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Simultaneous Control of Tonic Vibration Reflex and Kinesthetic Illusion for Elbow Joint Motion Toward Novel Robotic Rehabilitation

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***Abstract*— Robotic rehabilitation is one of the most promising applications of robotic technologies. It is known that patients' active participation in rehabilitation is important for their recovery. On the other hand, mechanical vibration stimulation to muscles induces tonic vibration reflex (TVR) and kinesthetic illusion (KI) in the joint motion. In this paper, the possibility of a novel robotic rehabilitation method, in which the TVR is applied to an agonist muscle to enhance the intended motion of patients and the KI is simultaneously applied to an antagonist muscle to enhance the kinesthetic movement sensation of the generating intended motion by changing the frequency of vibration stimulation, is investigated. As the first step toward novel robotic rehabilitation, the proposed method is evaluated in elbow joint motion. The experimental results show the possibility of the proposed novel rehabilitation method.**

***Clinical Relevance*— This study shows the possibility of novel robotic rehabilitation.**

I. Introduction

Many stroke survivors or spinal cord injury patients suffer from movement disorders. Robotic rehabilitation is one of the most promising applications of robotic technologies. Many rehabilitation robots have been developed to realize effective rehabilitation for stroke or spinal cord injury patients [1]-[4]. It is known that patients' active participation in rehabilitation is important for their recovery. Several effective control strategies of rehabilitation robots such as assist-as-needed strategies [5]-[8] have been proposed to take into account the active participation of patients in rehabilitation. Hybrid robotic assistance is one of the emerging technologies in robotic rehabilitation [9]-[11]. In hybrid robotic rehabilitation systems, electric stimulation and/or vibration are/is used in addition to robot assistance to improve motor functions.

On the other hand, mechanical vibration stimulation of muscles induces tonic vibration reflex (TVR) [12] and kinesthetic illusion (KI) [13] in human joint motion. The TVR is involuntary muscle contraction induced by certain mechanical vibration stimulation. Therefore, unintended joint motion is generated by the TVR. The KI is the illusion in which the vibrated muscle is stretched by the effect of certain mechanical vibration stimulation. Therefore, a person feels as if his/her joint is moving even though the joint is not actually moving. The effect of the KI has been applied in rehabilitation to generate artificial feelings [14]. The effect of the TVR has also been applied in rehabilitation to generate motor responses [15]. The amount of these effects is changed in accordance with parameters such as the frequency of mechanical vibration. Recently, these effects have been applied to modify human motion [16] or suppress undesired tremor motion [17].

In this paper, the possibility of a novel robotic rehabilitation method, in which the TVR is applied to an agonist muscle to enhance the intended motion of patients and the KI is applied to an antagonist muscle to enhance the kinesthetic movement sensation of the generating intended motion of the patients at the same time by changing the frequency of vibration stimulation, is investigated assuming that the intended motion of the patients can be estimated with patients' biological signals such as electromyography (EMG) [18] or electroencephalography EEG [19]. The proposed method enables patients to generate the intended motion and its movement sensation for neurorehabilitation. It is not easy, however, to separately control both the TVR and the KI at the same time in the same muscle since they are induced in a similar frequency range. Whether the movement induced by the TVR and the sense of its movement induced by the KI on antagonist muscles can be generated at the same time by adjusting the frequency of vibration stimulation is experimentally investigated in this paper. As the first step toward novel robotic rehabilitation, the proposed method is evaluated in elbow joint motion. The experimental results show the possibility of the proposed novel rehabilitation method.

II. Effect of Mechanical Vibration Stimulation

A. Tonic Vibration Reflex (TVR)

Mechanical vibration stimulation of muscles induces the TVR [12], so that involuntary muscle contraction is induced in the vibrated muscle. It has been confirmed that the frequency of vibration stimulation from 20 to 200 Hz is an effective range to induce TVR. In the effective frequency range, the amount of the TVR is affected by the frequency of the vibration stimulation. Johnston *et al.* reported that the maximum amount of the TVR is induced with vibration stimulation at approximately 120 Hz in biceps muscles [20]. Thus, if the relationship between the amount of the TVR and the frequency of the vibration stimulation is known, the desired amount of TVR can be induced to generate the intended movement by adjusting the frequency of the stimulating vibration to a patient.

B. Kinesthetic Illusion (KI)

Mechanical vibration stimulation of muscles also induces the KI [13], which is a sensory illusion that the person feels as

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if the vibrated muscle is stretched. It has been reported that the effect of the KI increases in the vibration frequency range from 30-70 Hz and decreases in the vibration frequency range from 70-100 Hz in biceps and triceps [21]. Therefore, a vibration stimulation frequency range from 50 to 80 Hz can effectively induce the KI. This means that the effective frequency range for the KI is completely included in that for the TVR. Therefore, it is not easy to generate either of them alone.

III. Proposed Method

In this paper, a novel robotic rehabilitation method in which the intended joint motion of the patients is enhanced by the effect of the TVR and the kinesthetic movement sensation of its motion is enhanced by the KI effect is proposed. To realize the proposed robotic rehabilitation, the TVR and KI must be separately controlled in both the agonist muscle and the antagonist muscle at the same time by changing the vibration stimulation frequency. To investigate the possibility of the proposed method, in this study, experiments are performed for elbow joint flexion/extension motion.

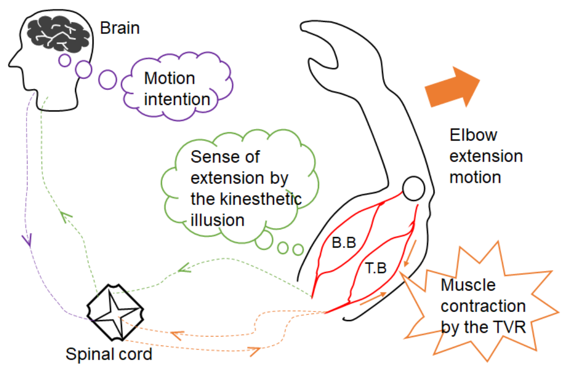


Figure 1. Concept of the proposed method for elbow joint extension motion

The concept of the proposed method for the elbow joint extension motion is shown in Fig. 1. When the patient performs elbow joint extension motion, the TVR is induced in the triceps brachii muscle to enhance the elbow joint extension motion and the KI is induced in the biceps brachii muscle to enhance the kinesthetic movement sensation of its motion at the same time. In this case, the TVR must be induced without inducing the KI in the triceps brachii muscle and the KI must be induced without inducing the TVR in the biceps brachii muscle. On the other hand, when the patient performs elbow joint flexion motion, the TVR is induced in the biceps brachii muscle to enhance the elbow joint flexion motion and the KI is induced in the triceps brachii muscle to enhance the kinesthetic movement sensation of its motion at the same time. In this case, the TVR must be induced without inducing KI in the biceps brachii muscle and the KI must be induced without inducing TVR in the triceps brachii muscle.

To realize the proposed method, a higher frequency of approximately 140 Hz is preferred for the agonist muscle to induce only the TVR without the effect of the KI since frequencies lower than 110 Hz might induce the KI [22][23]. On the other hand, a lower frequency of approximately 60 Hz is preferred for the antagonist muscle to induce only the KI with vibration stimulation although the effect of the TVR cannot be avoided perfectly.

IV. Experiments

Experiments were carried out to investigate whether vibration stimulation can generate motion in an antagonist muscle by the TVR and sense of movement by the KI in an antagonist muscle at the same time. The experimental procedures were approved by the research ethics committee of Kyushu University, School of Engineering (H28-04).

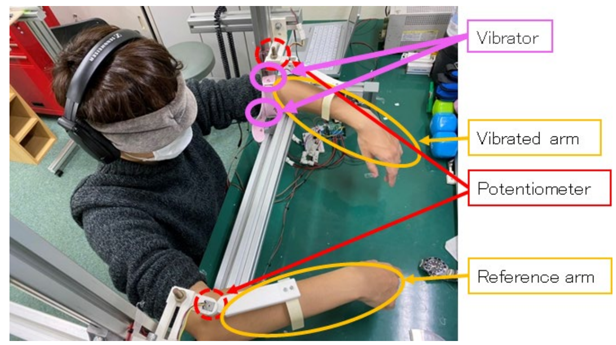


Figure 2. Experimental setup

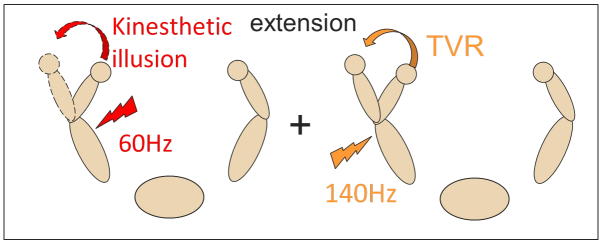
A. *Experimental Appratus*

The experimental setup is shown in Fig. 2. Vibrators were attached to the biceps brachii and triceps brachii muscles on the left arm (vibrated arm) of the subjects. The amplitude of the vibrator was 1.0 mm and its frequency can be adjusted between 20 and 140 Hz. The initial contact force of the vibrator attachment is 4 N. The subject was instructed not to move the left arm spontaneously during the experiments. Therefore, the amount of the joint movement of the left arm during the experiment indicates the effect of the TVR. The forearms of the subject were positioned in the pronated posture. The right arm of the subject was used as a reference arm which indicates how the subject senses the elbow joint angle in the left arm (vibrated arm). The elbow angles of the subject were measured with potentiometers. The subject wore an eye mask and a headphone to exclude visual and auditory sensation during the experiment. Experiments were carried out with three healthy males. Table I shows the data on the age, sex, height, and weight of each subject.

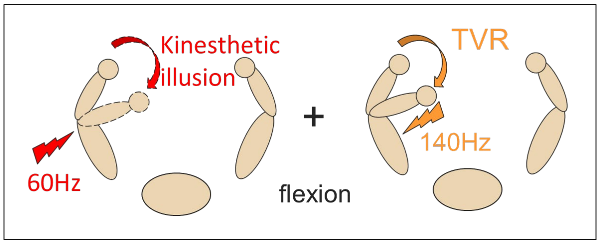
In the experiments, the frequency given to the agonist muscle for the TVR was 140 Hz and that given to the antagonist muscle for the KI was 60 Hz as shown in Fig. 3.

TABLE I. Perticipant Details

	Gender	Age	Weight [kg]	Height [m]
Subject 1	Male	21	60	1.76
Subject 2	Male	22	71	1.78
Subject 3	Male	22	65	1.68



(a) Elbow extension



(b) Elbow flexion

Figure 3. Experiments

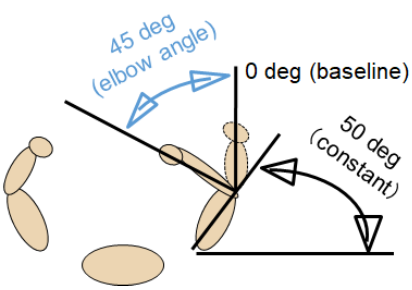


Figure 4. Initial position

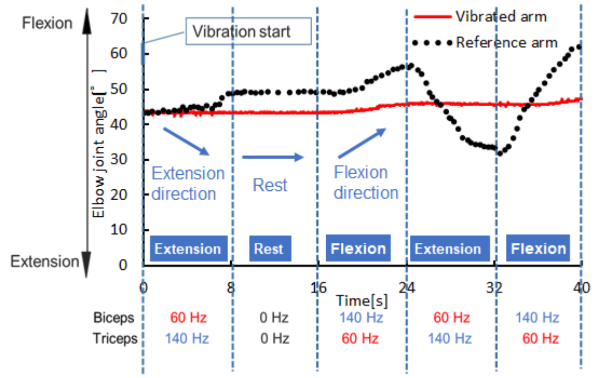
The initial position in the experiments is shown in Fig. 4. To exclude the effect of gravity, elbow joint motion is generated in the horizontal plane.

B. Experimental Protocol

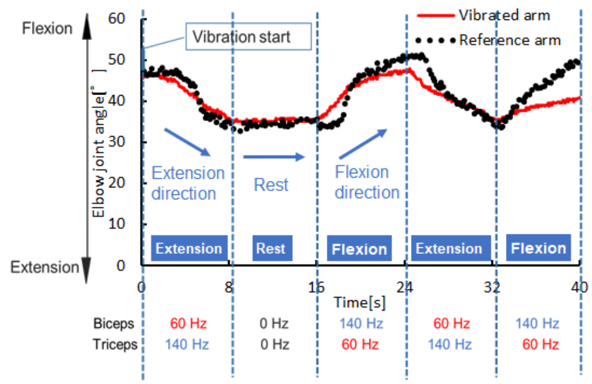
The subjects were asked to relax their left arm (vibrated arm) and match the elbow joint angle between left and right using the right arm (reference arm) during the experiment. The experiment for each subject was carried out as shown in Fig. 5. The elbow joint extension motion was given to the subject for the first 8 s in the experiment, then the elbow flexion motion and the elbow extension motion were repeated in turn after a rest time of 8 s. During the elbow joint extension, a frequency of 140 Hz was applied to the triceps muscle and simultaneously 60 Hz was applied to the biceps muscle so that TVR was induced in the triceps muscle and KI was induced in the biceps muscle. Additionally, during elbow joint flexion, 60 Hz was applied to the triceps muscle and 140 Hz was applied to the biceps muscle at the same time so that TVR was induced in the biceps muscle and KI was induced in the triceps muscle.

	Extension →	Rest →	Flexion →	Extension →	Flexion
	0 s ~ 8 s	8 s ~ 16 s	16 s ~ 24 s	24 s ~ 32 s	32 s ~ 40 s
Biceps	60 Hz	0 Hz	140 Hz	60 Hz	140 Hz
Triceps	140 Hz	0 Hz	60 Hz	140 Hz	60 Hz

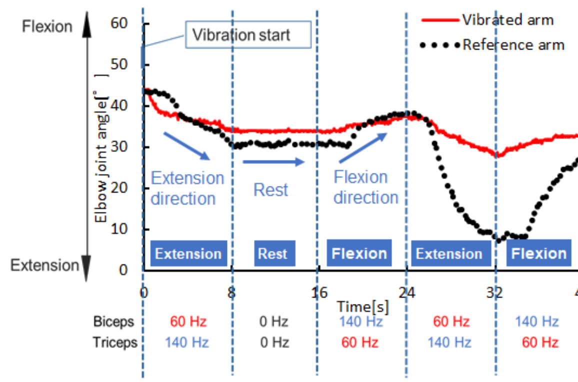
Figure 5. Experiment for each subject



(a) Subject 1



(b) Subject 2



(c) Subject 3

Figure 6. Experimental results

V. Experimental Results

Figure 6 shows the experimental results for all subjects. The results for subjects 2 and 3 show that the TVR and the KI for the target joint motions are simultaneously induced although the result of the TVR for subject 1 is not prominent. Generated flexion/extension angles during each 8 s are described in Table II. It is confirmed that the TVR is induced in the biceps brachii muscle and the KI is induced in the triceps brachii muscle at the same time for the elbow joint flexion motion, and the TVR is induced in the triceps brachii muscle and the KI is induced in the biceps brachii muscle at the same time for the elbow joint extension motion. These experimental

TABLE II. Generated Angles

		0s~8s Extension	8s~16s Rest	16s~24s Flexion	24s~32s Extension	32s~40s Flexion
Subject1	Vib. arm	-0.73	0	2.54	0	1.82
	Ref. arm	5.45	0.36	7.26	-22.5	29.75
	Ref-Vib	6.18	0.36	4.72	-22.5	27.93
Subject2	Vib. arm	-10.88	-0.73	11.98	-11.25	5.44
	Ref. arm	-11.61	1.09	14.51	-14.51	13.79
	Ref-Vib	-0.73	1.82	2.53	-3.26	8.35
Subject3	Vib. arm	-10.16	0	3.63	-9.8	5.45
	Ref. arm	-13.06	0.36	7.26	-29.76	19.6
	Ref-Vib	-2.9	0.36	3.63	-19.96	14.15

results also show that the responses of the TVR and the KI become larger after 24 s. This can be explained by the phenomenon that the TVR is increased at the onset of vibration stimulation [12][24] and the effect of the KI is enhanced with a possible joint movement [25]. Since rehabilitation motion is repeatedly performed, this phenomenon is suitable for the rehabilitation. Thus, simultaneous stimulation to the biceps and triceps muscles can induce TVR in an agonist muscle and KI in an antagonist muscle, and continuously generate elbow joint motion and its movement sensation.

VI. Conclusion

In this paper, the possibility of a novel robotic rehabilitation method, in which the TVR in the agonist muscle was applied to generate the intended motion and the KI in the antagonist muscle was simultaneously applied to enhance the feeling of generating the intended motion, was investigated by adjusting the frequency of the vibration stimulation. The experimental results showed the possibility of the proposed novel rehabilitation method.

The proposed TVR and KI simultaneous generation method for rehabilitation should be applied in conjunction with the intended motion estimation of the patient because active participation of the patient is necessary for the effective rehabilitation. Consequently, further study on real-time intended motion estimation of the patients is necessary to realize the proposed robotic rehabilitation.

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