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Development of Integrated Analysis of Spinal Cord and Skeletal Muscles for Joint Movement

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Parkinson's disease is a degenerative disorder of central nervous system and causes various motor dysfunctions. The motor dysfunction is generally considered to be caused by abnormal activities of the basal ganglia, which results from the death of dopamine-producing cells in a midbrain region. However, the cause of the depletion is not clarified yet. Therefore, treatments remain palliative and we cannot stop the development of the disease.

In this research, we are now developing a numerical model for the motor dysfunction such as parkinsonian syndrome on a high performance computer system. The final target of this research activity is to develop the integrated analysis of brain, spinal cord and three-dimensional musculoskeletal system, and to reproduce primary symptoms of Parkinson's disease in order to clarify the cause of the motor dysfunction in Parkinson's patients and obtain the knowledge about effective treatments.

Towards the goal, firstly we have developed each part (brain, spinal cord and skeletal muscles) separately. Then, we are now integrating the spinal cord model and musculoskeletal model together. In this paper we will report the current status of the activity and our strategy to integrated modelling.

Towards the development of numerical modelling for whole spinal cord network, we had constructed the simulator of alpha motoneuron pool firstly, following the report by Cisi.[1] It was confirmed that the model can reproduce the recruitment and rate coding, which are important mechanisms to control exerted muscle force. Next, the models of interneurons were added into the simulator. Figures 1 and 2 show the numerical results about recurrent inhibition by alpha motoneuron and Renshaw cell interaction. It is confirmed that the developed simulator reproduces the well-known linear relationship of the firing rates between alpha motoneuron and Renshaw cell. The inhibitory effect of Renshaw cells decreases muscle force by about 25 %. Then we have developed whole spinal cord network, adding gamma motoneuron and two kinds of sensory system of muscle spindle and Golgi tendon organ.[2,3] Figure 3 shows one of the results about activities of one pair of muscles (agonist and antagonist). In this case the descending commands to motoneuron are assumed to be periodically fluctuating. The result shows the both muscle activities follows the fluctuating pattern of the descending commands.

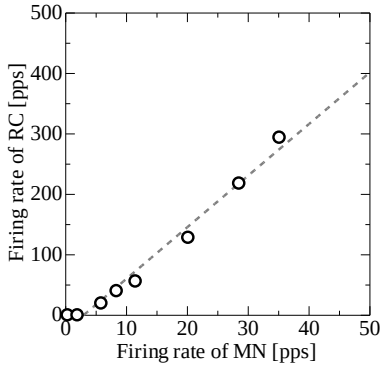

Fig.1: Relation motoneuron activity and Renshaw cell activity.

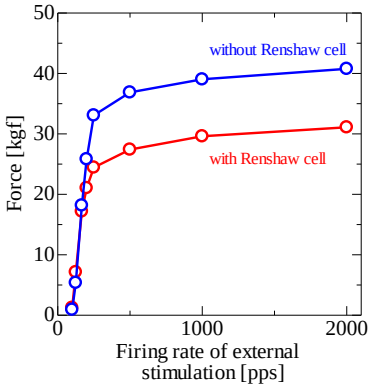

Fig. 2: Decrease of exerted force by recurrent inhibition

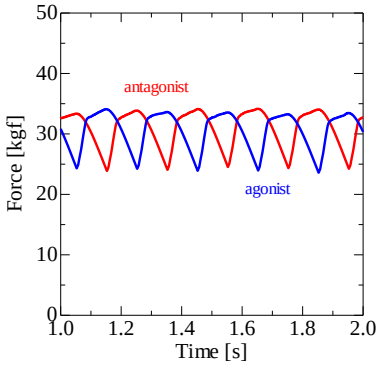

Fig. 3: Muscle activities by periodical descending commands

The numerical modelling for musculoskeletal system is based on a nonlinear finite element method under the assumption of incompressibility of biological soft tissues such as muscle and tendon. Here, a mixed type displacement-pressure finite element formulation, a total Lagrangian formulation, and a fully implicit time integration procedure are adopted. Numerical results for isometric contraction of a human triceps surae muscle are shown in Fig. 4. In this calculation, modelled surae muscle is based on medical images. It is seen that each muscle causes a contraction in the fibre directions. The Achilles tendon is stretched by the aponeurosis existing between gastrocnemius and soleus, resulting in the force generation.

Finally, these spinal cord model and three-dimensional musculoskeletal model are integrated together through the activities of alpha motoneurons and sensory systems. The active stress by muscle fibre contraction is decided by alpha neuron activities. Moreover the deformation of a muscle generates action potential in muscle spindle and exerted force generates action potential in Golgi tendon organ. These action potentials are sent to the spinal cord and related neuron activities in spinal cord are updated continuously. We are now developing the integrated analysis of spinal cord based on conductance-based neuron model and skeletal muscle model based on three-dimensional nonlinear finite element method for hyperelastic material. We are going to talk about our strategy and show some results for integrated analysis.

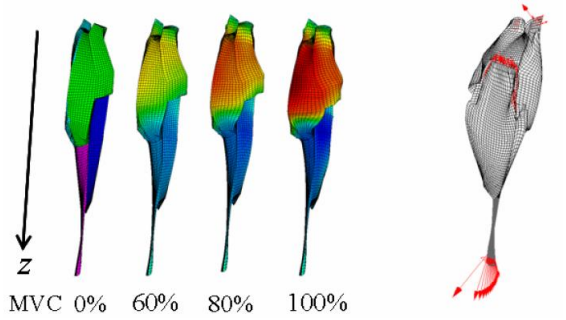

Fig. 4: Fig.4. Simulation results of the isometric contraction of a human triceps surae muscle. Four figures in the left-hand side illustrate the deformation and displacement of the longitudinal direction. The right-hand side figure shows the nodal force vectors at the end of the con-traction.

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