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The Cybernetic Rehabilitation Aid: a Novel Concept for Direct Rehabilitation

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***Abstract* - The evaluation and teaching of motor skills in relation to patients are two important aspects of motor skill training. These two points or problems must be resolved in order to make such training effective. To address the issues simultaneously within a single system, this study proposes a Cybernetic Rehabilitation Aid (CRA) under the concept of direct teaching using tactile feedback with an EMG-based motor skill evaluation function. The CRA involves a human–machine–human (physiotherapist–rehabilitation robot–patient) interface known as a Cybernetic Interface Platform using biological signals not only to monitor patients' motor skills but also to directly teach such skills to them. The CIP can also be used as a human–human (physiotherapist–patient) system as well as a human–machine (physiotherapist–rehabilitation robot) system. In order to evaluate motor skills, the motions of the physiotherapist (T) and the patient (P) were analyzed using a log-linearized Gaussian mixture model that can classify motion patterns via electromyography (EMG) signals. Tactile stimulators were used to convey the instructions of the therapist or the system to the patients. A rehabilitation robot known as the Biodex System was integrated into the developed setup for a number of rehabilitation tasks.**

Index terms - Direct rehabilitation, human-machine interface, tactile stimulator

I. Introduction

The demand for rehabilitation increases daily as a result of disease, occupational and traffic accidents and population growth. In parallel with this increase, the equipment and techniques used in the field of rehabilitation are constantly becoming more advanced. Ideas gleaned from motor learning research suggest that rehabilitation should include a good deal of practice that involves the repetition of activities as well as their performance in a way that promotes solutions to new and novel motor problems [1]. The evaluation and teaching of motor skills in relation to patients are two important aspects of motor skill training. These two points or problems must be resolved in order to make such training effective. However, because of the redundant degrees of freedom that exist in the human musculoskeletal system, the same movements and/or joint torques can be realized by different muscular activities, meaning that muscular activities as well as movements and/or joint torques must be considered. As muscular activities are closely related to the coordination of multiple muscles, which is one of the keys of motor skills, EMG can be used effectively to evaluate such activities.

A number of researchers have used EMG as a control signal for rehabilitation robots in human–machine (patient–rehabilitation robot) systems. Rosen *et al*. controlled an exoskeletal robot manipulator using EMG signals. With the same aim, a human–machine interface was set at the neuromuscular level using EMG signals [2]. Kiguchi *et al*. designed and controlled an exoskeleton system for human upper-limb motion assist. To control the system, a fuzzy-neuro controller was realized to adjust the elbow and shoulder joint angles of the exoskeleton system based on the surface EMG signals of the arm and shoulder muscles and the generated wrist force. The assist level of the manipulator (i.e. the support level) can be adjusted until the EMG signals of patient's arm and shoulder muscles reach the desired level [3]. Andreasen, Allen and Backus developed a prototype robotic system to facilitate upper extremity rehabilitation. A control system based on EMG signals was implemented to provide the appropriate amount of assistance or resistance necessary to promote a patient's movement recovery [4]. Hua *et al*. investigated the motor functional recovery process in chronic stroke patients during robot-assisted wrist training using EMG parameters to monitor neuromuscular changes and generate assistive torque commands [5]. Other researchers have also used EMG signals to evaluate patient performance during training or exercise sessions. Morita *et al*. used an impedance-controlled XY table for upper-limb exercises. In order to quantify the physical condition of the subjects, they measured the EMG, position and angles of upper-limb joints during the exercises [6]. Lee *et al*. developed a haptic device system for a training program. To investigate the functional effect of this system using a training program, the grip position, velocity, grip force and EMG signals were measured during a reaching task for five healthy subjects [7].

Conveying instructions to patients is another important part of motor skill training. This can be done by a therapist or a computerized training system, but with either case, effective feedback channels are necessary. Essentially, humans benefit from three types of real-time feedback – visual, audial and

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tactile – in building motor skills. Consequently, the provision of such feedback is very important in motor learning and the recovery of such skills.

Recent years have seen a focus on the development of human–machine systems based on virtual reality (VR) techniques with visual and audial feedback for the rehabilitation of neurophysiologic and post-stroke patients [8]. VR setups work as computerized training systems, and some research studies have used tactile feedback such as FES and tactile stimulators with VR. Hauschild *et al*. proposed a system to test prosthetic arms using VR with FES and EMG signals [9]. In addition, Phillips *et al*., Castro and Cliquet, and Batavia *et al*. used VR and tactile feedback for gait analysis in their studies [10, 11, 12]. The advantages of VR include patient motivation, adaptability and variability based on the patient baseline, transparent data storage, online remote data access, economy of scale and reduced medical costs. On the other hand, the technique has some disadvantages, such as the difficulty of its use for rehabilitation by therapists with low computer skills, a lack of support infrastructure, high initial equipment expenses, inadequate communication infrastructure (for telerehabilitation in rural areas) and patient safety concerns [13]. Treatment also takes longer than with other traditional rehabilitation techniques [14] and they are not developed as a human–human (P–T) system.

Conveying the therapist's teaching capacity to the patient is not easy, because in the process of motor skill teaching, the teacher (or therapist) can not stimulate all the necessary limbs or muscles of the student (or patient) simultaneously due to the limited motion of the human body. In this regard, the study of Lieberman and Breazeal [15] stands out. They designed a system that can transfer the therapist's teaching capability to the student directly. If an error occurs during the following of a constant trajectory on the screen, the system can stimulate the subject's muscles via tactile feedback [15]. Over the last decade, the implementation of rehabilitation robots (such as human–machine systems that use intelligent techniques and aim to convey the therapist's motion capability to the patient) has gained momentum [16, 17, 18]. However, these studies were generally developed based on the learning of therapy motion using force and position feedback. They cannot detect muscular activation and change the rehabilitation process accordingly, nor do they have specifications to stimulate the muscles for motor learning.

In order to solve the problems of evaluation and teaching in motor skills simultaneously within a single human–machine–human system, this study proposes a Cybernetic Rehabilitation Aid (CRA) under the concept of direct teaching using tactile feedback with an EMG-based motor skill evaluation function. The CRA includes a human–machine–human (patient–rehabilitation robot–therapist) interface known as a Cybernetic Interface Platform (CIP) using biological signals not only to monitor and evaluate patients' motor skills but also to teach such skills. Direct rehabilitation can be performed even in web-based environments using the proposed CRA, so that the difficulties inherent in transferring patients to medical centers can be eradicated. Furthermore, since the CIP can be used as a human–human (therapist–patient) system as well as a human–machine (patient–rehabilitation robot) system, multiple patients can be treated by a single therapist. In order to evaluate motor skills, the motions of the therapist and patient are analyzed using a log-linearized Gaussian mixture model [19] that can classify motion patterns via EMG signals. Tactile stimulators in the form of tactors (which are safer than electrical stimulation) are used to convey the instructions of the therapist or the system to patients. A rehabilitation robot known as the Biodex System is integrated into the developed setup for a number of rehabilitation tasks.

II. Cybernetic Rehabilitation Aid (CRA) System: The Main Concept

The proposed system structure (shown in Fig. 1) is a kind of human–machine–human (therapist–rehabilitation robot–patient) system (HMHS) that can be used as a human–human (therapist–patient) (HHS) system as well as a human–machine (patient–rehabilitation robot) system (HMS).

The system elements are the physiotherapist (T), the Cybernetic Interface Platform (CRA), a rehabilitation robot (RR) and the patient (P). The system can be used by both therapist and patient via a graphical user interface (GUI). The user (i.e. the therapist or patient) enters the patient's information (name, age, sex, height *etc*.) and the training process data (working mode, duration *etc*.) through the GUI. Using these data, the CRA sends rehabilitation instructions to the patient. These instructions can be generated either by the system or by the therapist. If the patient is trained with instructions from the system, it works as an HMS. If the patient is trained with instructions from the therapist without using the RR, the system works as an HHS. In the case of the RR and the therapist working together to train the patient, the system works as an HMHS. The EMG signals received from the patient's and therapist's muscles are used as biofeedback; their joint angles are measured using goniometers, and are evaluated for comparison.

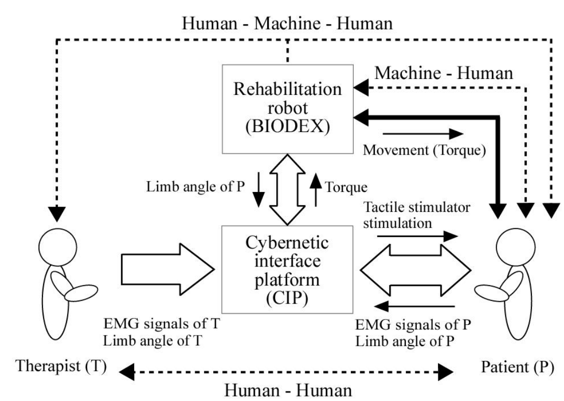

Fig. 1 Main concept of the CRA

Tactile stimulators are used to send therapy commands such as motion direction and muscular contraction level. In the HMHS system, the necessary torque commands are sent from the CIP to the RR, and the patient's limb position data are obtained using information from the RR. The four different working modes planned for the CRA are *re-education*, *facilitation*, *strengthening* and *training*. These modes were realized using information from physiotherapists, and are explained below.

Re-education mode: This is used for patients with very low or non-existent muscle contraction. It is aimed at the education of the patient's muscles with correct limb motion. Passive and mild isotonic exercise can be used in this mode.

Facilitation mode: This is used for patients with low or painful muscle contraction. The limb motion of patients with low muscle contraction is supported, meaning that active assistive exercise can be used. To this end, the RR helps motion. For patients whose muscle contraction is sufficient but painful, active exercises are performed without resistance. To this regard, therapist performs the necessary limb motion, the therapist's muscle signals are received via EMG and classified. According to these results motion direction and muscular contraction level commands are sent to patients via tactile stimulators.

Strengthening mode: This is used for patients who need muscle strengthening. To achieve this, active exercises such as isotonic, isometric and isokinetic work are performed using the RR. Tactile stimulators are used to send the therapist's command like in the facilitation mode.

Training mode: This is used for patients with motor function disorder. In this mode, the therapist trains the patient directly, or different training games are used to promote the recovery of motor skills. In the training, the therapist performs the necessary exercise motions, and the patient tries to imitate them. If the patient fails to recreate the desired motion, tactile stimulators connected to his or her muscles provide stimulation. If the patient's muscular contraction level (MCL) is expected to increase, the therapist increases his or her MCL, and the vibration level in the tactile stimulators increases. In the training-game method, the patient's muscles are trained via games or tasks such as trajectory following, timing control and contraction-level regulation. The patient is expected to achieve certain tasks, but if his or her MCL is insufficient or he/she is otherwise unable to achieve the training motion tasks, tactile stimulators stimulate the patient's muscles.

III. Prototype System

A. System Implementation

1) EMG amplifiers and goniometers: The system uses four-channel EMG amplifiers (EMG-025 with EMG-BB04, Harada Electronics Industry Ltd.) and goniometers to measure the EMG signals and limb angles of the therapist and the patient. A/D data conversion is realized using National Instruments NI 6024E 12-bit Multifunction Data Acquisition (DAQ) cards with a sample time of 0.001 s.

2) Tactile stimulators (*tactors*) *and amplifier unit*: Teaching via tactile feedback and accurate, regular training of muscles via stimulation are extremely important in rehabilitation. To this end, functional electrical stimulation (FES) has been used in some studies [20, 21, 22, 23], especially for the restoration of paralyzed motor function and the rehabilitation of stroke patients. However, electrical stimulation application may cause some accidents and/or pains, and its use requires expertise. We therefore adopted the tactile stimulators (VBW32C, Audiological Eng. Corp.), which are safer than electrical stimulation. A tactile stimulator is a device that generates tactile sensations against the skin of its user. It has an ideal working frequency of 250 Hz and a nominal voltage of 2.5 volts (rms). For the details of its other specifications, see [24]. To drive the tactile stimulators, an amplifier unit encompassing a Motorola MC34119 Low Power Audio Amplifier was designed. A tactile stimulator can be driven by sinusoidal or square wave signals; with the former, the vibration level is adjusted with the amplitude of the signal; with the latter, it can be adjusted with the signal's duty cycle.

3) Rehabilitation robot (*Biodex*): To realize the exercise motions in this study, a Biodex Multi Joint System 2-AP was used as a rehabilitation robot (RR) according to the system's working modes. It can be used in the testing and rehabilitation of knees, ankles, hips, shoulders, elbows and wrist joints. The modes of operation are isokinetic (concentric), isometric, eccentric and passive (continuous) [25].

4) Software: MATLAB/Simulink was used as a platform for the development of the system's control algorithms, and supported by Microsoft Visual C++ 6.0 software for GUI design. For rapid prototyping, the system uses xPC Target.

B. Cybernetic Interface Platform (CIP):

The CIP is the central processing unit of the CRA. It can work as a human–machine interface (HMI), a human–human interface (HHI) and a human–machine–human interface (HMHI). The structural details of the CIP are shown in Fig. 2, and an explanation is given below.

1) Pre-processing and LLGMN units: The CIP includes two pre-processing units. One is used for the therapist and the other for the patient. EMG signals measured from the muscles of the therapist and the patient with L pairs of electrodes, respectively, are rectified, amplified and filtered (using a second-order Butterworth filter with a cut-off frequency of 1 Hz), and are digitized using a DAQ card in the pre-processing unit. These sampled signals are defined as EMG_i (n) (i = 1, 2,…, L) and sent to an LLGMN unit for motion classification. The sampled EMG signals are discriminated using LLGMN for evaluation of the subject's motion. This LLGMN is based on the Gaussian mixture model (GMM) and the log-linear model of the probability density function, and the *a posteriori* probability is estimated based on GMM by learning [19]. The feature vectors calculated from these motions are then input to the LLGMN as teacher vectors, and the unit is trained to estimate the *a posteriori* probabilities of each motion.

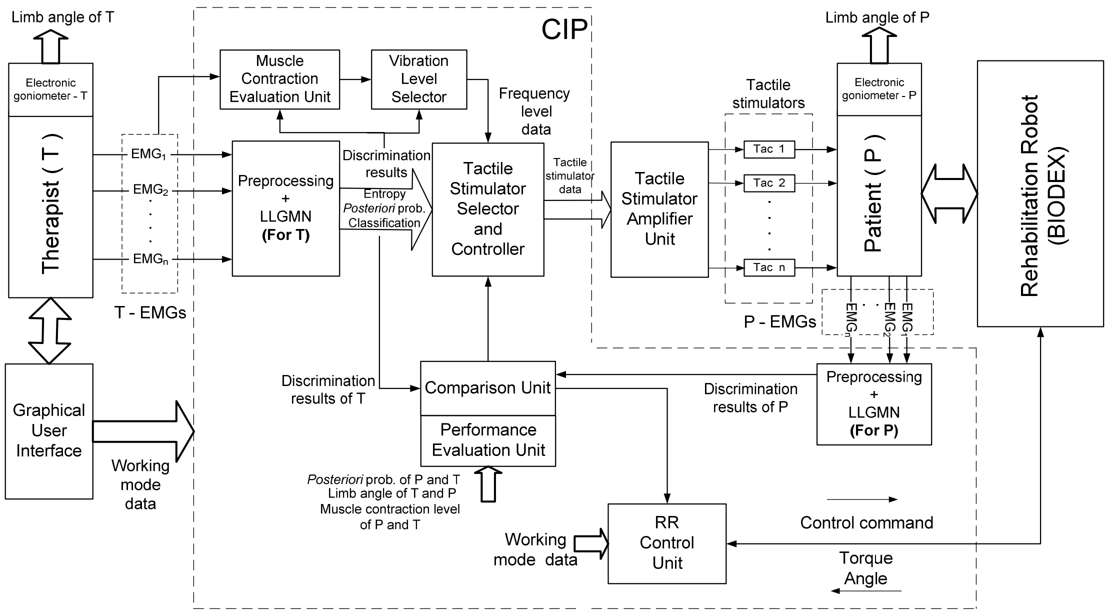

Fig. 2 Detailed block diagram of the CIP

After the training, the system can calculate the similarity between patterns in the subject's movements and trained motions as *a posteriori* probabilities by inputting the newly measured vectors to the LLGMN. In order to prevent discrimination errors, the entropy $E(t)$ (which shows the obscurity of the information) is here calculated from the LLGMN outputs. Since the output $O_k\ (t)$ of the LLGMN represents *a posteriori* probabilities for each motion M ($M = M_1, M_2, \ldots, M_K$), entropy is defined in (1) as

$$E(t) = -\sum_{k=1}^{K} O_k(t) \log O_k(t) \qquad (1)$$

If $E(t)$ is smaller than the discrimination determination threshold value E_d , the motion with the highest *a posteriori* probability becomes the result of discrimination. Otherwise, if $E(t)$ exceeds E_d , discrimination is suspended as an obscure motion.

2) Muscle contraction evaluation (*MCE*) *and vibration level selector unit*: The MCE unit calculates the muscular contraction level (MCL) of the therapist and patient from (2).

$$MCL(n) = \frac{1}{L} \sum_{i=1}^{L} \frac{EMG_i(n) - EMG_i^{rest}}{EMG_i^{\mathbf{max}} - EMG_i^{rest}} \qquad (2)$$

where EMG_i^{rest} and EMG_i^{max} are the mean values of $EMG_i(n)$ while relaxing the arm and keeping the maximum voluntary contraction (MVC), respectively. During the training process, if the MCL of the patient is insufficient, the vibration level of the tactile stimulators is increased by the system, or the therapist increases his or her own MCL to increase that of P. To this end, a vibration level selector (VLS) unit determines the appropriate level of vibration according to the MCL value, and the selected vibration level data are sent to the tactile stimulator selector and controller unit.

3) Tactile stimulator selector and controller unit: First, this unit determines which tactile stimulators should work according to the classified motion data. Then, according to the vibration level of the tactile stimulator data from the FLS unit and the motion data from the LLGMN unit, it determines the driving data for the tactile stimulators and sends this information to the tactile stimulator amplifier unit.

4) Rehabilitation robot (*RR*) *control unit*: This unit controls the RR according to the working mode data entered by the therapist through the GUI. It sends control commands to the actuators of the RR according to the selected exercise mode. Angle and torque data generated by the patient are also received via this unit.

5) Comparison and performance evaluation unit: In the comparison unit, the motion patterns of the therapist and patient are compared, and tactile stimulators are controlled according to the unit's outputs. The performance evaluation unit is used to evaluate patient performance during the rehabilitation session. Four different performance indices are used according to the working mode. These are the EMG pattern index, the EMG amplitude index, the joint angle index and the mechanical parameter (torque, velocity) index. Each has two different evaluation versions – a patient index and an error index. The patient index reflects patient performance only, while the error index shows the differences between patient performance and commands from the therapist or system. In the patient index, three scores are computed or measured:

- The instant values depending on time
- The time average value for each trial
- The ensemble average value for all trials

For the instant values depending on time, the normalized EMG signals, MCL, joint angle and mechanical parameters (torque, velocity) are computed or measured. Then, these parameters are shown on the display for the therapist or patient, and the tactile stimulators and RR can be controlled using these parameters. With the time average value for each trial, the patient or therapist can understand the evaluation results after each trial. Using the ensemble average value for all trials, the patient or therapist can check changes in the indices depending on the day, and compare values before and after training. The aim of the error index is to evaluate patient performance using system or therapist commands. The index consists of the success rate and the mean square error of tasks. The success rate is computed from the rate of patient motion, while task commands and the mean square error come from the square of the difference between the patient's motion and system or therapist commands.

IV. EXPERIMENT

A. Method

In this study, the results of preliminary experiments using the proposed system are given. To this end, the ability of the proposed system to discriminate and compare patient and therapist motions and its capacity to control the tactile stimulators of the proposed system in accordance with the results of this discrimination and comparison are illustrated. In addition, the effects of the tactile stimulators are explained through the experimental results. The experiments were performed in relation to elbow joint movement. Four EMG electrodes (Ch. 1: biceps brachii, Ch. 2: triceps brachii, Ch. 3: brachioradialis, Ch. 4: pronator teres) and four tactile stimulators were used. These electrodes were attached to the subject with the tactile stimulators placed as close to them as possible, as shown in Fig. 3.

The units in the proposed system shown in Fig. 2 were realized using two different computers for preliminary experiments. During the experiments, four different motions were performed by the subjects (a virtual therapist and a virtual patient). These were flexion (Motion 1), extension (Motion 2), supination (Motion 3) and pronation (Motion 4). The tactile stimulators were positioned according to the directions in which the motions would be made. A sampling time of 1 ms was used for control signal generation and data recording.

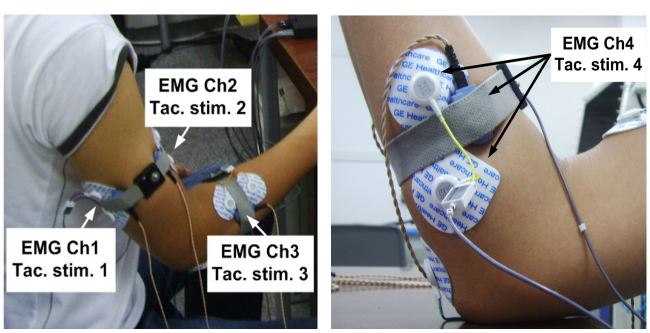

Fig. 3 EMG electrodes and tactile stimulators

B. Results

1) Motion comparison and tactile stimulator control ability of the proposed system: Fig. 4 shows the results of the experiment carried out to demonstrate the proposed system's capacity to discriminate and compare the motions of the therapist and patient and then to control the tactile stimulators in line with the results of this comparison. The virtual therapist realized the desired motion pattern (one motion every five seconds) and the EMG signals were recorded. Later, irregular motion patterns were realized by the virtual patient. These motions were discriminated by the LLGMN units for the patient and therapist and compared by the comparison unit. Fig. 4 shows (from the top) the raw EMG signals of the therapist and patient, the discriminated patient and therapist motions, the number of the tactile stimulator selected in line with the results of the comparison, and the generated control signals. Note that Motion 0 means no motion or suspended motion. According to the results, if there is a therapist motion and no patient motion, or if both motions exist but are different, the system is able to select and control the appropriate tactile stimulator.

2) Tactile stimulator effect: In order to show the tactile stimulator's effect, two different experiments were performed. In the first, tactile stimulators were selected in line with the desired motion patterns generated by the virtual therapist for 20 seconds, and were used to stimulate the virtual patient's skin surface. The virtual patient was then instructed to perform the correct motion without using visual feedback from the computer screen. The experimental results for three different trials are shown in Fig. 5. In the first trial, the virtual patient was able to perform two of the four motions. However, even in the successful motions, there were delays in the virtual patient's motion response. In trials 2 and 3, the motion success rate increased and the motion response delay decreased.

In the second experiment, the patient's performance was tested in terms of motion response delay. In this regard, the virtual therapist generated the desired motion pattern from four possible motions. Then, according to the generated motion pattern, the tactile stimulators were selected and the virtual patient's skin surface was stimulated. Each trial included three motions for twenty seconds, and fifteen trials were performed. The mean value of the motion response delay was computed using three motions in each trial. Fig. 6 shows the mean value of the patient's motion response delay with respect to the number of trials. As seen in Fig. 6, the virtual patient performed the motions with a mean motion response delay of about two seconds in the first trial and one second in the second trial. The difference here stems from the virtual patient's efforts to adapt to the effect of the tactile stimulator. The first seven trials resulted in an unstable mean response delay value, but after the seventh trial, the virtual patient was able to perform the motions more stably and with a lower level of motion response delay compared to the previous trials.

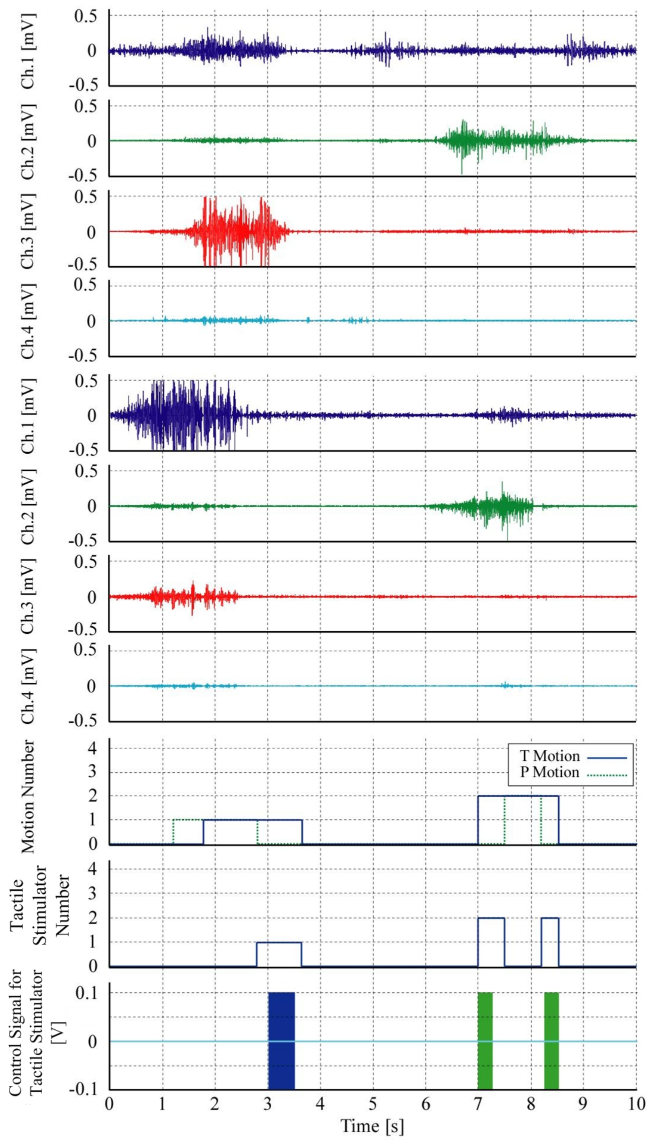

Fig. 4 Examples of experimental results (from the top): raw EMG signals of therapist and patient, discriminated motions, selection of tactile stimulators

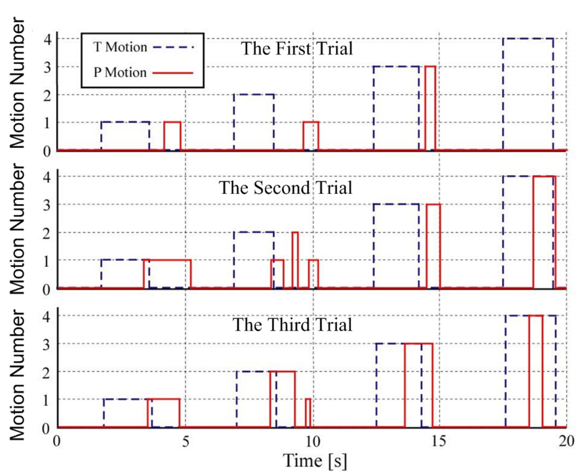

Fig. 5 The effect of tactile stimulators

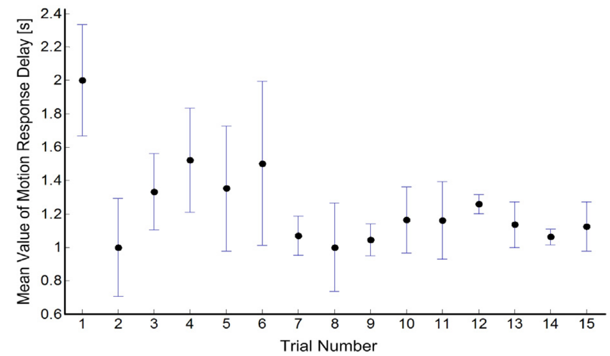

Fig. 6 Mean value of the virtual patient's motion response delay for different trials

In the first seven instances, the differences between the maximum and minimum mean values of the motion response delay was about one second, but fell to approximately 0.3 seconds between the eighth and fifteenth trials. On the other hand, the standard deviations of the motion response delay values between the eighth and fifteenth trials were smaller than those for the first seven trials. This shows that the response of the virtual patient was improved depending on the number of trials, and that the response went up to more stable levels. These results indicate that patients should undergo preliminary training for adaptation to the effects of the tactile stimulator prior to the treatment process. The level of motion accuracy was high in all the trials.

C. Discussion

The factors affecting the mean value of the motion response delay given in Fig. 6 are as follows: 1) The most dominant factor is the virtual patient, who feels the effect of the tactile stimulator and decides on/starts motion after its stimulation. 2) Two computers were used for the experiments, but not synchronized. Although the two machines had the same DAQ-card sampling time, constant delays were observed between the computers. 3) The control signals of the tactile stimulators were provided by a subprogram, which was continuously called by the software. This explains why, in some motions, the 0.25-second interval in the control signals matched the desired motion command of the virtual therapist. Nevertheless, during the experiments, it was generally observed that the virtual patient started the motion with a delay of at least one second after the tactile stimulator's stimulation, and this was also acknowledged by the virtual patient. In these experiments, four-channel EMG signals were used. During the discrimination process, the LLGMN unit sometimes failed to discriminate the motions accurately, because the discrimination results changed according to limb position. An EMG measurement equipped with a higher number of channels than four should be used to resolve this problem. In this study, the proposed system can compare the motions and stimulate the tactile stimulators for the situations of therapist motion but no patient motion, and therapist motion with a differing patient motion. However, situations involving patient motion but no therapist motion may also arise. In such cases, a different tactile stimulator should be used to stimulate the patient's skin surface. For this purpose, more than four tactile stimulators may be required. In this study, the selection of tactile stimulators was performed according to motion with a constant vibration level. However, some motions are related to more than one muscle. If the tactile stimulators are selected and stimulation is made in accordance with the EMG patterns, more effective and realistic results can be obtained.

V. Conclusion

In this study, a Cybernetic Rehabilitation Aid is proposed under the concept of direct teaching that uses tactile feedback with an EMG-based motor-skill evaluation function to accurately evaluate the motor skills of patients and teach them such skills simultaneously in a single system. To this end, a human–machine–human (physiotherapist–rehabilitation robot–patient) interface known as a Cybernetic Interface Platform was developed. It uses biological signals not only to monitor the patient's motor skills but also to directly teach such skills. The results of the experiments are summarized below:

- The proposed system can discriminate and compare therapist and patient motion patterns.
- According to the results of the comparison, it can select and activate tactile stimulators to stimulate the patient's skin surface.
- The virtual patient was able to feel the effect of the tactile stimulators on the surface of the skin and make the correct motion according to the stimulation.

In future research, we plan to realize the process of selecting and stimulating tactile stimulators by employing EMG patterns. More tactile stimulators will be used to analyze the negative error originating from comparison between the therapist and patient motions. In order to determine the effect of tactile stimulators in the different working modes of the CRA, a number of experiments will be performed. In addition, we would like to show the performance of the system with different parameters using the rehabilitation robot with real therapists and patients.

Acknowledgement

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