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Anatomical Model of the Spinal Nervous System and its Application to the Coordination Analysis for Motor Learning Support System

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***Abstract*— The motivation of this research is to compute internal perspective of humans through external observation. In this paper, we propose method for analyzing neural information through motion measurement. The method is on the bases of the anatomy and physiology of somatic and spinal nervous system. Muscles are classified by the innervated nerves originate from the spinal cord. The somatotopic organization inside the ventral horn of the spinal cord is utilized for topological structure of the spinal neural information. Time series of images which represent distribution of somatic information inside the spinal cord were successfully obtained through measurement and computation for sword swinging 'kesagiri' motion. The coordination of the motion at spinal level was analyzed. The proposed method provides fundamental for motor learning support system.**

***Index Terms*— Brain-computer interfaces, neural model, neuroanatomy, spinal cord, human behavior analysis**

I. INTRODUCTION

Recently, brain-computer interfaces (BCIs) attract wide attention since they can be used by people with severe motor disabilities. They enable users to control devices with electroencephalographic (EEG) activity from the scalp or with single-neuron activity from within the brain[1], [2]. For health and partially disabled, the spinal nervous system comprising peripheral nerves and spinal cords connect brain and muscles. Therefore, we should be able to estimate the brain activities through motion measurement. During rehabilitation process, analysis of walking motion is critical for monitoring functional recovery of the nervous system after stroke[3], [4]. Visualization and analysis of somatosensory information in the spinal nervous system would help us understand how the brain perceive and regulate its body movoment, since they interface the brain and muscles. The motivation of this study is to design motor learning support system for acquisition of motor skill considering neural mechanism. We should be able to obtain neural information through analyzing whole body muscle data, because the nervous system controls the musculoskeletal system, while the lengths and forces information gets back to the nervous system (Fig. I).

Human motion can be analyzed through combining motion capture system and musculoskeletal model. The body motion is mapped onto the musculoskeletal model so

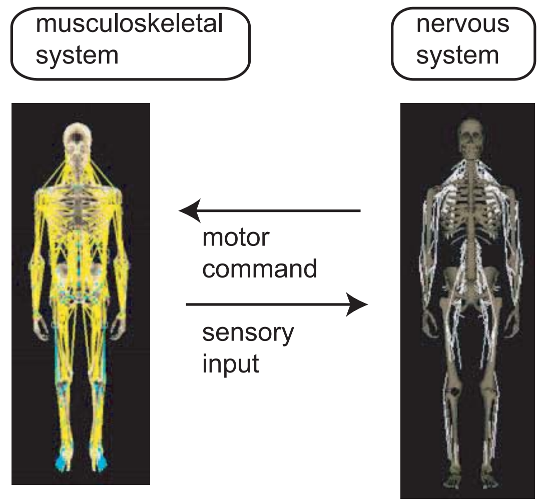

Fig. 1. The information flow between the musculoskeletal system and the nervous system

that the lengths and the forces of muscles are calculated[5], [6], [7], [8]. Dynamic simulation of musculoskeletal model has been studied, and it has been investigated that dynamic optimization to determine a set of muscle excitations that generate a simulation that best reproduces experimental data [9], [10]. Hundreds of time-series data of muscle lengths and forces are obtained utilizing whole body musculoskeletal model[11].

However, how this information is perceived inside the nervous system, and how humans improve our movements have not fully been studied. In most cases, some of the typical muscles are selected for analysis. In this paper, whole body motion data are processed in parallel by distributed and layered nervous systems model based on neuroanatomy and neurophysiology. In order to track the motor information, we developed the anatomical model of the peripheral nerves and the spinal cord. Motor neurons are arranged in each layer of the spinal cord and feedback signals which trigger simple reflex are mapped onto the plane. Groups of muscular data innervated by the same layer of the spinal cord are compared for each trial and the

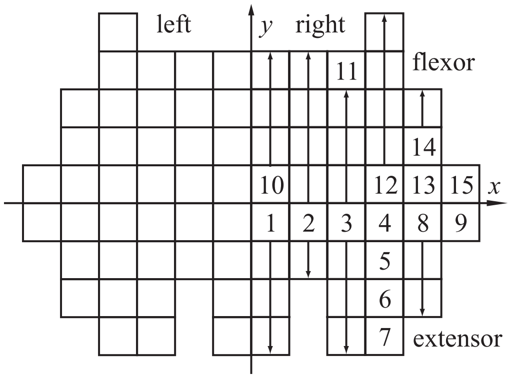

Fig. 2. Somatotopic organization of spinal cord at C5

way of regulation is studied over time. This paper proposes the concept 'behavior based neural-computer interface' consisting of motion capture, musculoskeletal and nervous systems model.

II. Mapping from Motor Information to Neural Information

Anatomy and physiology of the human spinal nervous system are summarized below[12], [13].

- The spinal cord is divided into 31 segments that correspond to attachments of groups of nerve roots. The skeletal muscles are classified by the innervated nerves.
- Motor commands are sent from the ventral horn of the spinal cord. Feedback signals from the muscle spindles and the Golgi-tendon organs are received by the dorsal horn of the spinal cord. The afferent nerves are connected directly or indirectly to the efferent nerves for the stretch and inverse stretch reflexes.
- Somatotopic organization is observed at ventral horn.

We found three problems for visualization the neural information in a given spinal root.

1) We cannot estimate the afferent (feedback) neural signals only by motion observation, because their gains are actively regulated by the efferent (command) neural signals., while can estimate efferent neural signals through EMG measurement[14].
2) Somatotopic organization is observed at ventral horn, however, there is no such organization in the dorsal horn.
3) The rules for somatotopic organization are known while the exact arrangements are unknown for each segments. The somatotopic organization in the spinal cord was made clear in cats[15], but not in humans.

In order to solve the first problem, our solution is to visualize the neural information which should be obtained by synthesizing the afferent and efferent signals inside the spinal cord. We refer the neural information as the group of motor information for each segments. For the second problem, we utilize the structure of the ventral horn for visualization, because the neural information coming from the dorsal horn are sent to lateral horn along the stretch or inverse stretch arc. The third problem was solved by combining muscular innervations and somatotopic organization rules.

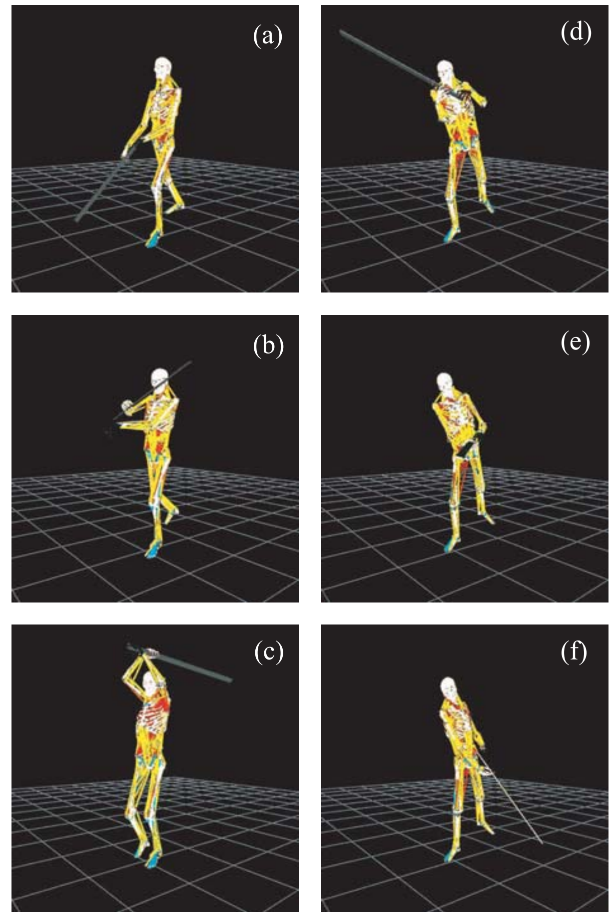

Fig. 3. Snapshot of sword swinging 'kesagiri' motion: Motion capture data are mapped onto the musculoskeletal model.

We show the procedure for generating map of each segments based on these rules. The spinal cord at C5 segment is described in detail. Table I shows the classification of muscles innervated by C5. The position of muscles is classified into 6 categories (1: trunk, 2: trunk to limb, 3: limb girdle to limb, 4: upper arms and legs, 5: lower arms and legs, 6: hands and feet). These categories are utilized for generating maps. The neural information from the innervating the muscles from the C5 segment is shown in Fig. 2. This map was generated by the following procedure.

Draw a horizontal line (x-axis) and a vertical line (y-axis) intersecting at the point O(the origin). In the area of $x<0$, the information from the left half of the body are arranged while that from the right half are arranged in the area of $x>0$. The neural information from the flexor muscles are put on the area of $y>0$, while that from the extensor muscles are put on the area of $y<0$. The neural information is classified into four quadrants in this way: the first quadrant represents information from right

TABLE I

CLASSIFICATION OF MUSCLES INERVATED BY THE FIFTH NN. CEVICALES (C5): THE FIRST COLUMN IS A SERIAL NUMBER; THE SECOND COLUMN INDICATES THE POSITION OF MUSCLES; THE THIRD COLUMN SHOWS WHETHER THE MUSCLE IS EXTENSOR OR FLEXOR; THE FORTH COLUMN IS THE NAME OF MUSCLES.

1	2	E	Mus.LevatorScaplae
2			Mus.RhomboideusMinor
3			Mus.RhomboideusMajor
4	3		Mus.Supraspinatus
5			Mus.Infraspinatus
6			Mus.Subscapularis
7			Mus.Teresminor
8			Mus.Deltoideus
9	5		Mus.Supinator
10	2	F	Mus.SerratusAnterior
11			Mus.Subclavius
12	3		Mus.PectoralisMajor
13	4		Mus.Brachialis
14			Mus.BicepsBrachii
15	5		Mus.Brachioradialis

and flexor muscles; the second represents one from left and flexor muscles; the third represents one from left and extensor muscles; the forth represents one from right and extensor muscles. In each quadrant, the neural information is placed so that the ones from the muscles of small category numbers (1: trunk, 2: trunk to limb) are nearer the origin while those from the muscles of large category numbers (5: lower arms and legs, 6: hands and feet) are farther from the point O.

The information from the flexor and extensor muscles of the same categories should be placed in the same x-axis. We can obtain the neural information representing the force, length and rate of changes in length of the muscles.

III. VISUALIZATION OF THE NEURAL INFORMATION IN THE SPINAL CORD AND PERIPHERAL NERVES

A. The 'kesagiri' motion

We measured 'kesagiri', a sword swinging motion. The motion was selected because it is a typical coordinated whole body motion which requires motor learning. The snapshot of 'kesagiri' is shown in Fig. 3. The procedure is described utilizing the snapshot.

1) At initial state, the person is looking forward. His or her left foot is one step ahead of the right foot. The root of the sword is in front of the center of the body and the tip of the sword is between the legs. The sword is on the right side of the body (Fig. 3(a)).
2) The tip of the sword goes up from lower left to upper right of the body (Fig. 3(b)).
3) The sword rotates above the head of the person. The right leg steps forward while the left leg steps backward at the same time (Fig. 3(c)).
4) The person swings down the sword from upper right to lower left of the body (Fig. 3(d)).

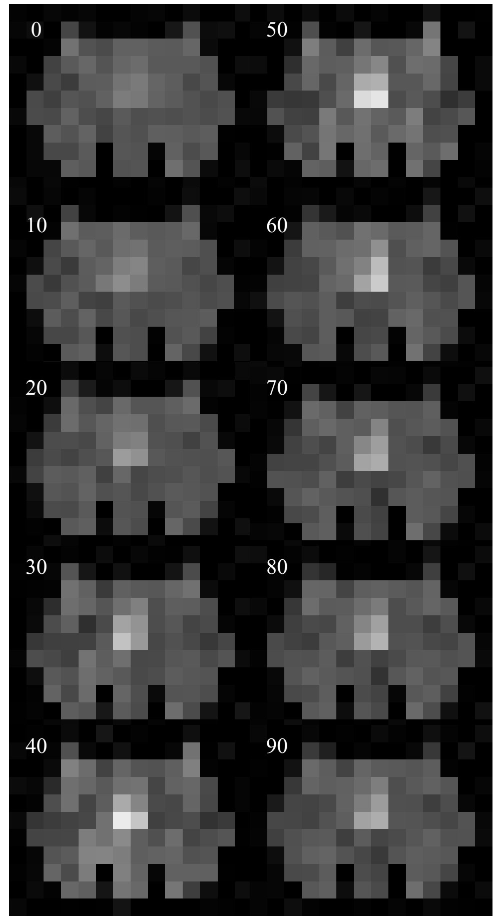

Fig. 4. Somatosensory image of spinal cord at C5 during 'kesagiri' motion for every 10 frames: The frame rate was 33 [msec/frame]. The lengths of the innervated muscles are encoded.

5) The trajectory of the tip of the sword should be straight and the speed of the sword should be maximum when crossing the center (Fig. 3(e)).
6) The movement of the sword should be stopped when the tip of the sword reaches the lower left of the body (Fig. 3(f)).

B. Computation of motor information through motion mesurement

The 'kesagiri' motion was measured utilizing the optical motion capture system. The positions of the markers distributed on the body were obtained. The frame rate was 33 [frame / sec]. The number of trials was 26. One of the trials was utilized for visualization, and two of the trials were selected for analysis. The positions and orientations of the bones, the angles of the joints, length and rate of changes in length of the muscles were calculated from the motion capture data. Inverse kinematics problem was solved utilizing musculoskeletal human model. The model contains 53 links and 366 muscles, whose degrees of freedom is 153. The forces of the muscles were obtained also utilizing musculoskeletal human model via inverse dynamics computation [11]. In this way, motor informa-

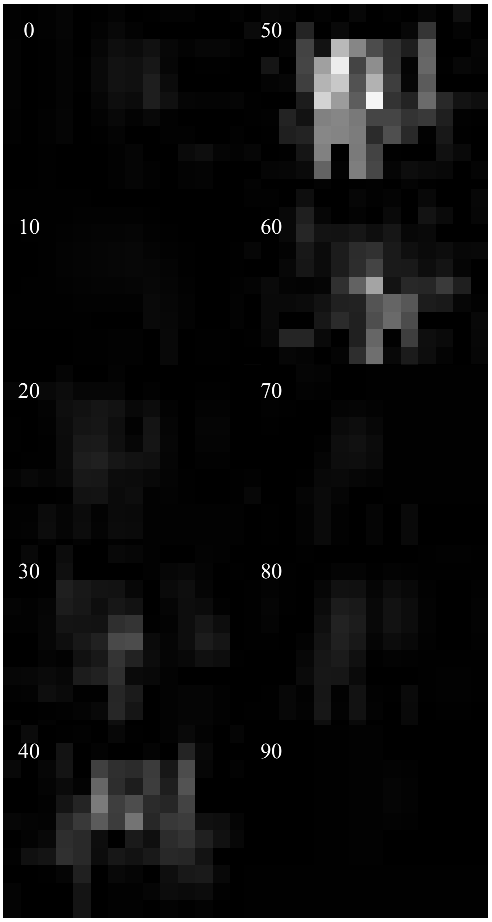

Fig. 5. Somatosensory image of spinal cord at C5 during 'kesagiri' motion for every 10 frames: The frame rate was 33 [msec/frame]. The stretching speeds of the innervated muscles are encoded.

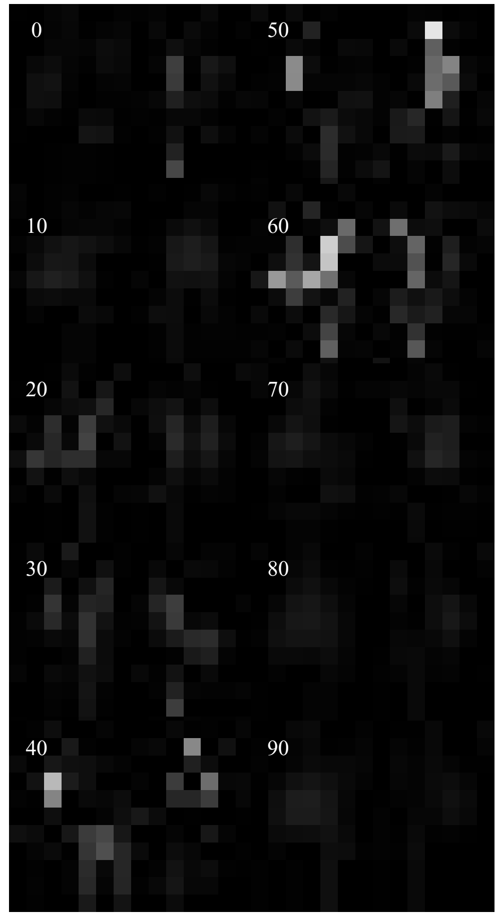

Fig. 6. Somatosensory image of spinal cord at C5 during 'kesagiri' motion for every 10 frames: The frame rate was 33 [msec/frame]. The forces of the innervated muscles are encoded.

tion, which should be obtained at mechano-receptors were calculated.

C. The images of spinal neural information during 'kesagiri' motion

The time series of images of the spinal neural information at C5 were mapped from the motor information utilizing the map shown in Fig. 2. The lengths of the muscles were normalized based on the length of the standing posture of the human. They were represented as intensities. Fig. 4 shows the spinal neural image at C5 which represents the length of the muscles innervated by the segment. C5 innervates the upper part of the body especially chest and upper arms. Both parts moves rapidly during 'kesagiri' motion. The left serratus anterior muscles were stretched when the tip of the sword goes up from lower left to upper right of the body (Fig. 3(b)). The area whose central coordinate is (-0.5, 0.5) was bright (Fig. 4: 40[frame]). The right serratus anterior muscles were stretched when the tip of the sword goes down from upper right to lower left of the body (Fig. 3(d)). The area whose central coordinate is (0.5, 0.5) was bright (Fig. 4: 60[frame]) in the same manner. The images of the rate of changes in length of the muscles (Fig. 5) and that of the force of muscles(Fig. 6) were obtained as well.

IV. Correlation and Phase Difference Analysis of the Neural Information

A. Correlation and corresponding time analysis method

Correlation and corresponding period of a pair of patterns were calculated in order to compare the motions of different trials observed from the nervous system. Let the spatiotemporal patterns of the first trial as source data, while those of the following trial as the target data. Computational procedure is as follows:

1) Take a template $x(i)$ from the source data of arbitrary period from time i to $i+N$. The partial target data of arbitrary period from time j to $j+N$ are taken as $y(j)$. The lengths of the source and target data are i_{end} and j_{end}, respectively.
2) Correlation of the $x(i)$ and $y(j)$ are calculated.

$$f(x(i), y(j)) = \frac{x(i) \cdot y(j)}{|x(i)||y(j)|}$$

The maximum value of $f(x(i), y(j))$ among every $y(j)$ ($0 < j < j_{end} - N$) and the corresponding time j_{max} were stored for each template $x(i)$.

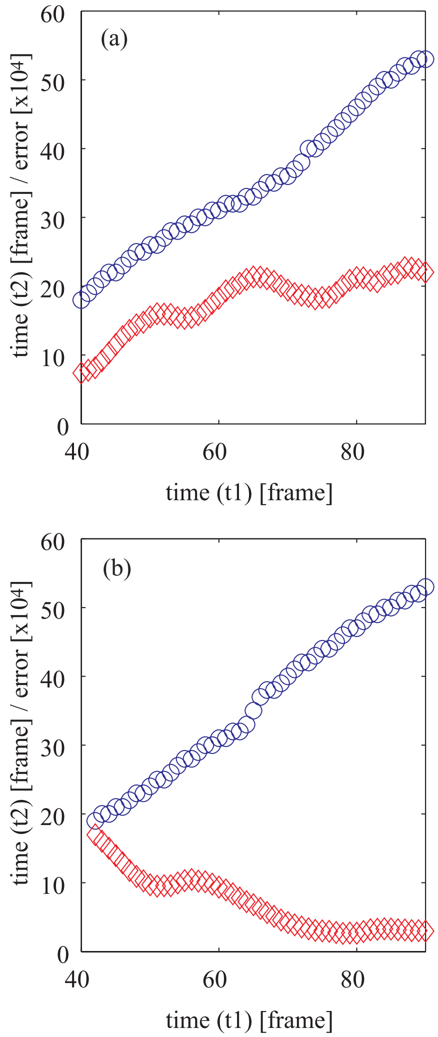

Fig. 7. Corresponding time and correlation between the neural information of (a) the fifth cervical nerve (C5) and (b) the second lumbar nerve (L2) during the two different trials for the 'kesagiri' motion. Corresponding times are plotted by blue circles and correlations are plotted by read rhombuses.

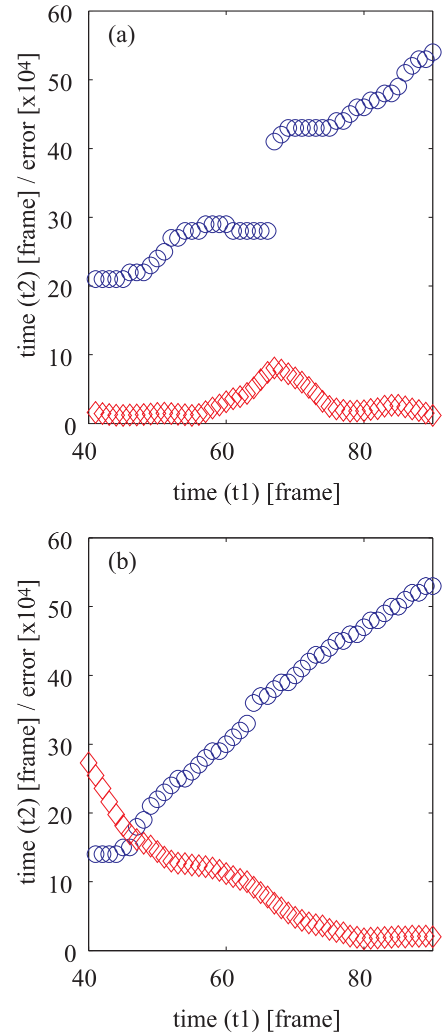

Fig. 8. Corresponding time and correlation between the neural information of (a) musculocutaneous nerve and (b) the obturatorius nerve during the two differnt trials for the 'kesagiri' motion. Corresponding times are plotted by blue circles and correlations are plotted by read rhombuses.

3) Maximum correlations $f(x(i), y(j_{max}))$ for each template $x(i)$ are obtained by substituting 0 through $i_{end} - N$ into i.

With this method, we can compare the differences of each neural pattern and corresponding time. In this study, the size of the template N was 9. Results were plotted in the following manner:

1) Draw a horizontal axis for the time of source data, and a vertical axis for plotting the corresponding time of target data and their differences. Variation $1 - f(x, y)$ was plotted since the correlation $f(x, y)$ was nearly equals to 1. Note that maximum value of correlation is 1 and its minimum is -1.
2) Make lines between the corresponding times of horizontal axis drawn in parallel: top axis for the time of source data and a bottom axis for the time of target data. The purpose of this time chart is to make clear the phase difference of each trial in the same segments.
3) Draw horizontal axes in parallel: top axis is for the time of target data of one segment, and bottom axis is for the one of another segment. In this way, relative phase differences between segments are obtained.

B. Correlation and phase difference between different segments of the spinal cord and peripheral nerves

Fig. 7 and Fig. 8 show the corresponding period and their correlations between the two of the repetitive trials for the 'kesagiri' motion. Fig. 7 shows corresponding time and correlation between the neural information of the fifth cervical segment (C5) and the second lumbar segment (L2). Fig. 8 shows that of the musculocutaneous nerve and the obturatorius nerve, for comparison. Corresponding times of the different trials in the same segment were continuous compared to those in the peripheral nerves.

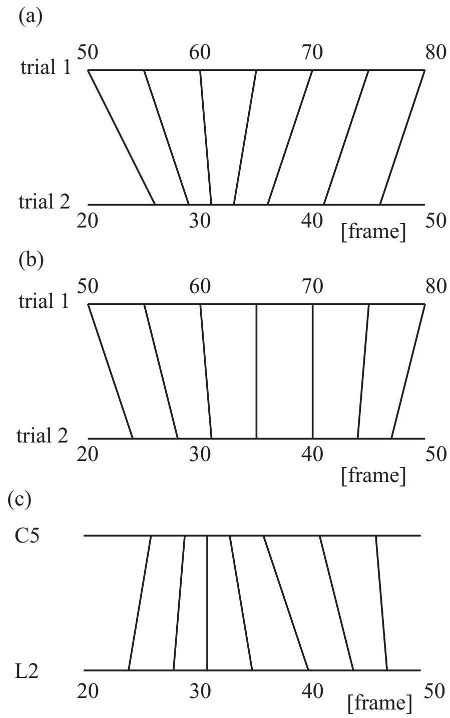

Fig. 9. Temporal diagram of the neural information of (a) the fifth cervical nerve (C5) and (b) the second lumbar nerve (L2) during the two trials for the 'kesagiri' motion. Phase difference between the neural information at C5 and L2 is plotted in (c).

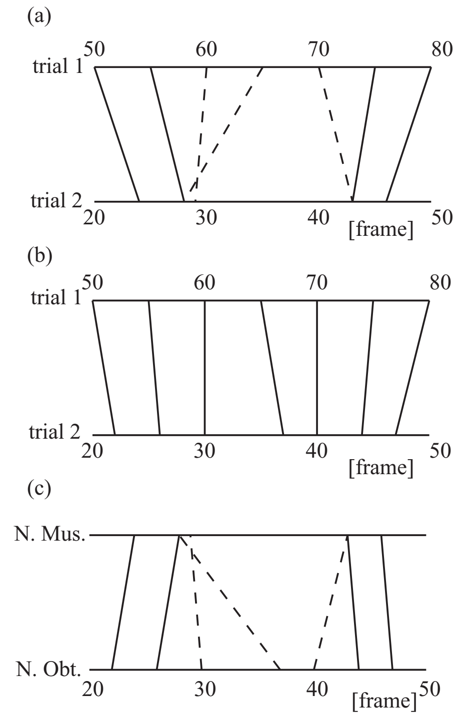

Fig. 10. Temporal diagram of the neural information of (a) musculocutaneous nerve and (b) the obturatorius nerve during the two trials for the 'kesagiri' motion. Phase difference between the neural information at musculocutaneous nerve(Mus) and the obturatorius nerve(Obt) is plotted in (c).

Variations of each trial were very small, whose order was 10^{-4}. For instance, the slope of the corresponding time plot for the second lumbar segment was smaller than 1. It exceeded 1 when the time of the first trial was 65[frame], which became below 1 again after 70[frame] (Fig. 3 (b)). This means that it took longer to reach the same posture in trial 1 than that in trial 2 in the beginning. Then, the speed of the trial 1 became faster around 65[frame], and became slower after 70[frame]. Corresponding time of the musculocutaneous nerve was discontinuous around 70[frame], and its gradient was almost 0 before and after the gap. Time chart of corresponding times are shown in Fig. 9 and 10, in order to visualize the difference of speeds. Fig. 9 demonstrates the time chart of neural information of the fifth cervical segment (C5) and the second lumbar segment (L2). Those of the musculocutaneous nerve and the obturatorius nerve are shown in Fig. 10. The periods for reaching the same posture are illustrated. At the fifth cervical segment, the trial 2 was faster around 25[frame] to 35[frame]. The speed of trial 2 was the same between 35[frame] to 45[frame]. In contrast, corresponding periods of musculocutaneous nerve and obturatorius nerve were unclear.

From these results, we can see that the neural patterns are similar in different trials, and their speeds are different at spinal cord level, while they are not synchronized at peripheral nerves. This result is reasonable since there are synaptic pathways organized by sensory neurons, motor neurons and interneurons in the same spinal cord segment[16]. During repetative trials of coordinated movoments, the speeds and timings of the group of muscules innervated by the same segment were altered coorporatively, while intersegmental phase differences were altered. The results indicates the brain strategy for motor skill enhancement.

V. Discussion

This paper proposes a new method for analyzing human whole body motions in spinal space instead of muscle or joint space. The structure of the spinal cord is utilized for segmentation of the muscular motion data. Our method aims to recognize the neural information through motion measurement. The benefit of this method is that it analyzes the local regulation and global coordination of movements simultaneously, considering the anatomical structure of the human body. We do not identify the physiological parameters of the spinal cord in this paper. Rather, we make use of the anatomical structure of the spinal cord for data analysis. The authors focus on the fact that the nervous system integrates the efferent and afferent information and recognizes the absolute length and generating force of the muscles. We use the structure of the spinal cord as frame for data analysis. Therefore, the active regulation of sensitivity is not dealt with in this paper. In order to identify these functions, combination of a centralpattern generator (CPG) and reflexes in the spinal cord should be considered. Study on functional neural circuit for walking through analyzing motion with musculoskeletal model[17], [18] and adaptive walking pattern generations via neural system models in simulations[19], [20], [21] and real robots [22], [23], [24] would serve as useful references.

VI. Conclusion

The conclusions of this paper are summarized as follows:

1) The procedure for generating map of each segments of the spinal cord was proposed. Somatotopic organization which is observed at ventral horn of the spinal cord was utilized for mapping. The neural information represents the spatial distribution of motor information of the muscles innervated by the arbitrary segment. The motor information is calculated through mapping the motion capture data of humans to the musculoskeletal human model. The spinal neural information is mapped from the motor information by applying the rules for somatotopic organization.
2) The effectiveness of the method was shown by the experimental results. The experiment was conducted and the time series of images of the spinal neural information were obtained successfully via motion measurement. The sword swinging 'kesagiri' motion was measured. These images were on the same segment of the spinal cord C5.
3) The analysis method was proposed which calculates correlation and phase contrast of the neural information. Corresponding periods were obtained by local correlations for each pattern of the different trials. As a result, phase contrasts were obtained. Results of the analysis indicated that intersegmental regulation occurs through repetative trials of coordinated movoments.

The result of this study is the first step towards behavior based neural-machine interface which visualizes and analyzes neural activities through motion measurement and computation. Musculoskeletal and nervous systems model converts motion capture data into neural information. Spinal nervous system model serves as interface between brain and whole body muscles. The method is to be included into the motor learning support system comprising motion capture system, musculo-skeletal model and nervous system model. With such a system, we can record the neural information and objective data such as the speed and straightness of the sword swinging. The learner will be benefited by comparing the subjective data and internal perspective of self motion in the nervous system. Future work includes modeling of neurons, sensory and motor cells and regulation mechanisms among them. Motion measurement is the traditional method, however, this will be the powerful way for the measurement of neural activities during motor learning, which is different from the direct measurement of the neural signals or brain imaging method.

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