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# Fundamental Study on the Influence of Muscle Fatigue on Tonic Vibration Reflex

Wenbin Liu, *Member, IEEE,* Youwei Chen, Kazuo Kiguchi, *Senior Member, IEEE* and Mikhail Svinin, *Member, IEEE*

***Abstract*— The tonic vibration reflex (TVR) phenomenon refers to the sustained involuntary contractions induced in skeletal muscles when subjected to mechanical vibration stimulation. Thus, utilizing vibration stimulation to induce involuntary limb movements promises to become a novel technique for human motion adjustment based on external devices. In recent years, an increasing number of studies have focused on how to apply TVR in welfare domains, such as tremor suppression and rehabilitation training. However, the characteristics of the TVR induced by vibration stimulation may vary across different muscle states, and changes in TVR effects under conditions of muscle fatigue have not been systematically investigated. In this study, by applying mechanical vibration stimulation to the tendon of origin in biceps brachii, the primary muscle in elbow flexion movements, the changes in the effects of TVR induced by vibration stimulation under muscle fatigue conditions are compared. Through experimentation, this study confirmed the efficacy of vibration stimulation-induced TVR in producing limb movements and investigated the variations in reflex intensity under different muscle fatigue states.**

## I. INTRODUCTION

In recent years, welfare robots have been extensively employed to assist the elderly and disabled with daily tasks, social interactions, and rehabilitation training [1]. Among these, the technique of utilizing external devices, such as actuators, to exert external forces and adjust human movements plays a critical role in assisting individuals [1]. On the other hand, when mechanical vibratory stimulation is applied to muscles, it can induce a phenomenon known as the tonic vibration reflex (TVR), characterized by sustained contractions of the stimulated muscles [2]. Since this reflex can lead to involuntary muscle contractions and consequently alter human movements, numerous studies are dedicated to exploring mechanical vibratory stimulation as a novel motion adjustment technology within the field of welfare robotics [3]-[5].

The TVR is triggered by the stimulation of primary afferent fibers through vibratory input and is capable of being elicited in all extensor and flexor muscles of both the upper and lower limbs [6]-[8]. Additionally, it is noted that the neural pathway involved in the TVR is confined to the spinal cord and does not involve the brain [9], indicating that muscle contractions occur independently of conscious control. Given its fundamental role in inducing muscle contractions and motor responses, the TVR has been explored in several studies for its potential applications in sensorimotor rehabilitation [3], prosthetics [4] and tremor suppression [5].

TVR is generated during the contact process between mechanical vibration and muscles, making it crucial to study the effects of different types of mechanical vibrations and muscle states on TVR efficacy. TVR is triggered by vibration stimulation ranging from 20 to 300 Hz, with observations indicating that reflex intensity escalates with increasing frequency [2]. Additionally, Demedt observed that enhancing the amplitude of vibration from 0.4 to 1.6 mm on the masseter muscle elevated the EMG potential of the affected muscle [10]. Furthermore, variations in reflex responses have been noted based on the muscular condition at the time of stimulation and individual variances among subjects [9].

Previous studies have also indeed identified that the intensity of the TVR is readily influenced by the state of the muscle. For instance, changes in muscle contractility or muscle temperature can alter the muscle's responsiveness to vibration stimulation, as well as the intensity of the TVR [2]. Elucidating these variations is crucial for the application of TVR, as it impacts the effectiveness of mechanically induced TVR. However, the influence of muscle fatigue on TVR has not been systematically explored. In this study, by applying mechanical vibration stimulation to the tendon of origin in biceps brachii, the primary muscle in elbow flexion movements, the changes in the effects of TVR induced by vibration stimulation under muscle fatigue conditions are investigated.

## II. METHODS

### A. Experimental aim

In this study, continuous mechanical vibration stimulation was applied to the biceps brachii of the upper limb. By comparing the intensity of the TVR in both fatigued and non-fatigued states of this muscle, this study aimed to investigate the impact of muscle fatigue on the TVR response induced by mechanical vibration stimulation.

### B. Experimental setup

This experiment involved three subjects, all of whom were in good health with no conditions that could potentially impair mobility. Additionally, none of the subjects engaged in high-intensity exercise in the three days prior to the experiment, ensuring that all were in a non-fatigued state at the start of the trial. Specific details regarding the subjects are presented in Table 1.

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W. Liu is with College of Information Science and Engineering, Ritsumeikan University, Osaka 567-8570, Japan (phone: +81-70-1826-4059; e-mail: liu-wb@fc.ritsumei.ac.jp).

Y. Chen is with Chongqing University of Posts and Telecommunications, School of Advanced Manufacturing Engineering, Chongqing 400065, China (e-mail: 13830792537@163.com).

K. Kiguchi is with the Department of Mechanical Engineering Kyushu University, Fukuoka 819-0395, Japan (e-mail: kiguchi@ieee.org).

M. Svinin is with College of Information Science and Engineering, Ritsumeikan University, Osaka 567-8570, Japan (e-mail: svinin@fc.ritsumei.ac.jp).

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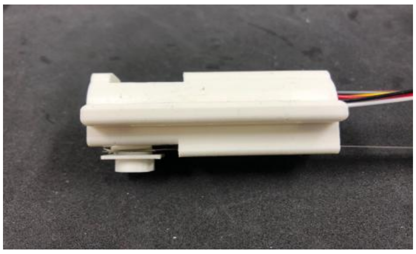
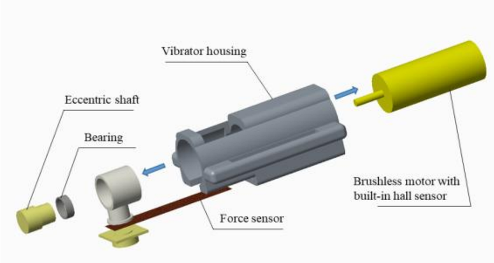
TABLE I. BASIC INFORMATION TABLE OF SUBJECTS

| Subject | Gender | Age | Height (cm) | Weight (kg) |
|---|---|---|---|---|
| 1 | Male | 20 | 175 | 70 |
| 2 | Male | 19 | 178 | 67 |
| 3 | female | 20 | 152 | 48 |

Mechanical vibration was applied to the tendons of the biceps brachii using our custom-made vibrator. The appearance and structure of the vibrator are shown in Figure 1. A compact brushless motor (Maxon Motor, ECXSP16M) is integrated into the housing of the vibrator. Attached to the motor's output shaft is a rotation shaft with 1.5 mm of eccentricity, which is responsible for generating the vibratory stimulation. This eccentricity functions as a crank, setting the stimulation's amplitude at 3 mm. The device is capable of operating across a frequency range from 20 Hz to 250 Hz. Vibration frequency is regulated by adjusting the motor's angular velocity. To monitor the rotation duration of the motor and ascertain the vibrator's frequency, a hall sensor is incorporated within the device. Additionally, a force sensor (Tekscan, Flexiforce) is utilized to gauge the contact force between the vibrator and the skin.



(a) The appearance



(b) The structure

Figure 1. Vibrator

A specific MPU6050 sensor, functioning as an angle detector, was employed to track the forearm's elevation angle following vibratory stimulation to the biceps brachii. This sensor features a built-in gyroscope that provides real-time updates on angular changes. The sensors were connected to an Arduino UNO microcontroller using the I2C protocol at a frequency of 50 Hz. The UNO’s AD converter transformed the analog signals from the sensors into digital format, and the angular velocity data of the forearm were instantly recalculated into angle measurements. To refine the data, a Kalman filter was used to selectively extract essential information from the sensor outputs, effectively minimizing noise. The sensors themselves were fastened to the skin with a flexible strap for stability and accuracy.

The degree of muscle fatigue was inferred from the electromyographic (EMG) signals of the biceps brachii. The EMG signals were analyzed in the frequency domain using MATLAB software, with changes in mean frequency used to determine if the biceps brachii was fatigued. The predictive method involves initially preprocessing the EMG data with bandpass filtering, followed by converting the signal into the frequency domain using Fast Fourier Transform (FFT), and finally analyzing the spectrum to detect shifts toward lower frequencies indicative of muscle fatigue. The muscle was considered fatigued when there was an 8-10% decrease in the EMG mean frequency [11]. In this experiment, the Cometa PicoX was employed to detect the EMG signals, with a sampling rate of 2000Hz. Figure 2 shows the placement of the vibrator and the two types of sensors.

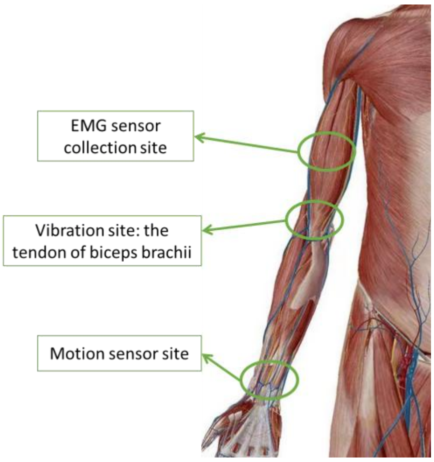


Figure 2. Vibrator and sensor site

### C. *Experimental procedure*

The experimental procedure for the three subjects was identical and is described as follows:

Prior to the start of the experiment, EMG signals were collected from the biceps brachii of the subjects' right arms. They were asked to sit upright at a desk, resting their forearm on the table, and contracts their biceps brachii with maximum effort (shown in Fig. 3). EMG signals were measured for 30 seconds and subjected to frequency domain analysis. The mean frequency of this set of EMG signals is considered the baseline for the muscle's normal state.

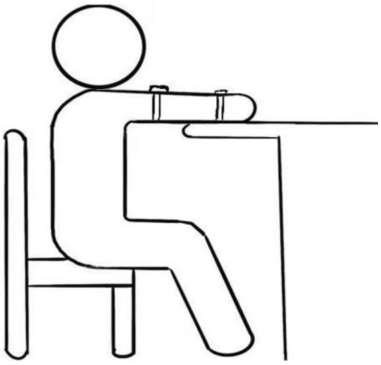


Figure 3. Subject's posture during the experiment

The subjects continued to maintain the posture shown in Figure 3 and keeps their right arm in a relaxed state. The vibrator was attached to the tendon of the right biceps brachii using an elastic strap tightened to the subject's comfort; the motion sensor was fixed face-up with straps at the subject's wrist. Vibratory tests were conducted at frequencies of 60Hz, 90Hz, and 120Hz, each lasting 8 seconds with a 1-minute interval between each trial. The experiment for each frequency was repeated three times. Each frequency experiment is repeated five times. All of the vibration stimulation condition are shown in the Table 2.

TABLE II. VIBRATION STIMULATION CONDITIONS

| | |
|---|---|
| **Amplitude (peak to peak)** | 3.0 mm |
| **Frequency** | 60, 90, 120 Hz |
| **Initial contact force** | 3 N |
| **Vibration Duration** | 8 s |

To induce a state of fatigue, after completing all three vibration trials, the vibrator and angle detector were removed. The subject then extended their right arm forward, holding a 3kg dumbbell, and remained still until signs of fatigue were noticeable. EMG data were recorded for 30 seconds after the subject reported significant fatigue. The peak frequency of this EMG signal was analyzed again and compared with the previously determined mean frequency for the fatigued state. If a decrease of more than 10% in mean frequency was observed, it was concluded that the right biceps brachii of the subject had entered a state of fatigue, at which point the next phase of the experiment could begin. Vibration stimulation tests were then continued in this state of fatigue using the same parameters as in the non-fatigued state. This marked the completion of all tests for the subject.

To minimize the influence of subjective human factors on the experimental results, each test began with the subject in a relaxed state. Additionally, the subjects' vision and hearing were obstructed, and they were not informed of the specific start and end times of each test group. Any flexion movement of the elbow joint observed during the experiment was attributed to the effects of the vibration stimulation.

### *D. Data Analysis Methods*

The elbow joint angle $\theta$ is defined as 0° when the arm is in a relaxed, upright position, with positive angles indicating extension from this state. To evaluate the degree of change in elbow joint angle for each subject before and after vibration stimulation, the average change in elbow joint angle was calculated using the following steps. First, based on the experimental results showing the transitions in elbow joint angle, the change in elbow joint angle was determined by subtracting the elbow joint angle at the start of vibration stimulation from that at the end. This is expressed by the following equation:

$$\phi = \theta_{Time=8[s]} - \theta_{Time=0[s]} \qquad (1)$$

After calculating the change in elbow joint angle for each trial at each frequency, the average change in elbow joint angle across all trials was determined.

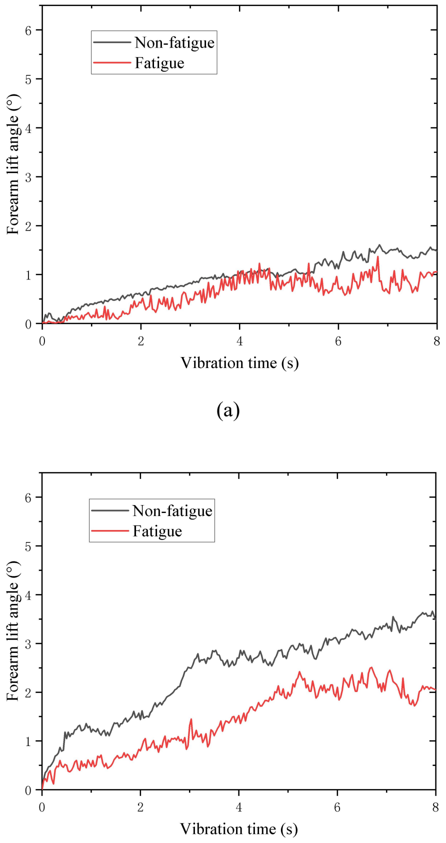
## III. EXPERIMENTAL RESULTS AND DISCUSSION

The average frequency reduction rates of the EMG signals from the three subjects are shown in Table 3. Based on this data, it can be determined that the muscle fatigue levels of the subjects differed between the two experiments, indicating that the muscles had entered a state of fatigue during the second vibration experiment.

TABLE III. CHANGE RATE OF MEAN EMG FREQUENCY OF SUBJECTS

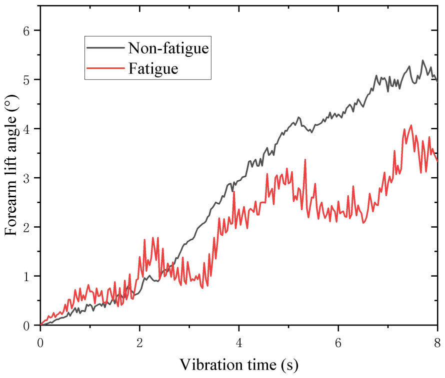
| Subject | Mean frequency decline rate (%) |
|---|---|
| 1 | 12 |
| 2 | 11 |
| 3 | 10 |

In this experiment, the strength of the TVR is represented by the elbow joint angle generated by the forearm lift caused by the contraction of the biceps brachii. A larger generated angle indicates a greater TVR strength. Figure 4 displays the changes in elbow joint angles (i.e., the elevation angle of the forearm caused by the TVR) at different vibration frequencies for a typical subject (Subject 1, trial 1). As shown, with increasing vibration stimulus frequency, the magnitude of change in the elbow joint angle also increases. Additionally, at the same vibration frequency, the change in elbow joint angle under fatigue conditions is lower than in the non-fatigued state, and there is more oscillation in the forearm during lifting, with the elevation curve showing significantly greater fluctuation compared to the non-fatigued state.



(a)

(b)



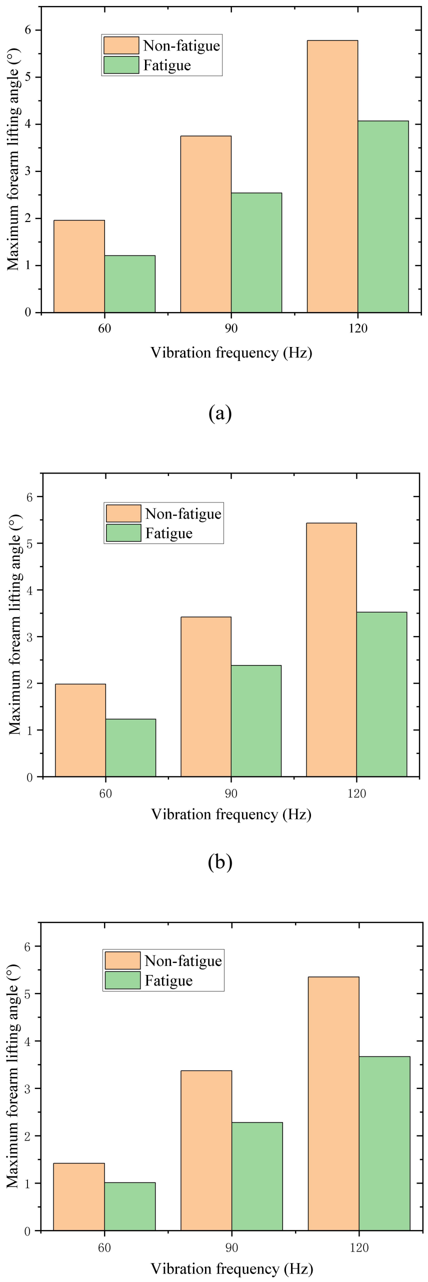
(c)

Figure 4. Vibration stimulation of subject 1 at different frequencies: (a) 60Hz, (b) 90Hz, (c) 120Hz

Figure 5 summarizes the average changes in elbow joint angles for all three subjects under different conditions, with similar experimental results observed among them; specifically, there is a notable reduction in TVR intensity when the muscles are in a fatigued state. Table 4 shows the reduction ratio of the average angle change in fatigued muscles compared to the non-fatigued state. It can be observed that the effectiveness of the TVR decreases by approximately one-third when the muscles enter a fatigued state. The reduction in TVR intensity shows little variation across different vibration frequencies.

Overall, under otherwise constant conditions, changes in muscle fatigue have a significant impact on the intensity of TVR induced by mechanical vibration stimulation. The strength of the TVR is notably weakened when the muscles are in a fatigued state. There is a recognized flaw in the current experimental setup, where the subjects' arms are laid flat on the table. This posture does not eliminate the influence of gravity, which may cause a reduction in the generated elbow joint flexion angle. The results show that, under fatigue conditions, the angle differs by about 2.0 to 3.0 degrees compared to the non-fatigued state. While this difference may not be particularly noticeable in upper limb movements, it is considered a significant change under the conditions of this experimental setup.

These findings are hoped to inspire the application of the TVR in the welfare sector, such as in rehabilitation training for stroke patients, tremor suppression, prosthetics, and other areas. As a preliminary step, the study initially focused on healthy subjects. However, the relationship between muscle fatigue and the intensity of TVR may vary between healthy individuals and those with illnesses. Future experiments will need to be conducted on specific patient populations.



(c)

Figure 5. Average angle change of forearm of three subjects: (a) subject 1, (b) subject 2,(c) subject 3

TABLE IV. FATIGUE STATE AND NON-FATIGUE STATE AVERAGE ANGLE CHANGE REDUCTION RATIO

| **Subject** | **Average angle change reduction ratio (%)** | | |
|---|---|---|---|
| | **60Hz** | **90Hz** | **120Hz** |
| 1 | 39 | 33 | 38 |
| 2 | 41 | 34 | 33 |
| 3 | 27 | 40 | 35 |

## IV. CONCLUSION

This study investigated the effects of mechanical vibration stimulation on the TVR in the biceps brachii under conditions of muscle fatigue. The findings confirmed that vibration-induced TVR can successfully produce involuntary limb movements, as evidenced by the changes in elbow joint angles. However, when the muscle was fatigued, the intensity of the TVR was reduced, resulting in lower joint angle changes and greater fluctuations in forearm movement during lifting. These results highlight the influence of muscle fatigue on TVR efficacy, emphasizing the importance of considering muscle condition when applying TVR in rehabilitation and welfare robotics. Future work will explore the variations in TVR effects across different muscles under varying levels of fatigue.

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