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Building multi-modal sensory feedback pathways for SRL with the aim of sensory enhancement via BCI *

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Abstract **- Recently, the Supernumerary Robotic Limbs (SRL) have emerged in the field of robotics for enhancing the user's ability without replacing natural limbs. Lots of researches have contributed to the mechanical design and control of SRL. However, building an artificial sensory nerve pathway of SRL has been largely ignored. In this paper, we built a multi-modal sensory feedback pathway for SRL. Three kinds of sensory pathway contained 1) fingertip pressure, 2) slippage and 3) proprioception information are built under the consideration of SRL platform through electrical stimulation. According to the experiment results of event-related potential (ERP) amplitude, establish the relationship between the physical parameters of the stimulus and the sensation. In addition, enhancement potentials of human sensation based on the brain-computer interface (BCI) is found in two aspects contained: 1) improvement of subjective perception resolution; 2) Shorten the time of sensory recognition. This paper can be used to objectively benchmark the human subjective and individualized sensation, and guide researchers to build the SRL sensory feedback pathways.**

Index Terms - SRL. Sensory feedback. ERP. Sensory enhancement. BCI.

I. INTRODUCTION

A kind of biomechatronics robot called Supernumerary Robotic Limbs (SRL) has emerged in the field of robotics in recent years. SRL, as a wearable robot, adds an extra mechanical limb for users to compensate or enhance human's ability without replacing human's natural limbs [1]. SRL can hold objects [5], lift weights [6] even manipulate objects, which help the wearer with multi-person movement ability [7]. Due to the promising enhancement potentials of movement ability, SRL was used in assembly tasks [2], construction works [3], and rehabilitation training [4]. Previous researchers have contributed to the mechanical design and control of SRL. However, building an artificial sensory nerve pathway to improve the proprioceptive sense and form the self-image of SRL has been largely ignored. Lack of sensory pathways, it is difficult for wearers to receive the following information: 1) touch information of the fingertip pressure, 2) slippage information for avoiding the object falling, 3) proprioception information for helping build the SRL self-image. It will take a long time for human brain to recognize SRL as an extension of human limb, and greatly influenced the movement-ability-enhancement performance of SRL. Therefore, the construction of an artificial sensory feedback pathway for SRL is a key technology to achieve limb extension and enhance limb movement ability.

In practice, the construction of sensory feedback pathway is not a new problem, but a common challenge, which already have an extensive research especially in the field of bionic prosthesis [8-15]. Nan applied vibration feedback to prosthetic hand users, the grasping success rate increased from 42 percent to 80 percent [16]. When the user performs a task, the electrical stimulation can give the user tactile information, and the user can dynamically adjust the hand posture and fingertip force until the task is completed [17]. According to the current research, with sensory feedback, the grasping accuracy of users can be increased, and the grasping time can be reduced, so that users can control the prosthetic hand better [18]. However, it should be noted that the construction of sensory feedback for SRL is different from that of the prosthetic hand. The purpose of SRL is to enhance human performance rather than compensate for lost performance. The research focuses on the sensory enhancement for normal people rather than the sensory compensation for disabled people. Here we address to develop the enhancement potentials of human sensation based on the SRL platform, especially the improvement of subjective perception resolution for helping people able to distinguish more sensory levels with the stimulation intensity changing, and cognition time of sensory information to bring forward. To the best of our knowledge, few studies have considered this.

For grasping, accurate sensory information is closely related to grasping success rate. Grasping task includes two stages, approach stage and grasp stage [19]. At the approach stage, the finger flexion degree sense should be applied to SRL wearer as the proprioception information for improving the SRL proprioceptive sense. At the grasp stage, the fingertip pressure sensation should be built when the SRL touch the

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objects in order to avoid the object destroy or slide. In addition, the grasped object slippage information even the slippage direction should be detected to the user so that he can react in time to prevent objects from falling. Therefore, three sensory information: 1) proprioception, 2) fingertip force, 3) slippage are considered in our paper.

Electric stimulation as one kind of most popular sensory pathway reconstruction methods, which can produce a sensation similar to human pressure feeling, is applied in our research. Brain-Computer Interface (BCI) is applied to build a mapping relationship which can objectively quantify the subjective and individualized human sensation. ERP technology is a popular and effective tool for understanding the brain activity objectively [20]. It can be used for quantitative assessment of subjective activities, such as the human sensation this paper focused on. Zhang's research reports the corresponding relationship between the physical parameters of electrical stimulation and the amplitude of ERP [21], which is very enlightening to us. After electrical stimulation, we observe four ERP components: N10, N1, P2, P3 [22]. The response to a somatosensory stimulus begins with the ERP components called N10 (ca. 10-20 ms) that reflects action potentials arising from the peripheral nerves. An N1 wave is then observed at approximately 150 ms, followed by a P2 wave at approximately 200 ms (together, these two peaks are sometimes called the vertex potential). P3 is of great help in understanding human stimulation psychology [23]. All of these can help us to further develop the enhancement potentials of human sensation based on the SRL platform, from two aspects contained: 1) improvement of subjective perception resolution; 2) cognition time of sensory information to bring forward.

Therefore, the contribution of this paper is to build the multi-modal sensory feedback pathways for SRL and the proposal of enhancement potentials of human sensation based on the BCI. Three kinds of sensory pathway contained 1) fingertip pressure, 2) slippage and 3) proprioception information are built under the consideration of SRL platform through electrical stimulation. According to the experiment results of ERP amplitude, enhancement potentials of human sensory based on the BCI are found in two aspects contained: 1) improvement of subjective perception resolution; 2) cognition time of sensory information to bring forward. The whole article is organized as follows: the first section is introduction to the whole work, the second section is the configuration strategy of electrotactile stimulation, the third section is experiment to establish ERP evaluation system, the fourth section is the result and discussion, and finally the future work.

II. Sensory Feedback Configuration Strategy

For the SRL control, the sensory feedback pathway and the feed-forward pathway is shown in figure 1.

According to previous electrotactile papers, it is found that electric stimulation can directly stimulate nerve without passing through mechanoreceptors to generate tactile sensation [24], so we can use electrical stimulation to generate tactile sensation. Electrical stimulation at frequencies ranging from 1Hz to 1500Hz can generate different tactile sensation, for example, low-frequency (0-30Hz) stimulation will generate a muscular response [25], 30Hz-60Hz electrical stimulation will generate vibration sensation [26], 60Hz-400Hz electrical stimulation will generate pressure sensation while pulse width is related to the size of pressure sensation [27], the switch of electrical stimulation between adjacent channels creates a sliding sensation [28].

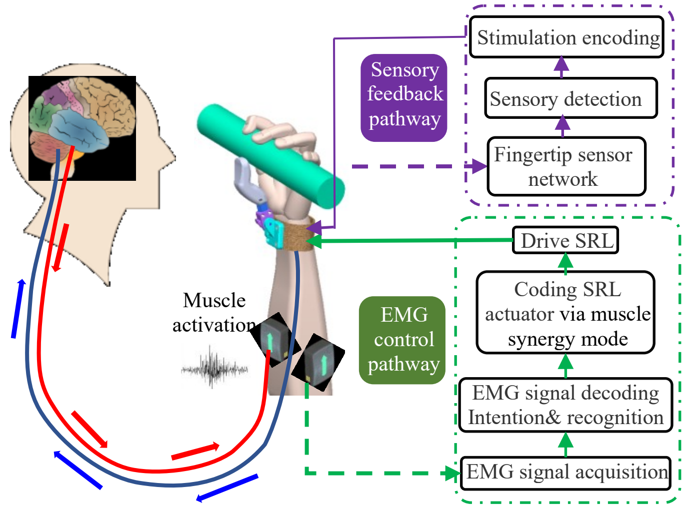

Fig. 1 SRL and sensory feedback system.

In our system, nine separate channels of electrical impulses are output by the electrical stimulator (Master-9, AMPI, Israel) and encoded via custom software based on Matlab R2017b (MathWorks, MA, USA) with the toolbox Psychtoolbox. In this way we can encode the physical parameters of the electrical stimulus including amplitude, frequency and pulse width. We design and manufacture the array electrode with 9 Ag/AgCl electrode to integrate three sensory feedback strategies into one system, wrap a medical bandage around it so that the electrodes stick tightly to the skin, as shown in figure 2.

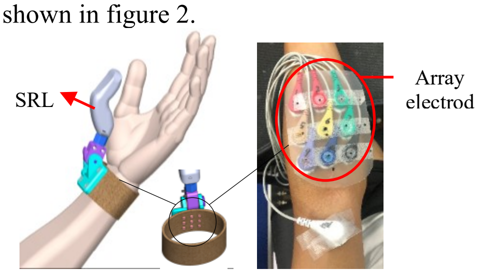

Fig. 2 Array electrode with 9 Ag/AgCl electrode.

Electrical stimulation is encoded into three types: fingertip pressure mode, slippage mode, proprioception mode. The sketch map of electrical stimulation is shown in figure 3.

A. Fingertip Pressure Mode

The electric stimulator outputs a single channel of negative pulse electrical stimulation at point 2 to simulate the pressure, maintaining a constant frequency but changing the pulse width to change the pressure size. The frequency is set as 100Hz and pulse widths range from 20 to 600μs. The subjects described the sensation of stimulation as a feeling of constant stress accompanied by a slight vibration, followed by a feeling of paralysis when the electrical stimulation is applied for too long. As the pulse width increased, the subjects felt the pressure increase. Therefore, the selection criterion of pulse width: the minimum was that the subject just felt pressure, and the maximum was that the subject just did not feel pain. Five pressure levels were set in the experiment (the pressure level in the SRL feedback can change continuously within the range). One to five level corresponding pulse widths are 20, 100, 200, 300 and 600μs.

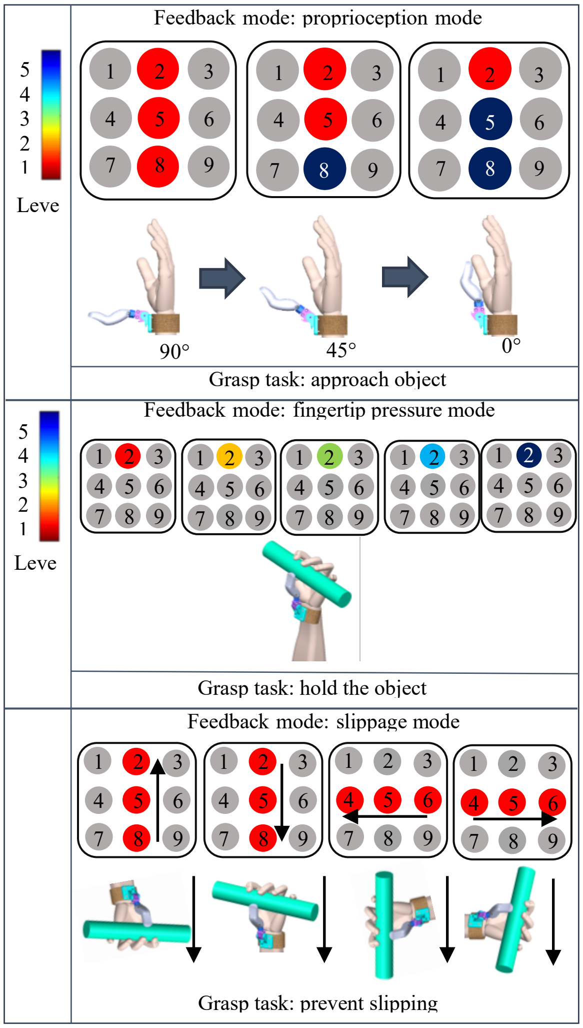

Fig. 3 Three sensory feedback mode.

A. *Slippage Mode*

Sliding can be simulated by electrically stimulated channel switching. The subjects described the electrical stimulation as a sharp stick running across the surface of their skin. There are four main sliding directions: up, down, left and right. The electrical stimulation parameters at each point are consistent with the pressure diagram. The time interval between two adjacent output points of electrical stimulation is 300ms, and electrical stimulation is gated along the set direction, for example, if the object slides downward, it will be gated in order 2,5 and 8; if the object slides leftward, it will be gated in order 6,5 and 4. By changing the direction of the electrical stimulus to simulate objects sliding in different directions.

B. *Proprioception Mode*

Proprioception feedback needs to provide the user with information about the flexion degree of finger joint and the SRL. 2, 5, 8 is the output point. 2 simulate far section of SRL, 5 simulate middle section of SRL, and 8 simulate near section of SRL. We will imitate three positions, SRL and palm 90°, 45°, 0°, electrical stimulation corresponding to three levels: 1) 2, 5, 8 full output pressure level 1; 2)2,5 output pressure level 1, 8 output pressure level 5; 3)2 output pressure level 1, 5, 8 output pressure level 5, that correspond to 90°, 45° and 0° respectively.

In order to apply our perceptual feedback strategy to SRL practice, we need to evaluate the feasibility of our strategy and find the direction of optimization. The following aspects need to be evaluated: 1)whether the human body can perceive the enhancement of somatosthesia, 2)whether the human body can distinguish the three senses, 3)the corresponding relationship between the physical parameters of different sensations and the human body sensation, such as the corresponding relationship between pulse width and pressure sensation, and the relationship between the selective direction of electrical stimulation and the sliding direction. In this paper, the evaluation system will be established by means of EEG experiment.

III. EEG EXPERIMENT

A. *Participants and Apparatus*

Fourteen healthy people (7 males and 7 females; mean age: 23 years old) from Tianjin University participated in the study. All subjects were required to be right-handed with normal hand movement and sensory function. The study was approved by the ethics committee of Tianjin University. Specifically, any participant with a history of serious hand and wrist injuries was excluded from the study. All subjects received personal consent.

EEG data were acquired simultaneously with a Neuroscan SynAmps2 amplifier, hardware-filtered in the frequency range of 0.015–250Hz and sampled at 1,000 Hz. EEG data was recorded with 64 electrodes. The signal was filtered by band pass of 0.1Hz-100Hz and notch of 50Hz, the sampling rate was 1000Hz. The experimental apparatus is shown in the figure 4.

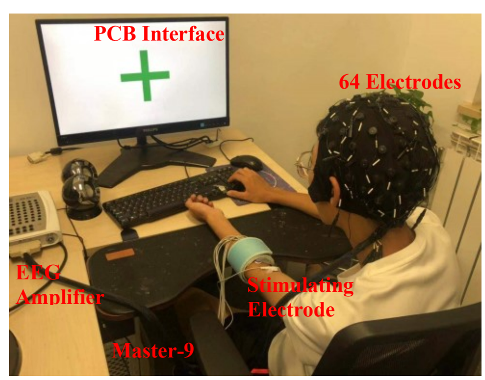

Fig. 4 EEG experiment

B. *Procedure and Experimental Paradigm*

1) Pressure grading experiment: In the process of grasping, the fingertip force changes continuously. We are supposed to the relationship between physical parameters and pressure sensation as well as establish a regression model, so that we can output the corresponding pressure sensation by changing the pulse width of electrical stimulation synchronous in practical application. Therefore, the purpose of pressure grading experiment is to establish the relationship between

Five levels of stimulation will random occur, and each pressure stimulation will occur 20 times, 100 times in total, each time lasting 900ms, a total of 4 blocks. A cross appears in the center of the screen and the stimulus begins. Subjects were asked to determine the stress level of the stimulus immediately after the stimulus ended. Record keystroke response and EEG data. An experimental trail is shown in the figure 5.

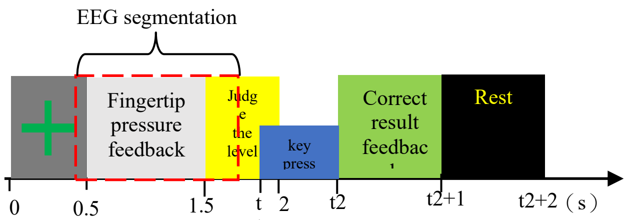

Fig. 5 EEG experimental process

2) Sliding direction discrimination experiment: The experiment set up four sliding stimulus directions. Each of the four stimuli appeared 20 times, a total of 80, each lasting 900ms, a total of 4 blocks. After the experiment started, a cross appeared in the center of the screen and the stimulus began. The subjects had to immediately determine the direction of the stimulus and type the key. Record keystroke response and EEG data.

3) Model judgment experiment: Whether the subjects could distinguish between the three senses was also a key question. In grasping task, first, we need to obtain the proprioception information. Once we touch the object, the fingertip force feedback information is more important. After sliding occurs, we need to accept the sliding direction information. Therefore, three modes need to be distinguished in the experiment: proprioception mode (maximum), fingertip pressure mode (minimum) and sliding mode. When the experiment was over, a cross appeared in the center of the screen and the stimulus began. Subjects were asked to determine which pattern the stimulus was in immediately after it ended. Record keystroke response and EEG data.

C. *Data Preprocessing*

The purpose of EEG data processing is: 1) to draw a topographic map of the brain and find the activated brain areas. 2) draw ERP waveform and find the main components. 3) establish the relationship between ERP characteristics and physical parameters of electrical stimulation.

The first step is to delete the EEG clip corresponding to the wrong keystroke. In the second step, ICA removes EOG and electrical stimulation artifacts. The third step, from 200ms before stimulation to 1000ms after stimulation, a time window of 1200ms was intercepted, and the previous 200ms data was used as the basis for removing baseline drift. In the fourth step, a Butterworth bandpass filter of order 3 was used to filter 0.1Hz-12Hz. In the fifth step: stack the average. In the sixth step: draw the ERP diagram and find out the main components.

IV. Results

A. *Pressure grading experiment results*

1) Behavioral results: All the subjects performed well in the recognition of pressure classification, with an average recognition rate of 66% (the maximum recognition rate was 79%, and the minimum recognition rate was 52%), among which the recognition rate for each grade was shown in figure 6. From the behavioral results, it is obvious to find that levels 1 and 2 were easily identified, whereas levels 3, 4 and 5 were easily confused.

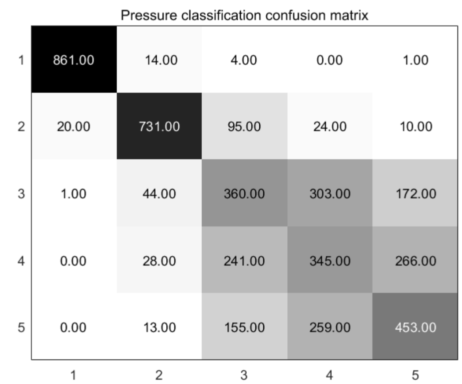

Fig. 6 Pressure classification confusion matrix

2) EEG results: The ERP waveforms and grand-averaged topographies are shown in figure 7. Three components can be clearly found in the ERP waveforms: N1(100.8615ms ± 5.8438ms), P2(198.8615ms±5.2031ms)and P3(350.9846ms± 5.5760ms). These three components relate to the brain's response to the sensory process of electrical stimulation. It can be clearly seen from the figure that among the five pressure levels, P1,P2 and P3 waveforms can be easily distinguished, among which P2 waveforms are the most obvious. Grand-averaged brain topographies shows somatosensory region activate at 100ms, after 100ms, the activated areas of the brain start moving left and forward, at 350ms, activation can be observed in the frontal lobe. The relationship between these three components and sensory processing will be mentioned in the discussion.

B. *Sliding experiment results*

1) Behavioral results: All the subjects performed well in the recognition of slippage classification, with an average recognition rate of 95% (the maximum recognition rate was 100%, and the minimum recognition rate was 88%).

2) EEG results: The ERP waveforms of different sliding directions can be clearly classified as shown in figure 8. Five components can be clearly found in the ERP waveforms: P1, N2, P3, P4 and N600. It's more complicated than the ERP waveforms of pressure. It can be found that the amplitude is differentiated in different sliding directions.

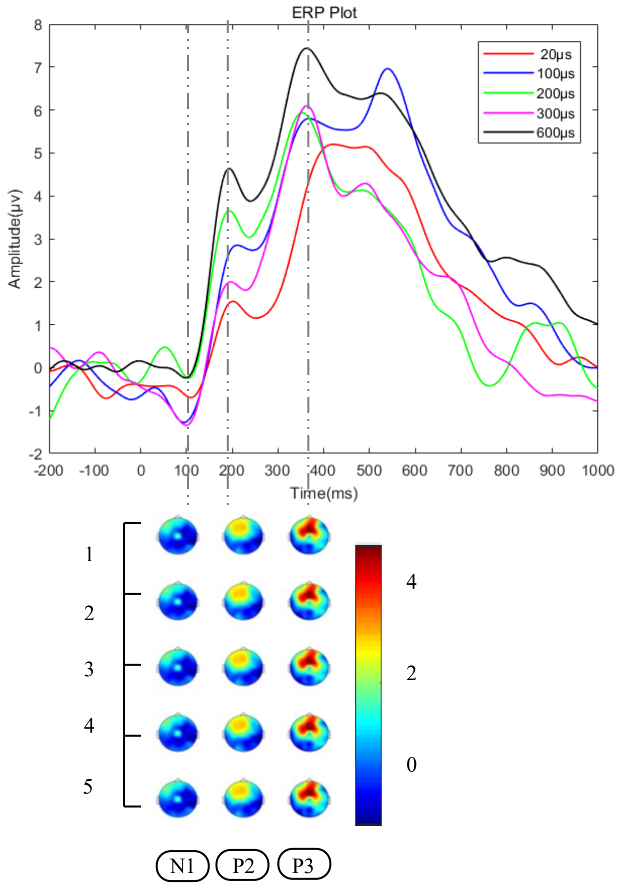

Fig. 7 The figure is the result of ERP. The abscissa in the figure is the time axis, and the origin represents the moment when the stimulus starts. The vertical coordinate is the amplitude of EEG. Red, blue, green, magenta and black represent the ERP figure of five types of pressure stimulation.

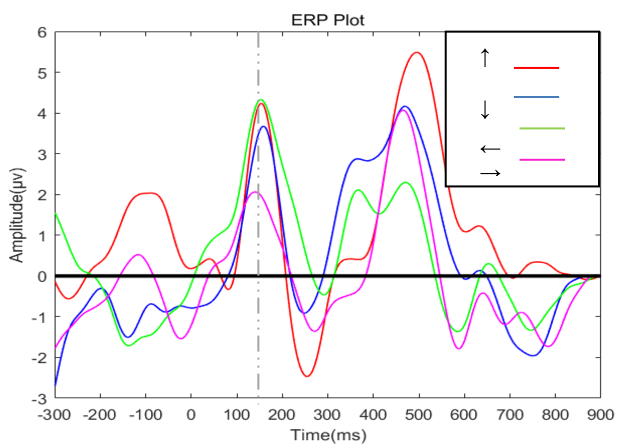

Fig. 8 The figure is the result of ERP. Red, blue, green and magenta represent the ERP figure of four directions of sliding

C. *Model judgment results*

All the subjects performed well in the recognition of model judgment, with an average recognition rate of 89% (the maximum recognition rate was 93%, and the minimum recognition rate was 81%).

V. Discussion

As shown in figure 6 and figure 7, levels 1 and 2 were easily identified, whereas levels 3, 4 and 5 were easily confused, which shows a clear correspondence between P3 amplitude and human subjective sense preception of pressure. The three components of ERP with five stress stimuli are shown in the figure 9. From the trend of P3 amplitude are shown in the figure 9(c), the human brain can clearly distinguish the five levels of stimulation

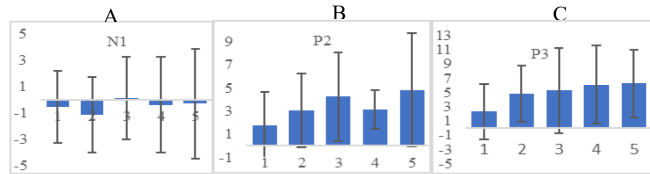

Fig. 9 The mean amplitude of the three components of all subjects. (A) N1 amplitude. (B) P2 amplitude. (C) P3 amplitude.

Therefore, we suppose that: 1) the EEG experimental protocol and data were reasonable and reliable as the P3 results were confirmed by the behavioral results of pressure grading experiment. 2) P3 is a significant metric for objectively and quantitatively understanding the human subjective sense preception of pressure. The relationship between user's sense preception of pressure and the width of the electrical stimulation pulse can be established through P3, which can guide the development to the sensory construction strategy of SRL. After regression of the average amplitude of P3 under five pressure stimuli of each subject, a regression curve was obtained shown in equation (1). In this way, the relationship between sensation and physical parameters of electrical stimulation can be established to guide the control strategy construction: the relationship between perceived stress levels and stimulated pulse width.

$$Y=0.0072x+5.0812 \qquad (1)$$

Although the linear fitting degree of the current results is not very good, we will use other curves to fit them in future studies, such as SVM, and find the most instructive curve in future work.

Two potentials of sensory enhancement are found according to the P2 amplitude: 1) according to the sharp contrast between the clear P2 amplitude distribution in figure 7, 9(b), and the confusing subjective perception of 3, 4 and 5 pressure level in behavioral results of pressure grading experiment, the resolution of pressure can be improved by detecting the P2 amplitude compared with human subjective perception; 2) as shown in figure 7 that P2 appeared 100ms earlier than P3, which means that people can understand the presure level applied to the body ahead of the subjective feelings occur. All of these illustrated that, P2 seems to be a good choice for identifying human sensations and provied the potentials of sensory enhancement. In future, we will make a further analysis on the time-frequency diagram to verify the potentials of P2 in sensory enhancement.

Combined with the mechanism of tactile production: primary somatosensory cortex (S1) receives the bulk of sensory information from the sensory input fields of thalamocortica [29]. Secondary somatosensory cortex(S2) memory and identify the differences between tactile shapes and textures [30]. We suppose that N1, P2 and P3 may be related to the activation of these two cortical areas: S1 simply determine the type of stimulus, which led to the production of the N1 and P2 waveform; S2 categorizes the stimulus intensity through comparison, which led to the production of the P3 waveform. This hypothesize will be verifed in future research via EEG source analysis.

There are more complicated components for the sliding direction identification, which is because the spatial recognition of sensation will be more complicated.

VI. Future work

The work discussed in this paper is: 1) establishment of sensory feedback strategy for electrical stimulation; 2) evaluation of sensory feedback system with ERP technology. The current work enhances the efficiency of future work by applying the cognitive feedback system to the SRL system. Future work could also consider bimanual collaboration SRL and establishment of a scenario of SRL, which combined with this paper establish sensory feedback strategy. It can achieve to establish complete SRL man-machine collaboration system and enhance operation efficiency of the users in their daily tasks.

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References

[1] I. Hussain, G. Spagnoletti, G. Salvietti, and D. J. F. N. Prattichizzo, "An EMG Interface for the Control of Motion and Compliance of a Supernumerary Robotic Finger," vol. 10, p. 18, 2016.

[2] F. Parietti and H. H. Asada, "Dynamic analysis and state estimation for wearable robotic limbs subject to human-induced disturbances," in IEEE International Conference on Robotics & Automation, 2013.

[3] W. Seo et al., "Applications of Supernumerary Robotic Limbs to Construction Works: Case Studies," in International Symposium on Automation & Robotics in Construction, 2016.

[4] I. Hussain, G. Spagnoletti, G. Salvietti, and D. J. F. N. Prattichizzo, "An EMG Interface for the Control of Motion and Compliance of a Supernumerary Robotic Finger," vol. 10, p. 18, 2016.

[5] B. Llorens-Bonilla and H. H. Asada, "Control and Coordination of Supernumerary Robotic Limbs Based on Human Motion Detection and Task Petri Net Model," in Asme Dynamic Systems & Control Conference, 2013.

[6] B. Llorens Bonilla and H. H. Asada, "A robot on the shoulder: Coordinated human-wearable robot control using Coloured Petri Nets and Partial Least Squares predictions," in IEEE International Conference on Robotics & Automation, 2014.

[7] N. Mizutani et al., "Control of wearable motion assist robot for upper limb based on the equilibrium position estimation," in Engineering in Medicine & Biology Society, 2013

[8] M. Nabeel, K. Aqeel, M. N. Ashraf, M. I. Awan, and M. Khurram, "Vibrotactile stimulation for 3D printed prosthetic hand," in International Conference on Robotics & Artificial Intelligence, 2016.

[9] H. Yamada, Y. Yamanoi, K. Wakita, and R. Kato, "Investigation of a cognitive strain on hand grasping induced by sensory feedback for myoelectric hand," in IEEE International Conference on Robotics & Automation, 2016.

[10]M. Benali-Khoudjal, M. Hafezl, J. Alexandrel, J. Benachourl and A.Kheddar, "Thermal feedback model for virtual reality", International Symposium on Micromechatronics and Human Science, 1, pp.153-158, 2003

[11]S. Dosen, M. C. Schaeffer, D. J. J. o. N. Farina, and Rehabilitation, "Time-division multiplexing for myoelectric closed-loop control using electrotactile feedback," vol. 11, no. 1, p. 138, 2014.

[12]F. Rattay, "Analysis of models for extracellular fiber stimulation," vol. 36, no. 7, pp. 676-682, 1989.

[13]P. Shi and X. Shen, "Sensation Feedback and Muscle Response of Electrical Stimulation on the Upper Limb Skin: A Case Study," pp. 969-972, 2015.

[14]K. Choi, P. Kim, K. S. Kim, and S. Kim, "Two-channel electrotactile stimulation for sensory feedback of fingers of prosthesis," in IEEE/RSJ International Conference on Intelligent Robots & Systems, 2016.

[15]Y. Szeto and F. A. J. I. T. o. B. E. Saunders, "Electrocutaneous stimulation for sensory communication in rehabilitation engineering," vol. BME-29, no. 4, pp. 300-308, 1982.

[16]L. Nan, L. Bo, H. Hong, Y. Yuxuan, and J. L. J. Robot, "Human-Machine Interaction Control Based on Force Myograph and Electrical Stimulation Sensory Feedback for Multi-DOF Robotic Hand," 2015.

[17]R. Zheng and J. Li, “Kinematics and workspace analysis of an exoskeleton for thumb and index finger rehabilitation,” in Proc. IEEE Int. Conf. Robot. Biomimetics, 2010, pp. 80–84.

[18]Chaubey et al., "Closed-Loop Vibratory Haptic Feedback in Upper-Limb Prosthetic Users," vol. 26, no. 3, pp. 120-127, 2014.

[19]I. Bullock, T. Feix, and A. J. I. T. o. B. E. Dollar, "Workspace Shape and Characteristics for Human Two- and Three-Fingered Precision Manipulation," vol. 62, no. 9, pp. 2196-2207, 2015.

[20]G. Pfurtscheller,.and F. H. Silva, Lopes Da %J Clinical Neurophysiology, "Event-related EEG/MEG synchronization and desynchronization: basic principles," vol. 110, no. 11, pp. 1842-1857, 1999.

[21]D. Zhang, X. U. Fei, X. U. Heng, P. B. Shull, and X. J. I. J. o. N. S. Zhu, "QUANTIFYING DIFFERENT TACTILE SENSATIONS EVOKED BY CUTANEOUS ELECTRICAL STIMULATION USING ELECTROENCEPHALOGRAPHY FEATURES," vol. 26, no. 02, p. 1650006, 2016.

[22] A. Ayaraman, K. A. Kaczmarek, M. E. Tyler, and U. O. Okpara, "Effect of localized ambient humidity on electrotactile skin resistance," in IEEE Northeast Bioengineering Conference, 2007.

[23]G. Pfurtscheller, .and F. H. Silva, Lopes Da %J Clinical Neurophysiology, "Event-related EEG/MEG synchronization and desynchronization: basic principles," vol. 110, no. 11, pp. 1842-1857, 1999.

[24]A. Ryszard, S. Bernhard, and B. J. J. o. N. Felix, "Recurrent neural processing and somatosensory awareness," vol. 32, no. 3, pp. 799-805, 2012.

[25]A. I. R. Kottink, L. J. M. Oostendorp, J. H. Buurke, A. V. Nene, H. J. Hermens, and M. J. Ijzerman, %J Artificial Organs, "The orthotic effect of functional electrical stimulation on the improvement of walking in stroke patients with a dropped foot: a systematic review," vol. 28, no. 6, pp. 577-586, 2015.

[26]M. E. Altinsoy, S. Merchel, “Electrotactile feedback for handheld devices with touch screen and simulation of roughness”, IEEE Transactions on Haptics, 2012.

[27]K. A. Kaczmarek, “Electrotactile adaptation on the abdomen: Preliminary results”. IEEE Transactions on Rehabilitation Engineering, 2000.

[28]K. A. Kaczmarek, M. E. Tyler, A. J. “Brisben, The afferent neural response to electrotactile stimuli: preliminary results” IEEE Transactions on Rehabilitation Engineering, 2000.

[29] A. N Viaene. "synaptic properties of thalamic input to layers 2/3 and 4 of primary somatosensory and auditory cortices". Journal of Neurophysiology. 2011

[30]R. M. Ridley, and G. Ettlinger, "Impaired tactile learning and retention after removals of the second somatic sensory projection cortex (S11) in the monkey". Brain Research. 1976