Modification of Distinction Method of Abnormality for Surgical Operation on the Basis of Surface EMG Signals

Chiharu Ishii and Takanori Sato

***Abstract*—We have proposed a method for automatic identification of a surgical operation and on-line recognition of the singularity of the identified surgical operation based on operator's surface electromyogram, so far [5]. In this paper, the method for on-line recognition of the singularity of the surgical operation is improved. Using the built laparoscopic-surgery simulator with two forceps, the automatic identification of a surgical operation for procedure of "suturing" and the distinction of the singularity for the identified surgical operation, namely "insertion of a needle" in suturing, were carried out. Experimental results showed the effectiveness of the improvement.**

***Index Terms*—Surface EMG, distinction of singularity in operation, self-organizing map, surgical operation.**

I. Introduction

In the robot supported surgery, master-slave system is employed. In such master-slave systems, usually motions of the master device are detected by sensors, and the slave device is controlled to follow the behavior of the master device based on the measured information by those sensors. Therefore, even a mistaken operation will be reflected. To perform a robotic surgery, a surgeon must have considerable skill. Operation by an unskilled surgeon may result in serious malpractice. Therefore, development of a system which urges an appropriate operation to the unskilled surgeon is in demand.

Most recently, in order to help surgeon's dexterity, force feedback to a surgeon through the master device of a surgical robot has been studied in [1]. In order to perform safe surgery, safe operation strategies, called "Safety operation space" and "Variable compliance system" for the surgical robot, were proposed in [2]. The former can prevent collision between the forceps and organs. The latter can reduce the collision force between the forceps and organs. In addition, training systems to practice operation of a surgical robot through a virtual reality environment (e.g. [3]), and navigation systems which guide a surgical instrument to the targeted location in the robotic surgery (e.g. [4]), have been studied. To the best of our knowledge, however, a system that recognizes and points out any singularity in a surgical operation, which is defined as abnormal operation usually caused by the inexpertness of an unskilled surgeon, has not been established yet.

In this study, to detect any singularity in a surgical operation, surface electromyography (SEMG) is employed. Our final goal is to develop such a system that recognizes and points out any singularity in a surgical operation to surgeons during the operation of the surgical robot. To this end, we have proposed a novel method for automatic identification of a surgical operation and on-line distinction of any singularity of the identified surgical operation on the basis of the SEMG measurements of an operator and movement of the forceps, so far[5].

Use of the SEMG has attracted an attention of researchers as a method of interaction between human and machines. The amplitude property of waveform and the power spectrum based on frequency analysis are typical information which can be extracted from the SEMG signal. In [6], to control a thumb and index finger of a myoelectric prosthetic hand independently, identification of six kinds of finger motion was executed using neural networks on the basis of the SEMG measurements. In such SEMG based interaction systems, hand gestures are identified by measuring the activities of the musculature system using the SEMG sensors. It is well known that by measuring SEMG signals, not only hand gestures but also distinction between skilled person and unskilled person, and fatigue of the muscle can be recognized (e.g. [7]).

In [8], recognition of 25 kinds of hand gestures consisting of various motions of wrist and fingers, was performed using only two electrodes, and high recognition accuracy was successfully obtained. In [9], an identification method for a hand gesture and a distinction method of any singularity of the identified hand gesture on the basis of the SEMG measurements, were proposed. On the other hand, as for the surgical operation, an automatic classification method of four basic surgical operations using a sensing forceps made of a forceps and strain gauges, was proposed in [10]. In [11], it is reported that in surgical operations, a difference arises between skilled surgeon and unskilled surgeon in the following points; the magnitude and direction of the handling force of the object, the manner of having surgical instrument, and surgeon's posture.

In this paper, the method for on-line distinction of the singularity of surgical operation proposed in [5] is improved so as to raise recognition accuracy for each state of singularity. Using the built simulation box for laparoscopic-surgery with two forceps, the automatic identification of a surgical operation for procedure of "suturing" and the distinction of the singularity for the identified surgical operation, namely "insertion of a needle" in suturing, were carried out. Experimental results showed the effectiveness of the improvement.

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Chiharu Ishii is with the Department of Mechanical Engineering, Hosei University, Tokyo 184 -8584, Japan (e-mail: c-ishii@hosei.ac.jp).

Takanori Sato is with the Master's Course, Major in Mechanical Engineering, Graduate School of Engineering, Hosei University, Tokyo 184 -8584, Japan (e-mail: takanori.sato.5t@stu.hosei.ac.jp).

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II. Experimental System

A. Simulation Box

Simulation box for laparoscopic surgery is shown in Fig. 1. Inside of the mannequin, a rubber sheet of 1mm thickness is installed. An operator performs surgical operation using the two forceps, a needle driver (right hand side) and assistant needle driver (left hand side) which are inserted into inside of the mannequin through the trocar. As shown in Fig. 2, the movement of the needle driver is measured by the haptics device PHANTOM Omni and attached four strain gauges.

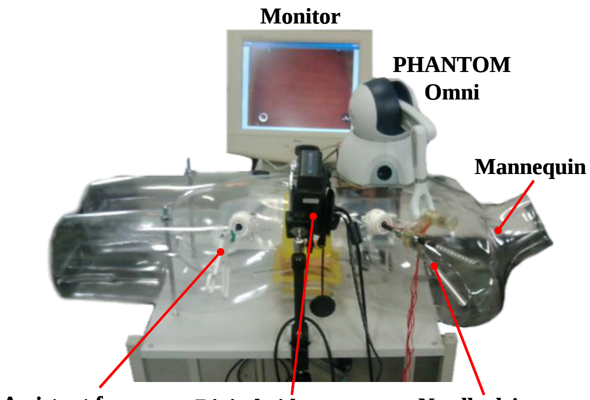

Fig. 1. Simulation box.

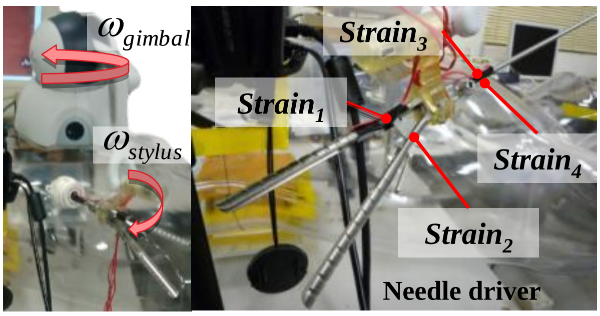

Fig. 2. Sensor allocation for needle driver.

B. Measurement of SEMG

The SEMG signals are measured by three electrodes stuck on the forearm of the operator as shown in Fig. 3.

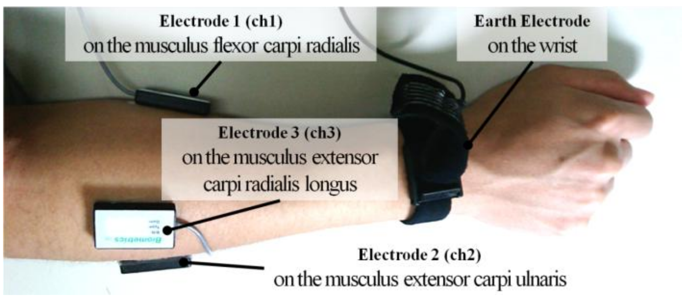

Fig. 3. Attachment position of surface electrode.

III. Distinction of Singularity of Surgical Operation

In this study, suturing is chosen as the objective surgical operation for automatic identification, and especially "insertion of a needle" in suturing is selected as the objective surgical operation for distinction of the singularity. Procedure of suturing is divided into six operations. First, the features of the operation are extracted from the measurements of the movement of the forceps, and then, on the basis of the threshold criteria for the six operations, a surgical operation is identified as one of the six operations. Next, the features of any singularity of operation are extracted from operator's SEMG signals, and the identified surgical operation is classified as either normal or singular using a self-organizing map (SOM) [12].

A. Features for Identification of Surgical Operation

For identification of a surgical operation, features of the operation are extracted from the measurements of movement of the needle driver. From measurements of the amount of distortion by four strain gauges and the angular velocity of a gimbal and a stylus by the haptic device, features are defined as follows.

$$St_{ch} = \frac{1}{N}\sum_{n=1}^{N} strain_{ch(n)} \tag{1}$$

$$\Omega_{gimbal} = \frac{1}{N}\sum_{n=1}^{N} \omega_{gimbal(n)} \tag{2}$$

$$\Omega_{stylus} = \frac{1}{N}\sum_{n=1}^{N} \omega_{stylusl(n)} \tag{3}$$

where $strain_{ch(n)}$ (ch=1, 2…4) is measured value from each strain gauge, $\omega_{gimbal(n)}$ and $\omega_{stylus(n)}$ are measured angular velocity from the haptic device, and n represents the number of sampled signals.

B. Features for Distinction of Singularity of Surgical Operation

Features of any singularity of operation are extracted from operator's SEMG signals measured by three electrodes. The SEMG signals are measured by sampling frequency Fs=2 kHz, and Fast Fourier Transform (FFT) is performed to each SEMG signal for every N=512 sampled data. Features are defined as follows.

Mean absolute value: In order to perform pattern recognition, a mean absolute value of SEMG signal is often used, which is given as follows.

$$MAV_{ch} = \frac{1}{N}\sum_{n=1}^{N} \left|EMG_{ch(n)}\right| \tag{4}$$

where $EMG_{ch(n)}$ (ch=1, 2, 3) is the SEMG signal of each electrode, and n represents the number of sampled signals.

Center-of-gravity: In the case where the singular operation is performed, it is expected that change of a waveform can be observed in the SEMG signal. Therefore, as a value representing change of the waveform of the SEMG signal, a value of center-of-gravity is employed, which is defined as follows.

$$cog_{ch} = \sum_{n=1}^{N}\left(n\cdot\left|EMG_{ch(n)}\right|\right) \Big/ \sum_{n=1}^{N}\left|EMG_{ch(n)}\right| \tag{5}$$

Spectrum ratio: Also, in the case where the singular operation is performed, it is expected that change of a distribution of the power spectrum can be observed in the SEMG signal. Therefore, ratio of distribution of the power spectrum of the SEMG signal is also employed.

It is well known that the SEMG signal is distributed in the frequency bands between 5 Hz to 500 Hz. Therefore, to see the ratio of the spectrum, frequency bands are divided into 5 to 250 Hz and 250 to 500 Hz. Thus, a value of spectrum ratio is defined as follows.

$$Fr_{ch} = Fh_{ch} / Fl_{ch} \tag{6}$$

where

$$\begin{cases} Fl_{ch} = \sum_{kf=2}^{N/8} \left| F_{ch(kf)} \right|^2 & 5 \sim 250Hz \\ Fh_{ch} = \sum_{kf=N/8+1}^{N/4} \left| F_{ch(kf)} \right|^2 & 250 \sim 500Hz \end{cases} \tag{7}$$

and $|F_{ch(kf)}|$ is a spectrum value in frequency kf obtained by Fast Fourier Transform (FFT).

C. Automatic Identification of Surgical Operation

Procedure of the suturing is divided into six operations as shown in Fig. 4.

1) Grasping: the grasping state by closing the gripper of the needle driver.
2) Touch: the state where the needle driver touches the objects.
3) Haulage: the state where the needle driver touches the object with grasping the needle disposable.
4) Insertion: the state where the needle disposable is inserted.
5) Extraction: the state where the needle disposable is extracted.
6) Neutral: the state where nothing is operating.

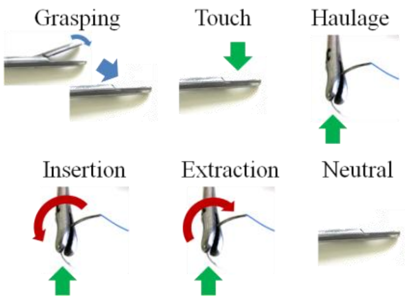

Fig. 4. Surgical operations for suturing.

In addition, to identify the state of operation of the needle driver using a threshold value, the following new features are defined using the features (1) to (3).

$$V_1 = St_1 \cdot St_2 \tag{8}$$

$$V_2 = \sqrt{St_3^2 + St_4^2} \tag{9}$$

$$V_3 = \Omega_{gimbal} \cdot \Omega_{stylus} \tag{10}$$

In order to identify the surgical operation, the following values are defined.

$$T_i = \begin{cases} 1 & V_i > TH_i \\ 0 & else \end{cases}, \ (i=1,2) \tag{11}$$

$$T_3 = \begin{cases} 1 & (CW) & V_3 > TH_{3H} \\ -1 & (CCW) & V_3 < TH_{3L} \\ 0 & & else \end{cases} \tag{12}$$

where TH_i (i=1, 2, 3H, 3L) is a threshold value for each new feature which is determined through trial and error. On the basis of the threshold criteria for the six operations, a surgical operation is identified as one of the six operations as shown in Table I.

TABLE I: LOGICAL DEFINITION FOR OPERATION OF NEEDLE DRIVER

Discriminant value /Operation	T_1	T_2	T_3
1.Grasping	1	0	0
2.Touch	0	1	0
3.Haulage	1	1	0
4.Insertion	1	1	1(CW)
5.Extraction	1	1	-1(CCW)
6.Neutral	Else		

D. Distinction of Singularity of Surgical Operation

In this study, a normal operation and a singular operation are defined as follows.

1) Normal operation: a surgical operation performed in normal manner.
2) Singular operation: a surgical operation which is assumed to be performed in the following abnormal manner.
   - Posture: a operation performed at a posture in which the operator's elbow is raised.
   - Straining: a operation performed in the state in which the operator is straining.
   - Sudden: a rough operation performed suddenly by the operator.

These are illustrated in Fig. 5. The surgical operation "insertion of a needle" in suturing is classified as either normal or singular by using a self-organizing map (SOM)[5].

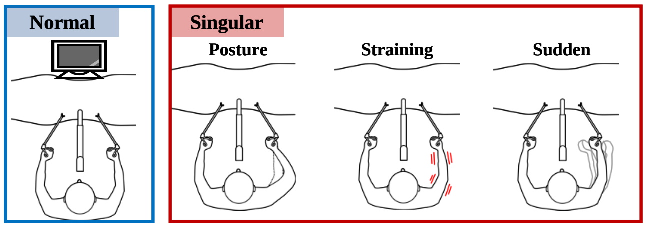

Fig. 5. Experimental situations for surgical operation.

IV. EXPERIMENTS AND RESULTS

Two early twenty years old novice for surgical operation were chosen as operators for automatic identification of the surgical operation, and for distinction of the singularity of the surgical operation, one more early twenty years old novice for surgical operation was added as an operator.

A. Method of Experiments

In the experiment, the operators repeatedly performed the suturing process 1) to 6), under the four situations a)Normal, b-1)Posture, b-2)Straining and b-3)Sudden. The surgical operation "suturing" performed in the experiment is shown in Fig.6. Then, recognition rate of the automatic identification for each surgical operation in "suturing" and recognition rate of the singularity distinction for the identified surgical operation "insertion" were examined.

B. Result for Automatic Identification

Recognition rate of automatic identification for the surgical operation "suturing" is shown in Table II.

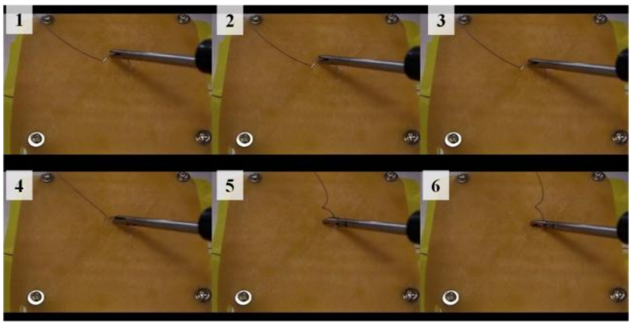

Fig. 6. Suturing performed in experiments.

TABLE II: RECOGNITION RATE FOR AUTOMATIC IDENTIFICATION

Operation	Operator A	Operator B
1.Grasping	87.5%	100%
2.Touch	Non	96.7%
3.Haulage	80.0%	100%
4.Insertion	89.5%	96.7%
5.Extraction	84.2%	80.0%
6.Neutral	100%	Non

As shown in Table II, each surgical operation was able to be identified with more than 80% accuracy.

The threshold values TH_i (i=1, 2, 3H, 3L) which were determined through trial and error, are shown in Table III.

TABLE III: THRESHOLD VALUES

Threshold	TH_1	TH_2	TH_{3H}	TH_{3L}
Value	0.045	0.5×10^{-9}	0.25	0.2

C. Result for Singularity Distinction

In order to classify the singularity of the surgical operation "insertion", a SOM was constructed by batch learning using the feature vectors of any singularity of operation pre-extracted from the SEMG siganal in the case of insertion. In [5], in order to classify a surgical operation, the following 9-dimentional feature vector was employed.

$$Xs=\left(\frac{MAV_1}{\overline{MAV}},\frac{MAV_2}{\overline{MAV}},\frac{MAV_3}{\overline{MAV}},\frac{cog_2}{cog_1},\frac{cog_3}{cog_1},\frac{cog_3}{cog_2},Fr_1,Fr_2,Fr_3\right)^T \quad (13)$$

where $\overline{MAV}$ is an average of MAV_{ch} (ch=1,2,3). Then, the constructed SOM and distribution of the mapping of the feature vectors extracted on-line from SEMG siganal in the case of insertion, is shown in Fig.7. The domain of the SOM is roughly divided into two fields, which include the domain for the normal operation denoted as "Normal" and the domain for the singular operation denoted as "Singular." In addition, the domain for the singular operation is divided into three fields, namely, "Posture," "Straining," and "Sudden." Then, recognition rate for singularity distinction is shown in Table IV.

As shown in Table IV, the normal and the singular operation of "insertion" was able to be distinguished with 76.5% and 81.8% accuracy, respectively. However, the accuracy of recognition in the singularity (i.e., "Posture," "Straining," or "Sudden") is approximately 30%.

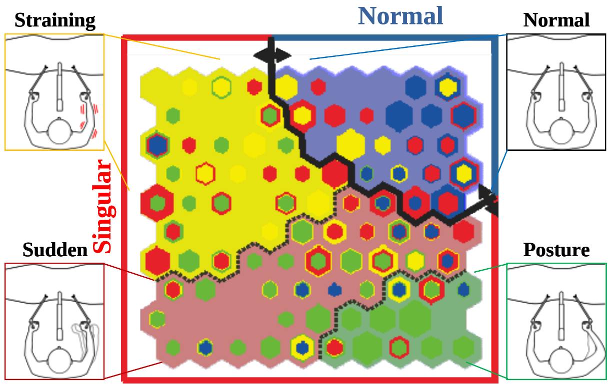

Fig. 7. Distribution of experimental operation on SOM.

TABLE IV: RECOGNITION RATE FOR SINGULARITY DISTINCTION (OPER. A)

	Recognition rate[%]	
Normal	76.5	(39/51)
Singular	81.8	(193/236)
Posture	30.8	(24/78)
Straining	33.3	(23/69)
Sudden	25.8	(23/89)

D. Modification of Feature Vector

As one of the reasons of this low recognition rate in the singularity distinction, the following cause is considered. In the states "Posture", "Straining" and "Sudden", the singular operation is similar, and the difference does not appear easily in the feature vector defined by equation (13). In order to examine efficiency of each feature, namely mean absolute value, center-of-gravity and spectrum ratio, singularity distinction was performed by the SOM using the 3-dimensional feature vector which consists of each feature only. Then, singularity recognition rate for each feature is shown in Table V.

TABLE V: SINGULARITY RECOGNITION RATE FOR EACH STATE

	Recognition rate[%]		
	Mean absolute value	Center-of -gravity	Spectrum ratio
Normal	76.5	7.84	37.3
Singular	80.9	85.2	84.7
Posture	35.9	24.4	59.0
Straining	42.0	39.1	24.6
Sudden	31.5	30.3	24.7

From Table V, it turns out that the mean absolute value contributes to distinction of normal operation compared with other two features, and conversely, the center-of-gravity and the spectrum ratio contribute to the whole singularity distinction compared with the mean absolute value. Based on the above results, to raise the singularity recognition rate in each state (Posture, Straining, and Sudden), singularity distinction was performed repeatedly by combining three kinds of features in the feature vector (Mean absolute value, Center-of-gravity, and Spectrum ratio) through trial and error. As a result, the best singularity recognition rate was obtained for the following 6-dimensional feature vector by removing the spectrum ratio.

$$Xs = \left(\frac{MAV_1}{MAV}, \frac{MAV_2}{MAV}, \frac{MAV_3}{MAV}, \frac{cog_2}{cog_1}, \frac{cog_3}{cog_1}, \frac{cog_3}{cog_2} \right)^T \quad (14)$$

Then, recognition rate for the singularity distinction using the feature vector given by (14) is shown in Table VI.

TABLE VI: MODIFIED RECOGNITION RATE FOR SINGULARITY DISTINCTION

	Recognition rate[%]					
	Operator A		Operator B		Operator C	
Normal	76.5	(39/51)	72.0	(36/50)	86.0	(43/50)
Singular	81.4	(192/236)	89.3	(134/150)	72.0	(108/150)
Posture	25.6	(20/78)	74.0	(37/50)	44.0	(22/50)
Straining	31.9	(22/69)	96.0	(48/50)	82.0	(41/50)
Sudden	25.8	(23/89)	56.0	(28/50)	32.0	(16/50)

From Table VI, for the operators B and C, the singularity recognition rate for "Posture" and "Straining" was improved.

V. CONCLUSION

In this paper, a novel method for on-line distinction of the singularity of the surgical operation proposed in [5] was improved. The dimension of the feature vector for the singularity distinction was reduced from 9 into 6 to raise the singularity recognition rate. Then, the distinction of singular or normal for the surgical operation "insertion" was able to be distinguished with approximately 80% accuracy on an average. On the other hand, recognition rate of each state in the singular operation was approximately 30% to 90% accuracy depending on the individual difference.

Still, it is difficult to distinguish three kinds of the states in the singular operation with sufficient accuracy. However, in a complicated surgical operation such as "insertion of a needle", it can be said that the general distinction of normal operation or singular operation was able to be recognized with high accuracy.

VI. FUTURE DIRECTIONS

In this study, operator for the experiments was only three persons. In order to demonstrate the reliability of the proposed method for automatic identification and singularity distinction, it is necessary to perform verification of the proposed method by many operators. However, since the SEMG signal highly depends on individuals, it is considered that training of the SOM for singularity distinction for every operator is required.

In addition, it is also necessary to extend the proposed identification and singularity distinction method for a surgical operation performed with not only a right hand but also both hands. As for this point, we are now applying the proposed identification method to a surgical operation "ligation" performed with both hands, and the singularity distinction method to a "thread knotting" also performed with both hands.

Furthermore, construction of a system for malpractice avoidance by presenting recognition of the singular operation to an operator so as to provide safe endoscopic-surgery is left as a future work.

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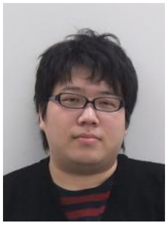
Chiharu Ishii received his PhD in Mechanical Engineering from Sophia University, Japan in 1997. From 2002 to 2009, he was an Assistant Professor with Kogakuin University. Currently, he is a Professor at the Department of Mechanical Engineering, Hosei University, Japan. His research interests are in medical robotics, assistive technology and robust control. He is a member of JSME, SICE, RSJ, IEEJ and IEEE.



Takanori Sato received his BE in Mechanical Engineering from Hosei University, Japan in 2011. Currently, he is a Master Course student at Graduate School of Engineering, Hosei University, Japan. His research interest is in medical robotics.