Abstract—In order to discriminate multiple sources in somatosensory area of human cortex, we measured SEF (somatosensory evoked field) elicited by electrical stimulation to three different fingers (the thumb, fourth finger, and little finger), respectively. First, we applied singular value decomposition (SVD) method to the measured SEF data to discriminate second somatosensory (SII) activity from primary somatosensory (SI) activity overlapping in time. Time-frequency analysis (wavelet transforms, WT) was also applied to the calculated SEF data to examine frequency component of the SEF data. It was shown that the SI activity of the measured SEF data was represented with reconstructed SEF data with first singular value. And the SII activity was detected by the reconstructed SEF data with the fourth and fifth singular value in the thumb and fourth finger stimulation, respectively. Second, in the result of time-frequency analysis, distribution of dominant power spectrum of the SEF to the thumb (median nerve) stimulation was different to that of the little finger (ulna nerve) stimulation (thumb: 16-18Hz, little finger: 13-15Hz). In the result of fourth finger stimulation, the frequency of dominant power spectrum existed between that of the thumb and little finger stimulation. Source localization was done by the SEF data to the fourth finger stimulation, having different frequency ranges (13-15Hz and 16-18Hz band-pass filter). We conclude that the proposed method, combining the SVD method and the time-frequency analysis, is useful for discriminating multiple source activities of the somatosensory area overlapping in time.

I. INTRODUCTION

Magnetically somatosensory evoked responses are important for functional research on somatosensory areas of human cortex. The somatosensory evoked field (SEF) measured on the scalp reflects the activity of the primary somatosensory cortex (SI) [1],[2]. Secondary somatosensory (SII) activity is overlapped in time with the SI activity [3]. Median nerve and ulna nerve are also activated in fourth finger (ring finger) overlapping in time by electric stimulation [4]. There are only a few reports for discriminating multiple sources of SEF to the fourth finger stimulation generated by two nerve activities. Many methods were developed to discriminating multiple sources overlapping both in space and time [5],[6]. Only a few methods focused on the frequency component for discriminating multiple sources were suggested [7].

The aim of this study is to discriminate and estimate multiple sources in the human somatosensory cortex using singular value decomposition (SVD) and time-frequency analysis (wavelet transforms) of SEF to different finger stimulation (thumb, fourth, and little finger). We analyzed the frequency component of these SEF data following the stimulation of three different human fingers and discriminated multiple sources of the SEF to the fourth finger stimulation.

II. METHOD

A. Singular value decomposition (SVD)

The measured data are stored in a $[k \times m]$ matrix $B$ that contains $k$ channels with $m$ time samples each. The SVD of $B$ yields [8]

$$B = U \Omega V^T \quad (1)$$

each column of $U$ $[k \times n]$ corresponds to a magnetic field pattern and each row of $V^T$ $[k \times m]$ corresponds to temporal behavior of eigenvector. The number of sources is based on the number of dominant singular values [6],[7]. Thus, the Equation (1) is modified to the following

$$B_S = U_S \Omega_S V_S \quad (2)$$

$B_S$ is a $[k \times m]$ matrix of the signal subspaces obtained by SVD. $U_S$, $\Omega_S$, and $V_S$ are $[k \times s]$, $[s \times s]$ and $[s \times m]$, respectively ($s$ is the number of signal sources).

Score proportion is the rate of $n$-th singular value in the sum of singular values. Score proportion ($s_j$) is defined as
duration with 3 to 6mA. Inter-stimulus interval (ISI) was 2000±100ms. Digital filtering was performed with 1-80Hz BPF and notch filter. Sampled SEF data was averaged with 150 times. And the SVD and time-frequency analysis (wavelet transform) were applied to each SEF data.

III. RESULTS

Fig.2 shows examples of measured SEF waveforms and the results of SVD method to each SEF data (sub. A). Upper panels in Fig.2 show the superimposed waveforms obtained by all measurement point (48 positions) in each SEF data. Early responses around 20ms are observed in all SEF data. And deflections of middle latency are observed at around 60ms and 110ms in the SEF data. These results are well matched to previous study [4]. Lower panels in Fig.2 show all score proportions of the singular values calculated by equation (3). Singular value of the SEF data with thumb stimulation (Fig.2 (a)) shows significantly decreasing at the third value. On the other hand, decreasing of the singular value to the little finger stimulation (Fig.2 (b)) appears sharply decreasing at the second values. And that of fourth finger stimulation (Fig.2 (c)) is similar to the thumb stimulation.

IV. DISCUSSION

A. Discrimination of SII activity from SI activity

Because activities of various somatosensory areas overlap in time, their identification with electroencephalogram (EEG) is difficult. Actually, it is difficult to differentiate activities in close cortical areas by measuring EEG. Locations of several simultaneous activities in somatosensory areas can be more easily defined by using MEG measurement [11]. In order to discriminate multiple activities in human cortex, many algorithms for separating
multiple sources have been suggested using the principle component analysis (PCA) or with the SVD method [12]-[14]. Although there are some reports of separating the SI and SII activities, location of the SI activity evoked by somatic stimulation was apart from that of the SII activity in the cortex [3], [15].

In this study, we applied the electric stimulation to three different fingers to obtain the evoked field in the somatosensory area. The SVD method was applied to spatio-temporal SEF data and reconstruction of SEF data with each singular value was done. In order to investigate frequency component of the calculated SEF data, the WT analysis was also applied. Fig.3 to 5 show the result of the time-frequency analysis. Upper panels of those figures show the superimposed waveforms reconstructed by the first singular value (SV1). Temporal distributions of those waveforms are similar to the measured SEF waveforms (Fig.2 upper panels, correlation coefficient (\(\gamma\)) between measured SEF data and reconstructed SEF data with the first the SV1: the thumb: 0.76±4.2, little finger: 0.85±5.6, and fourth finger: 0.80±4.7, \(\gamma\) was averaged by 48 measurement positions). And lower panels are the results of the WT

![Figure 3](image1.png)  
Fig.3 Results of time-frequency analysis to the reconstructed SEF waveform (the thumb, (a) to (d) are calculated by each first to fourth singular value, respectively).

![Figure 4](image2.png)  
Fig.4 Results of time-frequency analysis to the reconstructed SEF waveform (little finger, (a) to (d) are calculated by each first to fourth singular value respectively).
analysis to the reconstructed SEF waveforms with each first to fourth singular value, respectively. Fig.3 to 5 show an averaged in each calculated data and three colors (black, gray and white) in each figure show distribution of normalized power spectrum. Black is 0.67-1.0, gray is 0.33-0.67, and white is less than 0.33, respectively. Power spectrums of the SV1 (the calculated SEF data by first singular value) in Fig.3 to 5 were similar to those of measured SEF data. It showed different distribution of power spectrum from the SV2 in Fig3 to 5. The numerically significant singular values are related to the independent activities that significantly contribute to the signal. Previous report focused on these dominant singular values [5]. However, The SII activity is generally weaker than SI activity [3],[15]. To discriminate the SII activity from the SI activity, spatial distribution with each calculated data was examined. Fig. 6 shows typical results of spatial distribution of calculated SEF data to the thumb and fourth finger stimulation. A to H and 1 to 6 in Fig.6 are measurement points shown in Fig.1. Gray area (positive field) shows the outflow of magnetic flux from the scalp. The SV1 of the thumb and fourth finger (Fig.6 (a) and (c)) shows dipole pattern having the center at around E5 (the thumb) and D4 (fourth finger). These dipole patterns well matched with the measured SEF data. However, SV4 of the thumb (Fig.6 (b)) and SV5 of the fourth finger (Fig.6 (d)) show different dipole pattern. These location and latency ((b): 86ms, (d): 106ms) agree in general terms with the related findings in previous study about SII activity [3],[8]. Namely, SV4 in the thumb stimulation and SV5 in fourth finger stimulation represent the SII activity.

B. Discrimination of multiple sources in the somatosensory area

From the SV1 in Fig.3 to 5 (a), it was found that the distribution of power spectrum was different to each SEF data. Dominant power spectrum of the thumb stimulation appeared at 17Hz (Fig.3 (a)). And dominant power spectrum of the little finger stimulation also appeared at 13Hz (Fig.4 (a)). In the result of fourth finger stimulation, the dominant power spectrum (15Hz) existed between that of the thumb and little finger stimulation. These results showed that the SEF elicited by the median nerve (the thumb) stimulation

Fig.6 Examples of isofield contour map by the calculated SEF data with singular values (latency: (a): 53ms, (b): 86 ms, (c): 58ms, and (d): 106ms).
had different power spectrum compared with the SEF by the ulna nerve (little finger)[4]. Table 1 summarized typical results of coherence between all the set of SEF data with different finger stimulus [16]. Spatial distribution of each SEF data was also examined. To compare the spatial distribution of different frequency ranges, band-pass filtering (13-15Hz and 16-18Hz) was used by the SEF data of the fourth finger stimulation. Source estimation was done with each SEF data to different finger stimulation and the two band-pass filtering data of the fourth finger. Single source estimation was done by moving the dipole inverse solution with a spherical homogeneous conductor model (93 mm radius obtained from MR images) as a human head [17]. Source parameters such as amplitude and orientation were varied, and the minimum cost function was obtained by iterative calculation.

Table 2 and Fig.7 show results of source estimation and isofield contour maps of the SEF data to fourth finger stimulation. Table 2 shows the result of source estimation of each SEF data and two filtering data of fourth finger. The latency (58ms) for the source estimation showed the peak of the SEF waveforms. In the result of each SEF data, goodness-of-fit (GOF) between measured SEF data and calculated SEF data was greater than 80%. And correlation coefficient between the measured SEF data and the calculated data also showed above 0.8. Depth of the signal source from human scalp was 2.9 to 3.3 cm. Amplitude of calculated data also showed above 0.8. Depth of the signal coefficient between the measured SEF data and the goodness-of-fit (GOF) between measured SEF data and latency (58ms) for the source estimation showed the peak of stimulation. Table 2 shows the result of source estimation of isofield contour maps of the SEF data to forth finger iterative calculation.

Table 1. Typical results of coherence between all the set of SEF data with different finger stimulus (Br component, * significance of difference is P < 0.05).

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between thumb and little finger</td>
<td>0.22±0.06</td>
<td>0.30±0.04</td>
<td>0.18±0.02</td>
<td>0.33±0.03</td>
<td>0.27±0.04</td>
</tr>
<tr>
<td>Between thumb and forth finger</td>
<td>0.28±0.09</td>
<td>0.41±0.06</td>
<td>0.37±0.05</td>
<td>0.28±0.04</td>
<td>0.40±0.02</td>
</tr>
<tr>
<td>Between little and forth finger</td>
<td>0.37±0.03</td>
<td>0.40±0.03</td>
<td>0.33±0.06</td>
<td>0.71±0.05*</td>
<td>0.63±0.05*</td>
</tr>
<tr>
<td>Between thumb and little finger</td>
<td>0.05±0.02</td>
<td>0.08±0.03</td>
<td>0.03±0.01</td>
<td>0.05±0.01</td>
<td>0.04±0.02</td>
</tr>
<tr>
<td>Between thumb and forth finger</td>
<td>0.35±0.07</td>
<td>0.17±0.04</td>
<td>0.55±0.06*</td>
<td>0.61±0.06*</td>
<td>0.22±0.03</td>
</tr>
<tr>
<td>Between little and forth finger</td>
<td>0.28±0.04</td>
<td>0.42±0.02*</td>
<td>0.18±0.03</td>
<td>0.10±0.02</td>
<td>0.04±0.02</td>
</tr>
</tbody>
</table>

Fig.7 Examples of isofield contour maps with the SEF data of fourth finger and MR image of a subject’s head showing the superimposed source localization (Br component, latency: 58ms, gray triangle in (c) and (f): the thumb (1-80Hz BPF), white circle in (e) to (h): fourth finger (1-80Hz BPF), gray triangle in (g) and (h): little finger (1-80Hz BPF), black square of (c) and (f): fourth finger (16-18Hz BPF), and black square of (g) and (h): fourth finger (13-15Hz BPF)).
From the Fig.7 (d) and Table 2, the source of thumb was located in around D5 and E5 (GOF: 86.3%, open circle in Fig.7 (d)). The source location of little finger was in around D4 (GOF: 85.6%, open square). The signal source of the little finger is separating 2.32 cm from the signal source of the thumb. Fig.7 (e) to (h) were MR images of a subject’s head showing the superimposed source localization. These locations of three different fingers agree in general terms with the related findings in previous study [4]. The location of fourth finger with 13-15Hz BPF was located in around D4 (GOF: 87.5%, white diamond). And the location of 16-18Hz BPF was in around D4 and D5 (GOF: 85.9%, black diamond). The source locations of the 13-15 Hz and 16-18Hz BPF were similar to the results of the little finger and the thumb, respectively. These results showed that the SEF data to the fourth finger stimulus had two frequency ranges caused by activation of median nerve (thumb, 16-18Hz) and ulna nerve (little finger, 13-15Hz), respectively.

V. CONCLUSION

A SEF measurement with stimulus to three different fingers (thumb, fourth finger, and little finger) was carried out. The proposed method, combining the SVD method and the time-frequency analysis, was applied to each SEF data. It is concluded that the proposed method was useful for discriminating multiple source activities of the somatosensory area overlapping in time such as shown in this study of the SEF elicited by two different nerve activities in fourth finger stimulation and separating SII activity from SI activity.

REFERENCES


[8] B. S. Kim, K. Kobayashi, Y. Uchikawa, “Separation of overlapping activity in first and second somatosensory evoked fields with 3-D Source Location Table 2 Results of source estimation with each data (latency: 58ms, symbols corresponding to the Fig.7 (d), depth is distance from the scalp).

<table>
<thead>
<tr>
<th>Source</th>
<th>GOF [%]</th>
<th>Depth [cm]</th>
<th>Amplitude [nAm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thumb (◇)</td>
<td>86.3</td>
<td>3.1</td>
<td>14.1</td>
</tr>
<tr>
<td>Little finger (△)</td>
<td>85.6</td>
<td>2.9</td>
<td>9.4</td>
</tr>
<tr>
<td>Fourth finger (□)</td>
<td>87.2</td>
<td>3.2</td>
<td>12.9</td>
</tr>
<tr>
<td>Fourth finger* (◇)</td>
<td>85.9</td>
<td>3.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Fourth finger** (◆)</td>
<td>85.9</td>
<td>3.3</td>
<td>3.7</td>
</tr>
</tbody>
</table>

*13-15Hz BPF, **16-18Hz BPF