Model simulation for restoration of trunk in complete paraplegia by functional electrical stimulation

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Abstract

Purpose: ***To design a musculo-skeletal dynamic spine model with which we can perform FES effectively as well as the simulation of spinal motion and analysis of stress distribution to the vertebra.***

Method: The skeletal model was designed from computed tomography (CT) data of a young male healthy volunteer. The muscles, discs and ligaments were attached to the skeletal model correctly as possible as we could. Physical properties of the muscles, discs and ligaments, which could be used to design this model, were mainly obtained from past literatures. The simulation of dynamic spinal motion and analysis of vertebral von Mises stress were performed simultaneously by means of using 3D analysis software "Visual Nastran 4D".

Result: The spinal dynamic motion and vertebral stress distribution were observed from our spinal model.

Conclusion: We designed the musculo-skeletal spine model that would be useful for the simulation of dynamic motion and analysis of stress distribution with a role of FES to the trunk extensor muscles.

1. INTRODUCTION

Trunk extensor muscle strength is very important to support spinal stability for sitting or standing. The effectiveness of functional electrical stimulation (FES) or therapeutic electrical stimulation (TES) of trunk extensor muscle for paraplegic patients has been reported by some literatures [1, 2, 3]. But there has been no previous report with a computer simulation method about stimulating trunk extensor muscles.

In the meantime, finite element method is used for analysing stress only under static condition [4]. On the other hand rigid link method has been used for dynamics motional simulation [5, 6].

The purpose of this study is to combine these two methods and to design a musculo-skeletal dynamic rigid link model that can also analyse stress by means of finite element method.

2. METHODS

2.1. Design of skeletal model

A 28 years old healthy male was scanned with CT. After obtaining the CT data, we made three-dimensional (3D) model of spine, rib cage and pelvis by using 3D design software "MIMICS" (Fig. 1 *left*). This model could be worked under 3D analysis software "Visual Nastran 4D". The vertebrae could be meshed to analyse the stress distribution (Fig. 1 *right*). Meshing could be done to some vertebrae as far as the capacity of computer processing allows.

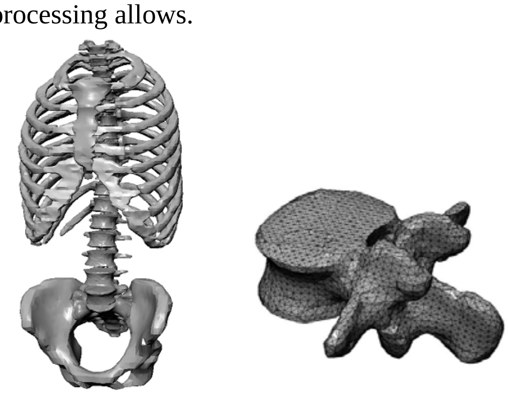

Figure 1. Three-dimensional spine model with the rib cage and pelvis (*left*), and vertebra with mesh (*right*)

2.2. Design of muscle model

We designed muscle component that had a contractile element. Our model included M. erector spinae (M. iliocostalis, M. longissimus and M. spinalis), M. semispinalis, M. multifidus, M. rotatores, M. interspinales, M. quadratus lumborum, M. rectus abdominis, M. psoas major, and M. psoas minor. We attached these muscles to the skeletal model on 3D analysis software "Visual Nastran 4D" (Fig. 2). Each muscle was represented as an "actuator" which was attached between two bones to transmit a muscle contraction. Thus this model could move.

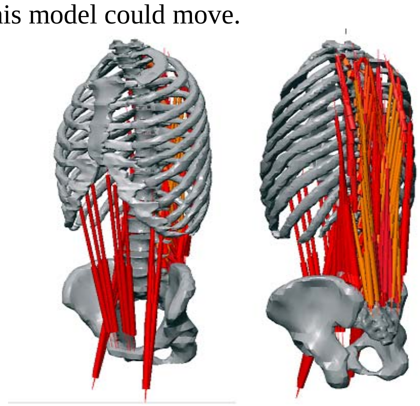

Figure 2. Three-dimensional spine model with muscles

2.3. Design of disc and ligament

Intervertebral discs and ligaments were also attached to our skeletal model. These two were represented by a "spring·damper" which had characteristics of both spring and damper. These eight spring·dampers connected two adjacent vertebral bodies to represent the disc so as to move the functional spinal unit multidirectionally (Fig. 3). As for ligaments, anterior and posterior longitudinal ligament, flavum, supraspinos ligament, interspinous ligament, Intertransverse ligament, and also capsule were included into this model. Physical properties and characteristics of discs and ligaments were already reported [7, 8]. They were attached anatomically to the skeletal model.

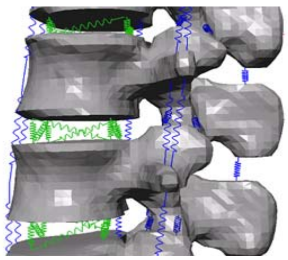

Figure 3. Spring·dampers connect the bones.

2.4. Analysis

In this model, the L2 vertebra was meshed, and the pelvis and sacrum were fixed. Body weight per each vertebral level was estimated from multiplication of the axial cross sectional area by the each vertebral body height. Then these data were put on the C7 sagittal plumb line by each level (Fig. 4). We supposed contractile power of muscles so as to maintain spinal posture against gravity and put these data into each muscle as appropriate. Then we stimulated all trunk extensor muscles. The analysis was performed mainly by "Visual Nastran 4D" and partially by MATLAB. These software and hardware cooperated to simulate spinal motion using our dynamic model, and simultaneously von Mises stress analysis could be performed.

Figure 4. Our model has weight per each vertebral level along to the C7 sagittal plumb line.

3. RESULTS

As a result of the contraction of actuator like as stimulating the muscles with FES or TES, we could observe the spinal motion backwardly like trunk extension. Besides we could also observe the stress distribution of the L2 vertebra mainly around the middle column (Fig. 5).

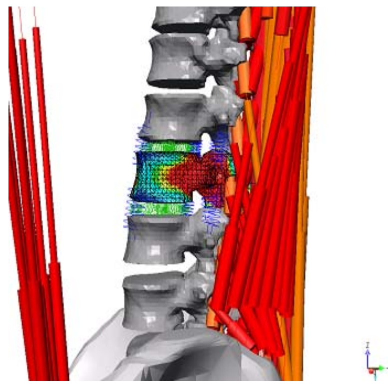

Figure 5. Stress concentration occurs around the middle column and pedicle of the L2 vertebra.

4. DISCUSSION AND CONCLUSIONS

The paraplegic patients after spinal cord injury decrease sitting ability due to the weakness of trunk extensor muscles. Kukke and Triolo reported that trunk instability causes difficulties in sitting and restricts the area of the bimanual workspace due to the weakness of moving ability of the trunk, and stimulation of back muscles causes anterior rotation of the pelvis to restore a more natural lumbar curve without backrest [3].

This time, our 3D dynamic spine model could simulate both the spine motion and the stress distribution simultaneously. This is the first simulation to analyse the stress under dynamic motion. Moreover our model has an ability to investigate not only the spine motion but also the vertebra stress with FES or TES for paraplegic patients. This is a preliminary model and we are now on the way to improve this spine model.

In conclusion, we designed the musculo-skeletal dynamic spine model that will be useful to simulate the dynamic motion as well as to analyse the stress to the vertebra for paraplegic spine with a role of FES.

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