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Core muscle Strengthening Effect During Spine Stabilization Exercise

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Abstract – Core spinal muscles are related to trunk stability and assume the main role of stabilizing the spine during daily activities; strengthening of core muscles around the spine can therefore reduce the chance of back pain. The objective of the study was to investigate the effect of core muscle strengthening in the spine during spine stabilization exercise using a whole body tilt device. To achieve this, a validated musculoskeletal (MS) model of the whole body was used to replicate the input motion from the whole body tilting exercise. An inverse dynamics analysis was executed to estimate spine loads and muscle forces depending on the tilting angles of the exercise device. The activation of long and superficial back muscles such as the erector spinae (iliocostalis and longissimus) were mainly affected by the forward direction (-40°) of the tilt, while the front muscles (psoas major, quadratus lumborum, and external and internal obliques) were mainly affected by the backward tilting direction (40°). Deep muscles such as the multifidi and short muscles were activated in most directions of the rotation and tilt. The backward directions of the tilt using this device could be carefully applied for the elderly and for rehabilitation patients who are expected to have less muscle strength. In this study, it was shown that the spine stabilization exercise device can provide considerable muscle exercise effect.

Keywords: Core muscle strengthening, Spine stabilization exercise device, Whole body tilt, Musculoskeletal model

1. Introduction

Trunk stability is known to be important for the prevention of injuries and for rehabilitation in the spine [1, 2]. In addition, corrupted stability due to the abnormal coordination of trunk muscles was found to induce low back pain [3]. Therefore, investigations to find the function of trunk muscles in stabilizing the spine have been intensively performed [4, 5].

It was reported that the core spinal muscles are known to be related to trunk stability and assume the main role in stabilizing the spine during daily activities; strengthening of these muscles around the spine can therefore reduce the chance of back pain [6] and prevent recursive pain [7]. Traditional exercises for core spinal muscle strengthening including various types of push-ups and abdominal crunches with supporting tools such as chairs and balls have been suggested to strengthen the muscles. However, for patients who have suffered from chronic low back pain or have undergone surgery the ability to perform these strenuous activities may be limited [6-8].

Recently, the spine stabilization exercise that allows strengthening of the core muscles under static body posture using 3D spinal stabilization devices has been introduced as an alternative and used in hospitals to provide rehabilitation treatment for surgery patients [9, 10]. However, the effect of these devices on spinal behavior such as internal forces at the joint level and muscle activation patterns during the exercise has not yet been investigated.

Recently, analytical spine models [11-14] for predicting internal spinal loads and muscle forces have been widely used to investigate the biomechanical behavior of the spine. These models can be useful to explore the area where the experimental approaches are seldom applied to quantify the effect of muscle strengthening exercise programs on the specific muscles. These musculoskeletal models simulate a detailed muscle architecture including hundreds of muscle fascicles, segments, and joints and their validity has been obtained in biomechanical studies through comparison with a series of experimental data. Therefore, this study aimed to investigate the effect of spine stabilization exercise on core muscle strengthening in the spine by estimating spine loads as well as muscle forces and their activation patterns using a musculoskeletal model.

2. The Model Description

A three-dimensional (3D) musculoskeletal (MS) model of a whole body was adopted using the geometry of the segments and muscles illustrated in the v. 1.1 repository of the AnyBody Modeling System v. 4.2 (AnyBody Technology, Aalborg, Denmark) in this study [11, 12]. Details of the development of the MS model are presented

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in the previous publications and the validity of the adopted model (Figs. 2 and 3) was obtained for the purpose of this study by comparison with the *in vivo* experiments in the previous studies [11-14]. In brief, the whole body model consists of several segments which are rigid bodies with simple joints: the skull, arms, legs, pelvis, and spine. The spine region includes the cervical, thoracic, and lumbar region as well as the sacrum. The cervical and thoracic spines are modeled as a single lumped segment. The lumbar spine, which is the region of the spine of major interest in this study, consists of five rigid bodies and the sacrum. Information regarding the masses and inertia properties of each segment were obtained based on the previous literature [15] and the body parameter of the whole body model was developed to be a weight of 72 kg and a height of 1.75 m. Intervertebral discs were expressed as rigid spherical joints, allowing for three rotational degrees of freedom. The rotation centers of the intervertebral joints were determined based on a previous study and the joint stiffness was applied depending on the segmental motion [16].

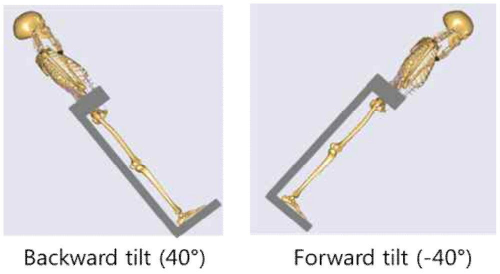
The following muscles were included in the spine model: the erector spinae (longissimus and iliocostalis), the front muscles (psoas major, quadratus lumbarum, external oblique, internal oblique), multifidi and short segmental muscles (interspinales, intertransversarii and rotatores). Long muscles were designed to wrap over the spinal curvature by connecting several attachment points between the insertion and origin depending on the body motions. The muscle properties were modeled as single force components and exerted only tensile forces, while passive element properties (tendons) were not considered [11, 12]. The 90 N/cm² of maximum muscle for capacity was set as the muscle strength for all muscle fascicles for the analysis in order to estimate the joint resultant forces and muscle forces [16].

All ligaments (anterior and posterior longitudinal, supraspinous, interspinous, intertransverse, ligamentum flavum, and capsular ligament) identified from previous studies were incorporated into the lumbar spine model. Tensile forces of ligaments were exerted depending on the nonlinear stiffness (the load-deformation curve) obtained from the previous experimental and analytical data [17, 18]. Ligaments were designed to activate as they were stretched over each slack length and calibrated in several activities [13].

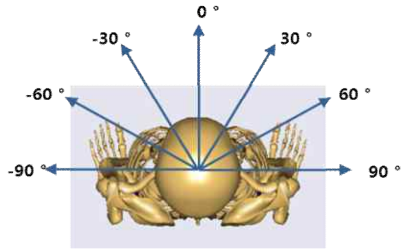
3. Simulated Activities Description

A schematic of the MS model is shown in Fig. 1, illustrating the replication of the core muscle strengthening through spine stabilization exercise using the device (Spine Balance 3D, CyberMedic Co., Korea). Both arms were folded and an upright standing position was maintained during the axial rotating and sagittal tilting of the device (Fig. 2) [10]. The core muscle strengthening mechanism of the tilting device utilizes the loads exerted through the upper body weight that are applied to the joints, while the core muscle strengthening effect was activated while stabilizing the body. The pelvis area was constrained to the machine while the trunk remained unsupported during the tilting motion. The tilting angle of the MS model ranged from 0° to ±40° (forward and backward) at 10° increments in the sagittal plane (Fig. 2(a)). The axial rotating angle ranged from 0° to ±90° (left and right side) at 30° increments in a transverse plane (Fig. 2(b)).

Fig. 1. Schematic of whole body tilt device (Spine Balance 3D, CyberMedic Co., Korea)



(a) Sagittal tilt angle



(b) Axial rotation angle

Fig. 2. Schematics of sagittal tilt angle (a) and axial direction rotation (b), replicating the tilting motion using the exercise device [10].

4. Simulation

Muscle recruitment in inverse dynamics is the process of determining the set of muscle forces that will balance a given external load. The minimum-maximum (min/max) and quadratic recruitment criteria built in the AnyBody Modeling System were selected as a muscle recruitment strategy to predict the joint resultant forces and muscle forces in the spine. This optimization solver attempts to minimize the maximum muscle activation and muscle stress simultaneously, hence delaying muscle fatigue and maximizing the synergy of all included muscles.

4.1 Inverse dynamics

Inverse dynamics analyses were performed to predict spinal loads and muscle forces using the min/max and quadratic criteria in muscle recruitment using the same musculoskeletal modeling software (AnyBody Technology, Aalborg, Denmark). The details of the muscle recruitment criteria are described in detail in a previous paper [19]. In brief, the min/max muscle recruitment criterion minimizes the activation of the maximal activated muscle in the system, which lowers the maximum relative load of any muscle. This recruitment is considered to be reasonable and efficient in conveying the physiological aspect of living organisms since fatigue is more likely to occur in the muscle when under the maximum relative load. Hence, it would mean that the body would maximize its endurance and delay the fatigue.

The muscle recruitment solver minimizes muscle activity and muscle fatigue, thus assuming that strong muscles can do more work than weak muscles [20]. The optimization scheme is formulated as follows,

$$\text{minimize} \quad \beta+\varepsilon\sum_{i}\left(\frac{f_i^{(M)}}{N_i}\right)^2, \quad \text{subject to:} \quad \frac{f_i^{(M)}}{N_i}\le\beta,$$
$$i\in\{i,..,n^{(M)}\}, \quad f_i^{(M)}\ge 0,\ i\in\{i,..,n^{(M)}\}, \ \mathbf{Cf}=\mathbf{r},$$

where β is the muscle activity, ε is a weighting factor in order to include a quadratic term in the objective function, $f_i^{(M)}$ is the force in the i^th^ muscle, and n is the number of muscles. **C** is a coefficient matrix depending on the geometry and kinematics of the muscle and body segments, **f** is a vector of muscle and reaction forces for predictiction, and **r** is a vector of external forces and inertia forces. N_i is the normalization factor, which is a measure of the strength of each muscle.

The vertical force (Fy) and resultant shear force (Fx and Fz directions), as the joint forces, were calculated and compared. The forces of the same muscle fascicles within the same muscle category were summed and the total muscle forces are given for the presentation of the result. For example, the forces in the 34 muscle fascicles of longissimus, running over the spinal curvature, were summed and then grouped. The following muscles in the same area of the body were grouped and compared for efficient result comparison: the erector spinae muscle (iliocostalis and longissimus), front muscles (psoas major, quadratus lumborum, and external and internal obliques), multifidi (lumbar and thoracic multifidi), and short segmental muscles (interspinales, intertransversarii and rotatores).

4.2 Joint resultant forces

Generally, the trend of vertical joint force in all joints was highest at the upright neutral position (0º) and decreased with the increase of axial rotation angle (Fig. 3, left column). The trend of shear force was also highest for the upright neutral position (0º) and increased as the axial rotation angle increased (Fig. 3, right column). The magnitudes of joint forces ranged from 512 N to 1957 N and 0 N to 438 N for vertical and shear directions, respectively, from the neutral to forward or backward tilt. Generally, a higher shear force (438 N) was estimated at the L1-L2 levels for the backward tilt with -60 and 60

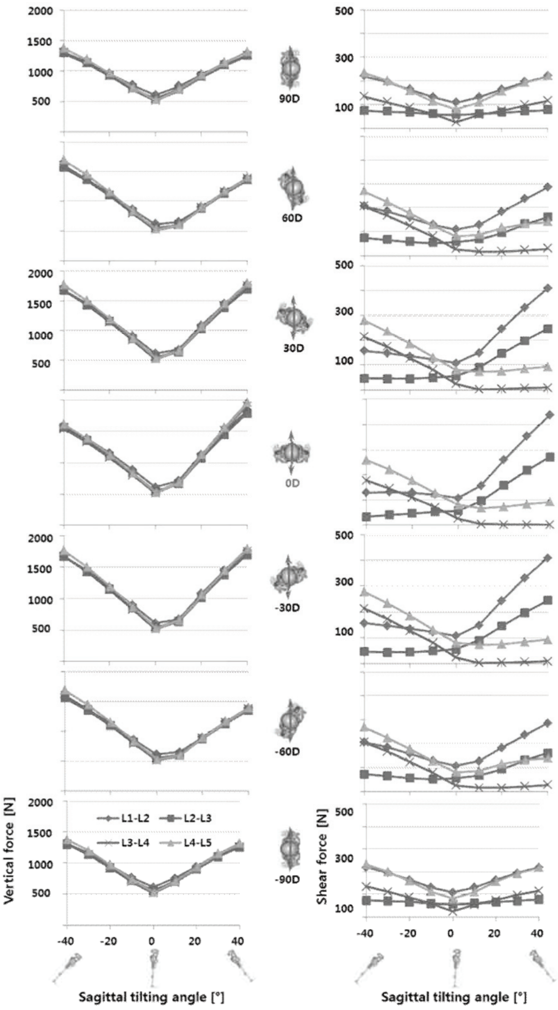


Fig. 3. Predicted vertical force (left) and shear force (right) at 90 N/cm² of muscle strength. The resultant force of the anterior-posterior and lateral direction components were given as shear force.

degrees of the axial rotation angle. In contrast, a higher shear force (279 N) was estimated at the L4-L5 levels for the forward tilt with the same range of axial rotation angle.

4.3 Forces in core muscles

In the case of muscle forces, as the sagittal tilting angles increase, the trend of all muscle forces increased (Figs. 4-6). The activation of long and superficial back muscles such as iliocostalis and longissimus in the erector spinae muscle (Fig. 4) were mainly affected as the forward direction tilt angle was increased (-40°). The magnitude of muscle forces ranged from 0 N to 415 N and 32 N to 518 N for iliocostalis and longissimus, respectively. The highest values of iliocostalis (415 N) and longissimus (518 N) were estimated for -30 and 30 degrees of the axial rotation with the forward direction (-40°) of the tilt.

The muscle forces in the front and side muscles (psoas major, quadratus lumborum, and internal and external obliques) are given in 5. Unlike the erector spinae muscle, the front muscles were mainly affected by the angle of the backward tilting direction (40°). The magnitude of muscle forces ranged from 0 N to 441 N, 0 N to 148 N, 0 N to 327 N, and 5 N to 134 N for psoas major, quadratus lumborum, external obliques, and internal obliques, respectively. The highest muscle force value was predicted for psoas major (441 N) for the right backward direction (40°) of the tilt. In the case of left and right quadratus lumborum, the maximum value (148 N) was estimated for -60 and 60 degrees of the axial rotation with the forward direction (-40°) of the tilt. However, the maximum values for the left and right external (134 N) and internal (327 N) oblique muscles were estimated for the backward direction (-40°) with the -60 and 60 degrees of the axial rotation

The muscle forces in the deep and short muscles such as multifidi and the short segmental muscles (interspinales,

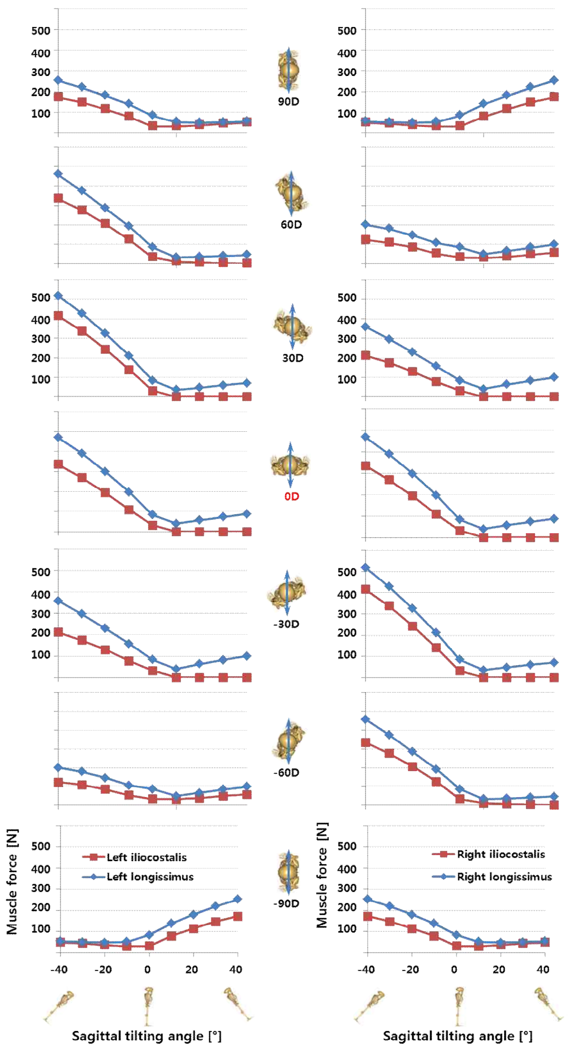


Fig. 4. Predicted muscle forces in the erector spinae muscle (iliocostalis and longissimus) at 90 N/cm² of muscle strength depending on sagittal tilt angle and axial rotation.

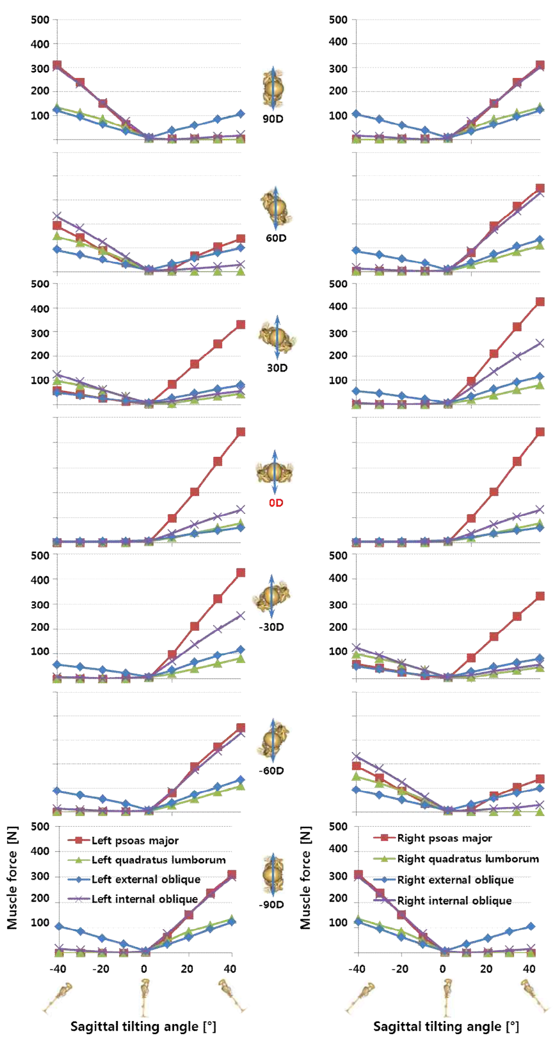


Fig. 5. Predicted muscle forces in the front and side muscles (psoas major, quadratus lumborum, and external and internal obliques) at 90N/cm² of muscle strength depending on sagittal tilt angle and axial rotation.

intertransversarii, and rotatores) are given in Fig. 6. Unlike the long and superficial muscles, multifidi and short muscles were activated in most directions of the rotation and tilt. The magnitude of muscle forces ranged from 20 N to 111 N and 10 N to 23 N for the multifidi and short muscles, respectively. The highest value was estimated for multifidi (111 N) for -30 and 30 degrees of the axial rotation with the forward direction (-40°) of the tilt. However, the highest value of the short muscle (28 N) was predicted for the backward direction (40°) of the tilt.

5. Discussion

In this study, the effect of core muscle strengthening using a spine stabilization exercise device on the joint forces and muscle forces in the spine was investigated using the previously validated MS model. Core spine muscle strengthening using spine stabilization exercise has been adopted for surgery patients who are not capable of performing the exercises that strengthen the muscle through the spinal motion due to post-surgical conditions. Unlike other muscle exercises, the advantage of using the device for spine stabilization exercise is that the muscle strengthening can be attained without the accompanying spinal motion. In this study, the muscle forces and joint forces that cannot be measured using the current experiment were estimated using a validated MS model. In addition, it was shown that the spinal stabilization devices could provide substantial muscle strengthening exercise effect on the spine.

Generally, front muscle activation (psoas major, quadratus lumborum, and internal and external obliques) was mainly affected by the backward tilting direction, while the back muscles (iliocostalis and longissimus) were affected by the front direction of the tilt. The activation of the left and right side muscles was considerably affected by the axial rotation angle changes and the effect was highest with the angle between 30° to 60°. Front and back muscles were symmetrically activated when the sagittal tilting angle changed in forward and backward directions (Figs. 4-6). With the combination of both angle changes, more diverse muscle activation patterns were derived. In the present investigation, certain muscle directions showed significant roles in the capability of the human body to maintain certain postures depending on the rotation and tilting angles.

The musculoskeletal model was validated in the previous studies, but is still limited in several respects. The musculoskeletal model includes most of the possible components of the spine such as muscles, ligaments, and disc, but is still a limited model that estimates trends of loadings in the spine depending on the chosen optimization criterion. Therefore, other values of joint and muscle forces can be predicted under different optimization criteria. Muscle dynamics, such as force-length and force-velocity relationships, were not considered in the analysis due to the lack of practical experimental data. Validation of muscle forces and their activation patterns was not completed due to the lack of previous experimental data [11, 12]. Although this study provides scientifically reasonable evidence to achieve the goal, further EMG study should be performed to gain the confidence with the results.

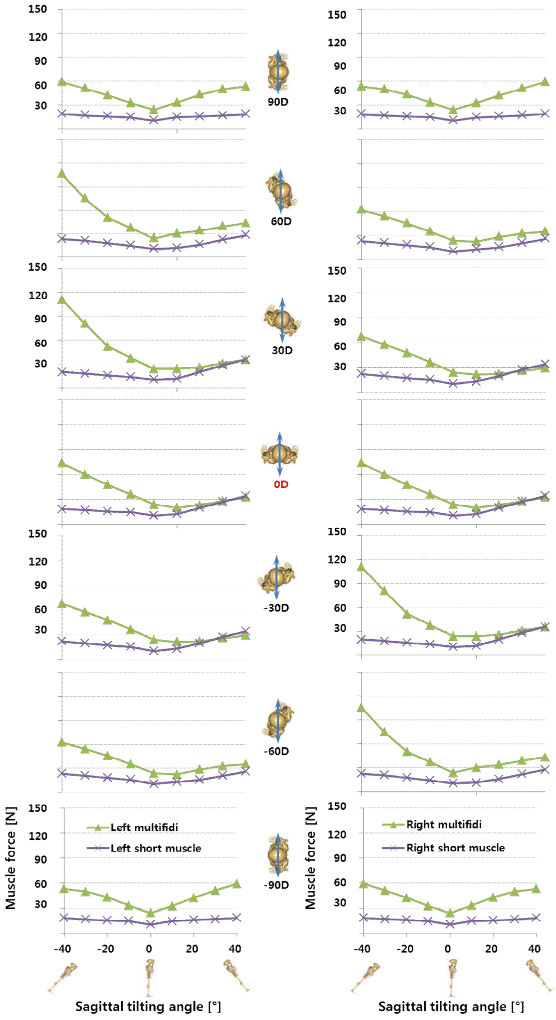


Fig. 6. Predicted muscle forces in multifidi and in the short segmental muscles (interspinales, intertransversarii, and rotatores) at 90 N/cm² of muscle strength depending on sagittal tilt angle and axial rotation.

6. Conclusion

The effect of core muscle strengthening using spine stabilization exercise was shown as considerable in estimating spine loads and muscle forces using a musculoskeletal model. The anterior directions of the tilt mainly induced the activation of long and superficial back muscles and the posterior directions were the front muscle activations. Deep muscles such as short muscles, lumbar, and thoracic mulifidi were activated regardless of the directions of the tilt.

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