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Original Article

Motion analysis of anterior inclination of the trunk while standing using a new three-dimensional musculoskeletal model combining the trunk and lower limbs

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ABSTRACT
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Purpose: We developed a three-dimensional musculoskeletal model and used this model for motion analysis of the change in posture from standing upright to maximum anterior inclination of the trunk.
Methods: A new three-dimensional musculoskeletal model combining the trunk and lower limbs was constructed from a healthy volunteer. For motion analysis using this model, five healthy volunteers participated in this study. A three-dimensional motion analysis system was used to analyze the flexion phase from standing upright to maximum anterior inclination of the trunk, and the return phase from maximum anterior inclination of the trunk to standing upright. The muscle activities of the erector spinae, the rectus abdominis and the gluteus maximus were calculated from the motion analysis. The ratio of muscle activity at standing upright phase to the peak muscle activity was analyzed statistically for each muscle.
Result: The mean ratios of muscle activity at standing upright phase to peak muscle activity were 1: 3.94 ± 0.65 (mean ± SD) for the erector spinae, 1:1.75 ± 0.22 for the erector spinae, and 1: 4.07 ± 0.68 for the gluteus maximus. The muscle activity at standing upright phase and the peak muscle activity were significantly different in all muscles (paired *t*-test ; $p < 0.0001$).
Conclusion: A new three-dimensional musculoskeletal model combining the trunk and lower limbs is useful for simultaneous analysis of muscle activities of the trunk and lower extremities.
Key words: three-dimensional musculoskeletal model, motion analysis, muscle activity

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Introduction

Remarkable advances in biomedical and computational dynamics in recent years have made possible numerous motion analyses using a variety of three-dimensional musculoskeletal models [1−3]. However, only a few motion analyses have examined the trunk, including the spine. Moreover, these studies used analytical models that assumed the thoracic spine to be a single unit and the courses of muscles to be linear, and simplified or unified joint shapes [4]. These modifications were necessary because of the complex structure: the spine comprises 24 individual vertebrae linked together by the intervertebral joints, as well as intervertebral discs and ligaments between them, and is also surrounded by numerous muscles that support the trunk [5]. These many joints, ligaments, intervertebral discs, and muscles also act and move in a complex manner, allowing movements not seen in other joints, which add further difficulties to the analysis of the trunk. Because of these issues related to the structure and mobility of the spine, precise motion analysis of the trunk has yet to be performed. Hatakeyama et al. [6] produced a 3-dimensional musculoskeletal trunk model from accurate whole-body computed tomography (CT) and magnetic resonance imaging (MRI) scans, and investigated joint moments and intradiscal pressure while standing upright.

The present study used this model to perform motion analysis of the change in posture from standing upright to maximum anterior inclination of the trunk. As the contribution of the pelvis and legs to anterior inclination of the trunk cannot be ignored [7], we combined the existing musculoskeletal trunk model with a musculoskeletal model of the pelvis and legs, and analyzed activities of the muscles involved in anterior inclination of the trunk.

Methods

Construction of the 3-dimensional musculoskeletal model

Because the contribution of the pelvis and legs has to be taken into account in spinal analysis, as described above, we constructed a musculoskeletal model of the whole body [8]. A healthy man (age, 31 years; height, 174 cm; weight, 78.5 kg) underwent whole-body CT and MRI after receiving a thorough explanation of the study and providing informed consent.

1) Production of the skeletal model

From the CT images, the skeletal regions of each bone were visualized, and reconstructed into 3-dimensional bone model. In this process, the Mimics software (Materialise, Belgium) was used to construct the whole-body skeletal model (Fig. 1).

2) Production of the musculoskeletal model

The Mimics software was used to visualize each muscle depicted on the subject's whole-body MRI, and reconstruct them into 3-dimensional model [9–11]. The anatomical literature was used as reference

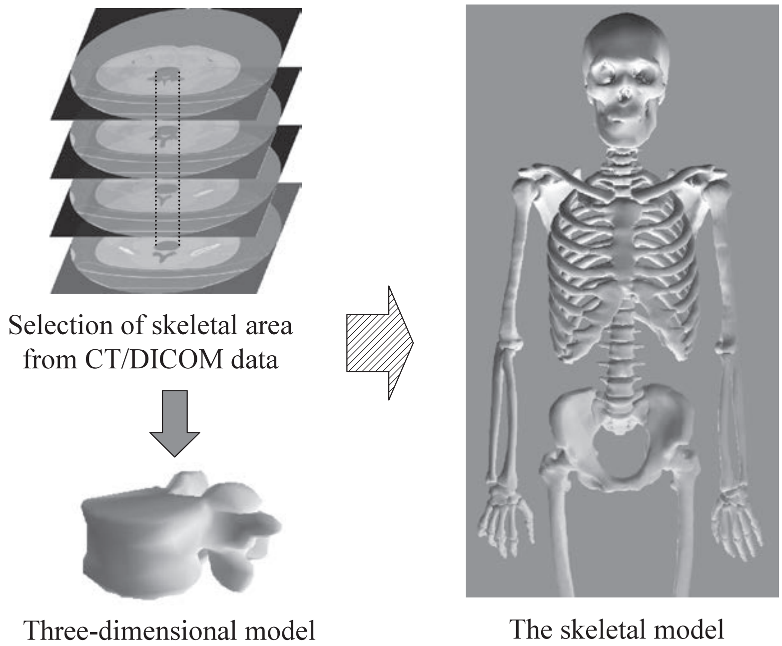
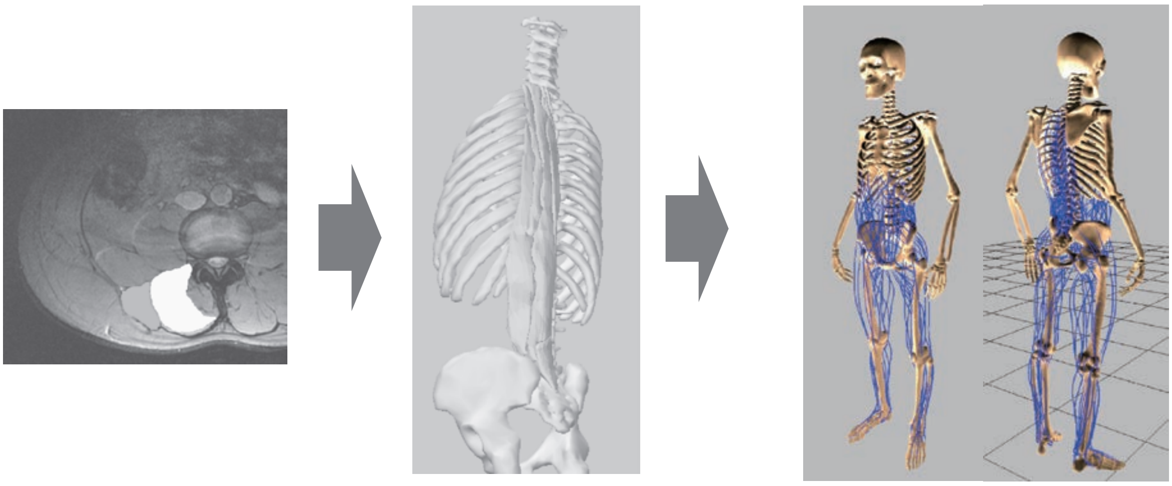


Figure 1. Construction of the skeletal model.

Table 1. Muscles in musculoskeletal model.

Trunk muscles
Rectus abdominis, obliquus internus abdominis, obliquus externus abdominis, quadratus lumborum, psoas magnus, iliocostalis, longissimus, spinalis, multifidus, rotatores, intertransversalis, interspinales.
Pelvic girdle muscles
Gluteus maximus, gluteus medius, gluteus minimus, quadratus femoris, piriformis, gemellus superior, gemellus inferior, obturator internus, obturator externus, iliacus.
Femoral muscles
Sartorius, rectus femoris, vastus lateralis, vastus medialis, vastus intermedius muscle, gracilis, pectineus, adductor longus, adductor brevis, adductor magnus, adductor minimus, biceps femoris, semitendinosus, semimembranosus.
Lower leg muscles
Tibialis anterior, extensor digitorum longus, peroneus tertius, extensor hallucis longus, peroneus brevis, gastrocnemius, soleus, plantaris, tibialis posterior, flexor digitorum longus, flexor hallucis longus.



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

Figure 2. Construction of the musculoskeletal model.

for sites of muscle attachment (points of origin and insertion). The wrapping method was used for more accurate reproduction of muscle courses and volumes [12, 13]. The wrapping method was used to connect the starting point of the muscle with the end, in the shortest possible route along a geometric pattern. In this model, there were a variety of muscles (Table 1), and all muscles were assigned maximum muscle strength at optimum length based on cross-sectional area. All joints were defined as so-called “ball joints”, a term used commonly in three-dimensional analysis, and joint ranges of motion were defined based on previous studies. The data thus obtained were reconstructed using the equivalent impedance characteristics analysis system (EICAS) (Toyota Central R&D Labs, Japan) to produce the musculoskeletal model (Fig. 2).

Motion Measurements

Five healthy men (mean age, 22.4 years; mean height, 172 cm; mean weight, 64.3 kg) participated in the study. A VICON MX 3-dimensional motion-capture system (Vicon Oxford Metrics, UK) equipped with seven cameras (MX-T40; Vicon Oxford Metrics, UK) was used to measure motion in the flexion phase from standing upright to the position of maximum anterior inclination of the trunk, and in the return phase from maximum anterior inclination of the trunk to standing upright. Subjects had 30 reflective markers attached to the head, 7th cervical vertebra (C7), 3rd thoracic vertebra (T3), 12th thoracic vertebra (T12), 3rd lumbar vertebra (L3), top point of the sternum, xiphoid process, acromia (left and right), lateral epicondyles of the humeri (left and right), styloid processes of the ulnae (left and right), posterior superior iliac spines (left and right), anterior superior iliac spines (left and right), intermediate points on the femurs (left and right), lateral points of the knees (left and right), intermediate points on the lower legs (left and right), lateral condyles of the ankles (left and right), second metatarsal bones (left and right), and heels (left and right) (Fig. 3).

Figure 3. Marker attachment positions.

Joint torque and moment arms were calculated based on the positional data from each part of the body obtained from these measurements and floor reaction force. The equation: joint torque = moment arm × muscular force, was used to estimate muscular force of each muscle. Muscular forces of the erector spinae, rectus abdominis, and gluteus maximus were estimated. For each muscle, the muscle activities at 30° of the flexion phase, 60° of the flexion phase, maximum anterior inclination, 30° of the extension phase, and 60° of the extension phase were estimated and expressed as ratios to the muscle activity at the standing position (taken as unity). For each muscle, the muscle activity at standing upright phase and the peak muscle activity were compared statistically by paired *t*-test. A *p* value less than 0.01 was considered statistically significant.

Results

The erector spinae exhibited a gradual increase in muscle activity during the flexion phase, peaking at the position of maximum anterior inclination, with a tendency of muscle activity to increase during the extension phase until returning to the upright position (Fig. 4-a). The ratio of the muscle activity at standing upright phase to the peak muscle activity was 1: 3.94 ± 0.65(Mean ± SD).There was a significant difference between the muscle activity at standing upright phase and the peak muscle activity (paired *t*-test ; $p < 0.0001$).

The rectus abdominis exhibited high muscle activity during the flexion phase from the upright position to the position of maximum anterior inclination, particularly at 60° of anterior inclination, and tended to peak at the position of maximum anterior inclination (Fig. 4-b). The ratio of the muscle activity at standing upright phase to the peak muscle activity was 1: 1.75 ± 0.22. There was a significant difference between the muscle activity at standing upright phase and the peak muscle activity (paired *t*-test ; $p < 0.0001$).

The activity of the gluteus maximus tended to peak from the position of maximum anterior inclination to 60º during the extension phase (Fig. 4-c). The ratio of the muscle activity at standing upright phase and the peak muscle activity was 1: 4.07 ± 0.68. There was a significant difference between the muscle activity at standing upright phase and the peak muscle activity (paired *t*-test ; $p < 0.0001$).

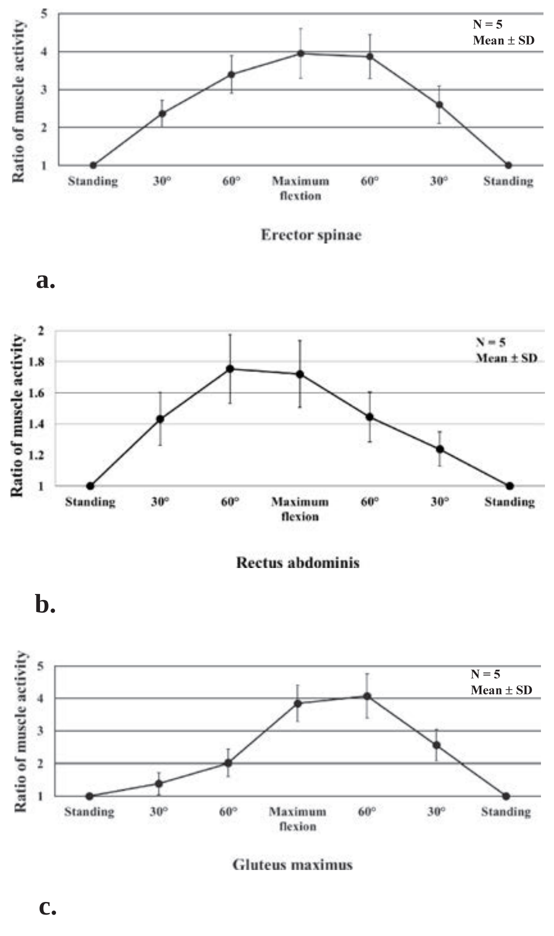


Figure 4. The ratios of muscle activity in the flexion phase from standing upright to the position of maximum anterior inclination of the trunk, and in the return phase from maximum anterior inclination of the trunk to standing upright.
a) erector spinae; b) rectus abdminis; c) gluteus maximus.

Discussion

Anterior inclination of the trunk is a compound movement of the spine, pelvis, and hip joint [14, 15], and investigation with a model including the pelvis and legs in addition to the spine is required during motion analysis. Existing models based on anatomical data from cadavers have various problems such as linear muscle courses and reduced muscle volume compared to the living body. In this study, to perform more detailed analysis, we constructed a whole-body 3-dimensional musculoskeletal model based on the data from a living body and used the results for analysis.

Many previous studies have used electromyograms to analyze muscle activity during standing anterior inclination of the upright trunk [16, 17]. We have not been able to find any report estimating muscular force from motion analysis. Our analysis estimated the muscular forces of the erector spinae, rectus abdominis, and gluteus maximus muscles, which are active during anterior inclination of the trunk.

With anterior inclination of the trunk, the erector spinae muscles are active during extension of the spine. However, Kippers et al. [15, 18] reported that muscle activity from eccentric contraction is also evident during anterior inclination, and the present investigation also found that muscle activity was evident in both the flexion and extension phases. The rectus abdominis not only flexes the spine, but is also believed to play a role in alleviating stress on the spine [19]. Nouwen et al. [20] found an increase in muscle activity during the process from standing upright to the position of maximum anterior inclination, while Paquet et al. [18] found an increase in muscle activity during the later part of the flexion phase, with a single peak from later part of the flexion phase to the position of maximum anterior inclination. The main action of the gluteus maximus is to extend the hip joint, but it also acts during the extension phase of anterior inclination of the trunk. Steindler et al. [21] reported that the gluteus maximus exhibits high activity during the early extension phase from the position of anterior inclination of the trunk to the upright position, with muscle activity peaking from the position of maximum anterior inclination to the early extension phase. Although we cannot directly compare the present results with previous reports of estimated muscular force during trunk muscle activity, similar tendencies are observed for the erector spinae, rectus abdominis, and gluteus maximus muscles.

A relationship between back muscle strength and spinal deformity has been reported in recent years. However, back muscle strength has yet to be investigated in detail. We intend to use the present model to confirm the relationship between the trunk muscles, including back muscles, and spinal deformity in the elderly, with the aim to establish physical therapies such as appropriate strength training for trunk muscles.

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