at each vertebrae. This model was made to cover the physiological mobility by the resistance. In this model, the physiological spinal mobility was able to be easily changed for each case.

Validation of the model

1) Kinematic Data Collection

Kinematic data were acquired from ten able-bodied men (mean age, 22.7 years ; mean weight, 65.5 kg ; mean height, 1.73 m) using a three-dimensional motion analysis system (VICON MX system ; VICON Oxford Metrics, Oxford, UK) with 8 cameras (MX-T40 ; VICON Motion Systems) operating at 100 Hz. Data were obtained while the subject remained motionless in a standing position. Three-dimensional orientation of body segments was obtained by tracking marker trajectories. In particular, vertebrae of the spine were measured in detail. We used 6-mm diameter markers, applied to four sites on the head, eight sites on the upper extremities (acromion, lateral epicondyle of humerus, radial styloid process, second metacarpophalangeal joint), four sites on the pelvis (anterior superior iliac spine and posterior superior iliac spine, bilaterally) and 14 sites on the lower extremities (great trochanter, femoral shaft, knee joint, tibial shaft, lateral malleolus, calcaneus and head of the second metatarsal). To analyze motions of the spine in detail, we applied markers to three different sites on each vertebral body from C7 to L5, for a total of 54 markers on the 18 vertebral bodies. We applied a total of 84 reflective markers to the body surface.

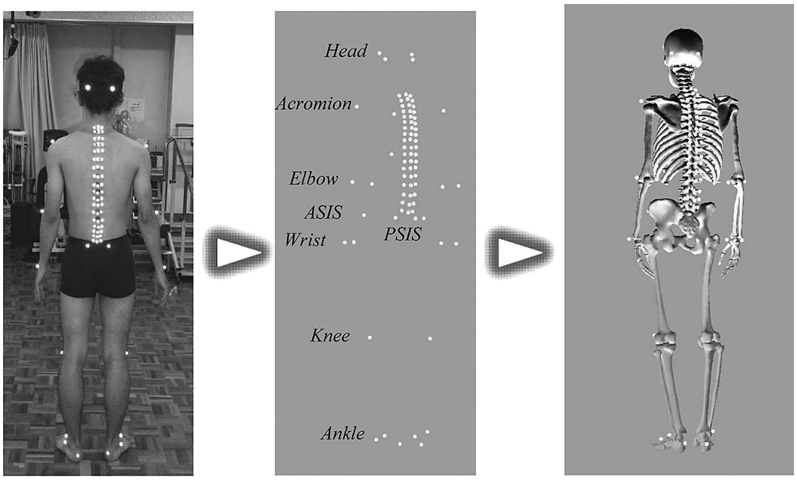
2) Data analysis

The three-dimensional trunk musculoskeletal model conformed to the detailed coordinate position data obtained from markers (Fig. 3), and we also calculated joint torque from the musculoskeletal model. Furthermore, we calculated L4/5 intradiscal pressure. Intradiscal pressure was based on muscular strength data. A comparison has been made with *in vivo* intradiscal pressure musurements of the L4/5 disk as reported by Wilke *et al*[15]. Muscle strength was calculated from flexion moments reflecting muscle cross-sectional area.

Results

Flexion Moments

Flexion moments at each spinal segment are shown in a static standing position (Fig. 4). Mean normalized flexion moment (N･m/BW･Ht ; where BW is body



A) Reflective tracking markers

B) Position data

C) Musculoskeletal model

Fig. 3. The musculoskeletal model using positions from reflective markers. A) The reflective tracking markers were applied to all thoracic and lumbar vertebrae. Spinal alignment was measured in detail. B) Position data from the VICON analysis system. White points indicate positions of reflective markers. C) The three-dimensional trunk musculoskeletal model conformed to coordinate position data.

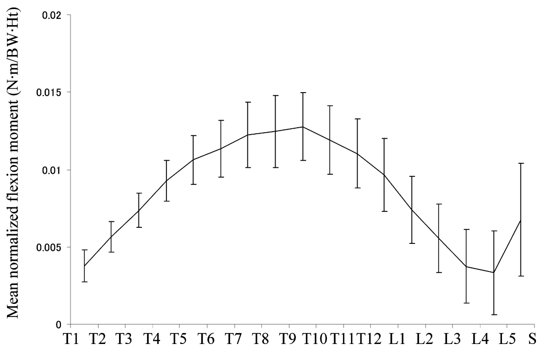


Fig. 4. Mean normalized flexion moment. Mean normalized flexion moment was similar to the physiological curvature. (BW, body weight ; Ht, height.)

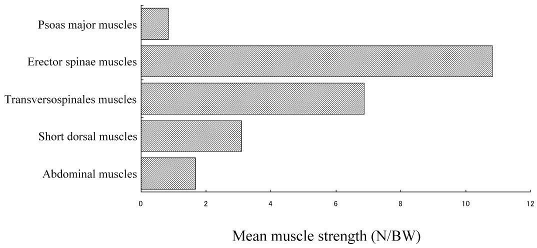


Fig. 5. Mean muscle strength. Mean muscle strength showed high activity at the erector spinae muscles.

weight (kg) and Ht is height (m)) was 0.0037 at T1, 0.0056 at T2, 0.0073 at T3, 0.0092 at T4, 0.0106 at T5, 0.0113 at T6, 0.0122 at T7, 0.0124 at T8, 0.0127 at T9, 0.0118 at T10, 0.0110 at T11, 0.0096 at T12, 0.0073 at L1, 0.0055 at L2, 0.0037 at L3, 0.0033 at L4 and 0.0067 at L5. Flexion moments showed parabolic shapes with T8-9 at the peak, and reversed at L3-4. This curve accorded with spinal curvature at the apex of curvature of the thoracic spine at T8-9.

L4/5 Intradiscal Pressure

Mean muscle strength was shown in a static standing position (Fig. 5). Erector spinae muscles showed high values for muscle strength. Mean muscle strength (N/BW) was 0.85 for psoas major muscles, 10.82 for erector spinae muscles, 6.87 for short dorsal muscles, and 1.68 for abdominal muscles. **Mean intradiscal pressure calculated from muscle strength was** 802.9 N (range, 771.0-848.7 N).

Discussion

In this study, we produced a detailed thoracolumbar three-dimensional trunk musculoskeletal model. Furthermore, this novel musculoskeletal model includes intra-abdominal pressure and physiological spinal mobility on the bone shape and soft tissues effects.

Many previous reports have described two-dimensional trunk musculoskeletal models. For instance, Briggs *et al.*[14,28] made a trunk musculoskeletal model based on radiographs in the sagittal plane, and reported thoracic spinal moments in elderly kyphosis patients. Conversely, very few reports have described dynamic analysis in three-dimensional musculoskeletal models. For example, The AnyBody Modeling System (AnyBody Technology A/S, Aalborg, Denmark)[13] could analyze dynamic motions with the three-dimensional musculoskeletal model including the trunk, but analysis of the thoracic spinal segment is impossible, because of the substitution of rigid bodies for the part of the thoracic vertebrae. Our three-dimensional trunk musculoskeletal model enabled analysis of dynamic motion at the thoracic spinal segment, which have previously been impossible to analyze. Dynamic motion analysis can be performed using this model.

Spinal Flexion Moment

Few reports have described trunk flexion moment in normal subjects. This study calculated spine flexion moment in normal subjects *in vivo* using a three-dimensional musculoskeletal model for the first time. As a result, flexion moments showed a peak value (0.127 N・m/BW・Ht) around the T8 level, as the apex of curvature of the thoracic spine. Furthermore, the torque curve conformed to the physiological curvature. It is considered that the torque curve was related with the distance from center of gravity line on sagittal plane. As previously noted, Briggs *et al.*[14] reported that peak flexion moment in kyphotic patients showed a peak (0.015-0.017 N・m/BW・Ht) around the T8 level as the apex of curvature of the thoracic spine. As peak flexion moment increases with high kyphosis[29,30], the finding of lower peak values in our normal subjects appears valid. Adam *et al.*[31] described torque curves showing a similar pattern with physiological curvature in a study of scoliosis. Our results showed a similar pattern between torque curves and physiological curvature, supporting the validity of our trunk musculoskeletal model.

L4/5 Intradiscal Pressure

This is the first report to calculate muscle strength in a standing position from a musculoskeletal model. The erector spinae muscles showed high levels of activity. This finding is not surprising, as these muscles act against the flexion moment. Intradiscal pressure was calculated using muscle strength in a standing position, and a comparison was made between *in vivo* intradiscal pressure measurements for the L4/5 disk as reported by Wilke *et al.*[15]. They measured pressures in the range of 774-900 N (mean pressure, 864 N (0.48 MPa)) in the L4/5 disk with the subject (weight, 70 kg ; height, 1.74 m) standing upright. Intradiscal pressure in our model was in the range of 771.0-848.7 N (mean, 802.9 N). The calculated value in this study approximated measured values. The present model thus seems valid, showing comparable results to the actual human body.

Perspectives

The model created in this study allowed analysis of dynamic motions such as standing, squatting, and walking. In addition, this model may be able to analyze trunk disorders that have not previously been analyzable. Our model is able to detect muscle weakness in the trunk, and thus direct physical therapy interventions to improve performance. In future studies, we hope to improve the accuracy and confirm the clinical utility of this model.

Conclusions

This study produced a thoracolumbar three-dimensional trunk musculoskeletal model. This model is able to analyze spinal moments and trunk muscle strength during static and dynamic motions. The present study confirms that the moment curve can be generalized in the various postures. The model has been validated, and was able to analyze three-dimensional motion (i.e., combinational factors of rotation and flexion). As a result, this model is expected to have clinical applications.

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