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Generation of Kinesthetic Illusion and Tonic Vibration Reflex Response in Trunk Flexion and Extension Motion with Mechanical Vibration Stimulation

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Abstract—**Mechanical vibration stimulation to muscles influences human motion through the phenomena of kinesthetic illusion (KI) and tonic vibration reflex (TVR). On the other hand, some people suffer from disability of their motor functions. Trunk flexion and extension are essential movements involved in many daily activities and often play a critical role in coordinating with limb motions. The effects of vibration stimulation on trunk muscles involved in flexion and extension might be applicable for the rehabilitation of the people suffer from disability of their motor functions. This research applies mechanical vibration stimulation to the trunk muscles for the aim of rehabilitation, measuring the resultant KI and TVR in the motion of trunk flexion and extension, comparing the outcomes across different vibration frequencies.**

INTRODUCTION

Motor disorders caused by stroke and spinal cord diseases significantly impact the daily lives of many patients. Mechanical vibration stimulation has emerged as a promising technology in the field of motor rehabilitation. Mechanical vibration stimulation to muscles, which can induce phenomena such as kinesthetic illusion (KI) and the tonic vibration reflex (TVR), alters the contraction and proprioception of the stimulated muscles and is developing into a technique for human motion modification [1]-[4]. In recent years, many studies have focused on the application of mechanical vibration stimulation in the field of human assist robotics, such as perception assist [1], tremor suppression [2], rehabilitation exercises [3], and prosthetics [4]. KI is a phenomenon in which the stimulated muscle generates the sensation of performing joint movements related to its extension when mechanical vibration is applied to the muscle. In other words, by stimulating the antagonist muscles of a specific joint movement, a person can experience the sensation of performing that movement [5]. When muscles are subjected to vibration stimulation, the TVR phenomenon typically occurs simultaneously with the appearance of the KI phenomenon. TVR is a phenomenon of involuntary muscle contraction in response to vibration stimulation, first discovered by Eklund *et al.* in 1966 [6][7].

A great deal of prior research has already been conducted on the characteristics of KI and TVR. Roll *et al.* [8] observed that when vibrations within the range of 10-120 Hz are applied to unloaded biceps and triceps brachii muscles, the most significant illusion occurs at 70 Hz. Similarly, Naito *et al.* [9] conducted a study using vibrations between 10-240 Hz on the unloaded elbow joint and found that the most pronounced KI is elicited at frequencies of 70-80 Hz. Based on these findings, they proposed that the maximum intensity of KI in muscles without load can be achieved at around 70 Hz. Moreover, other vibration factors, such as amplitude and initial contact force, are also believed to influence both the threshold and intensity of KI [10]. Additionally, it is recognized that muscle tone, along with individual differences such as gender and dominant hand, also affect KI [11]. On the other hand, TVR is triggered by vibration stimulation with frequencies ranging from 20 to 300 Hz, with studies reporting that the magnitude of the reflex increases as the frequency rises [6]. Additionally, variations in reflex responses have been observed depending on the condition of the muscles receiving the vibration and individual differences between subjects [12].

This study investigates the potential of mechanical vibration stimulation on trunk muscles to induce KI and TVR in flexion and extension movements, aiming to develop rehabilitation technologies that enhance motor control and support recovery in individuals with movement impairments. So far, existing research on KI and TVR has primarily concentrated on the joints of the limbs, such as the shoulder, elbow, wrist, knee, and ankle [1]-[14]. However, many daily limb movements also involve simultaneous trunk movements, making it equally important to investigate the generation of KI and TVR responses in trunk joint movements. Despite its significance, this aspect of research has not been thoroughly investigated. As a foundational study aimed at motor rehabilitation, this research explores the KI and TVR responses induced by mechanical vibration stimulation applied to trunk flexion and extension muscles. Specifically, mechanical vibration stimulation was applied to the related trunk muscles individually to determine whether it could induce KI and TVR responses. Furthermore, different vibration frequencies were tested to evaluate whether frequency variations influence the degree of movement changes, contributing to the development of rehabilitation strategies.

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METHODS

A. Experimental setup

In this study, the rectus abdominis and external oblique, which are superficial muscles primarily responsible for trunk flexion, and the iliocostalis lumborum, a superficial muscle primarily responsible for trunk extension, were selected due to their distinct functional roles in trunk movements and their accessibility for mechanical stimulation [15]. This research began by investigating whether stimulating these muscles could induce TVR and KI responses associated with trunk flexion and extension, as this had not been previously verified. As illustrated in Figure 1, subjects in standing postures received mechanical vibration stimulation applied individually to these muscles. One vibrator was applied to each side of these muscles, providing simultaneous vibration stimulation to both sides. Figure 2 outlines the structure of the vibrator, which is powered by a Carbon Brush Motor (Mabuchi Motor, RS-380PH). The motor's shaft coupling features an eccentricity of 1.5 mm, creating a vibration amplitude of 3.0 mm (peak to peak), with an adjustable frequency. The motor's rotation speed, measured by an Incremental Encoder (Nidec Copal Electronics, RE12D-300-201) attached to the eccentric shaft, is regulated using PD control to maintain constant target values, as processed by a microcontroller (Arduino, Arduino Mega). The initial force applied between the contact area and the skin, set at 3N, was measured using a Force Sensor (TekScan, FlexiForce A205-1). Trunk flexion and extension angles were calculated using motion capture system (OptiTrack, V120 Duo). Markers were placed on the cervical spine at C7, on the lumbar spine at L4, and on both sides of the lower back at the same height as the L4 marker. The initial standing posture was adjusted to ensure that the markers on both sides of the lower back had identical *y*-axis (forward-backward) and *z*-axis (up-down) values, minimizing potential lateral or rotational deviation. The flexion and extension angles were calculated based on the positional data of the markers on the cervical spine and lumbar spine. This study investigated KI of these three muscles by varying the vibration frequencies at 20 Hz intervals (60, 80, and 100 Hz), and the TVR by adjusting the frequencies at 30 Hz intervals (60, 90, and 120 Hz). The vibration stimulation lasted for 10 seconds in each trial. The experiments involved three healthy subjects (two male subjects and one female subject) with an average age of 32 years. Detailed information on each subject's gender, age, weight, and height is provided in Table 1. All subjects were free from any history of neurological or muscular disease. To minimize external distractions, they were equipped with eye masks and earphones. The experiments have been approved by the research ethics committee of Kyushu University, School of Engineering (H28-04).

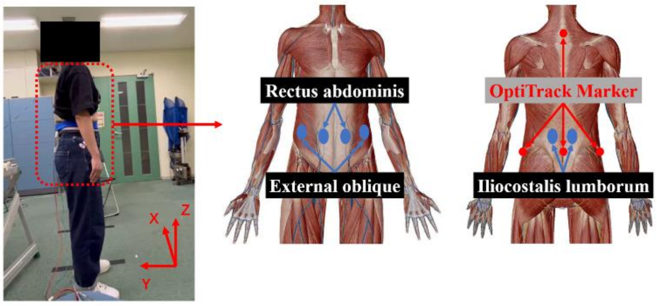
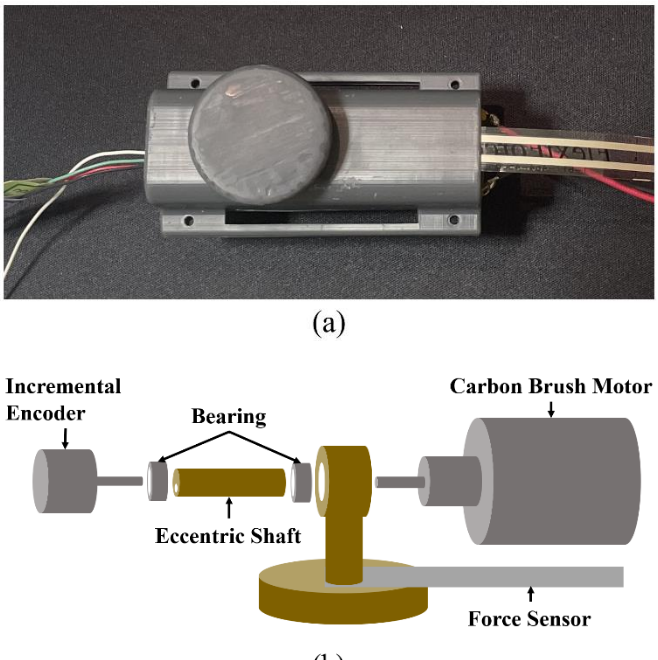


Figure 1. Stimulation site.



(a)

(b)

Figure 2. Vibrator outline and structure.

INFORMATION OF SUBJECTS

	Gender	Age	Weight [kg]	Height [m]
Subject 1	Female	31	53	1.60
Subject 2	Male	31	68	1.74
Subject 3	Male	34	70	1.68

B. Experimental procedure

In this study, two experiments were conducted. Continuous vibration stimulation was applied to the rectus abdominis, external oblique, and iliocostalis lumborum muscles, respectively. In Experiment 1, subjects were instructed to maintain their initial posture as closely as possible throughout the stimulation. If the vibration stimulation induces KI, the subject may produce movements that differ from the initial posture. Conversely, in Experiment 2, subjects were required to remain stationary and avoid any reactions to the vibration to observe posture deviations caused by the TVR. The vibration frequencies were set at 60, 80, 100 Hz for Experiment 1, and 60, 90, 120 Hz for Experiment 2. For each frequency, both sides of the targeted muscles were stimulated simultaneously across three trials. The procedures for Experiments 1 and 2 are described as follows.

1. Vibrators were fixed to the subject's rectus abdominis muscle using a rubber band, with an initial contact force adjusted to 3 N.

2. Subjects were instructed to stand upright with a relaxed posture.

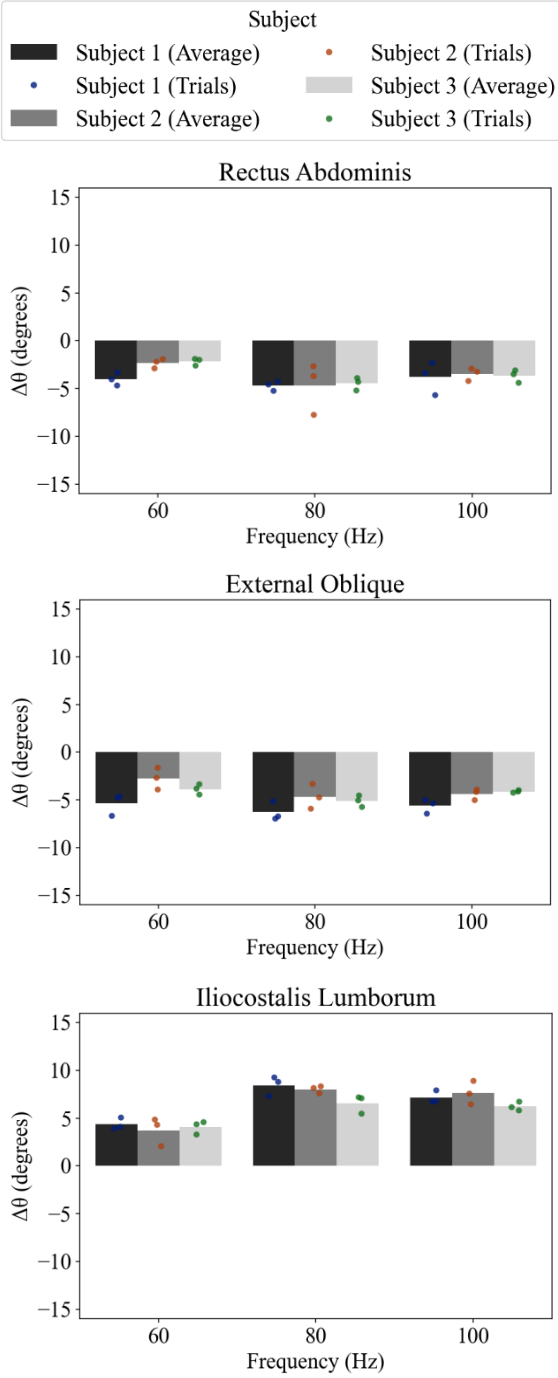


Figure 3. Change angles in the trunk flexion/extension from KI.

3. The vibration started and lasted for 10 seconds, during which trunk motion was recorded using the motion capture system.

4. The procedure was repeated for the external oblique and iliocostalis lumborum muscles, cycling through the three designated frequencies.

RESULTS AND DISCUSSION

To calculate the trunk flexion and extension angles, the relative position of the marker placed on the cervical spine (P_{cs}) with respect to the marker placed on the lumbar spine (P_{ls}) was determined by computing the directional vector $\boldsymbol{v}$.

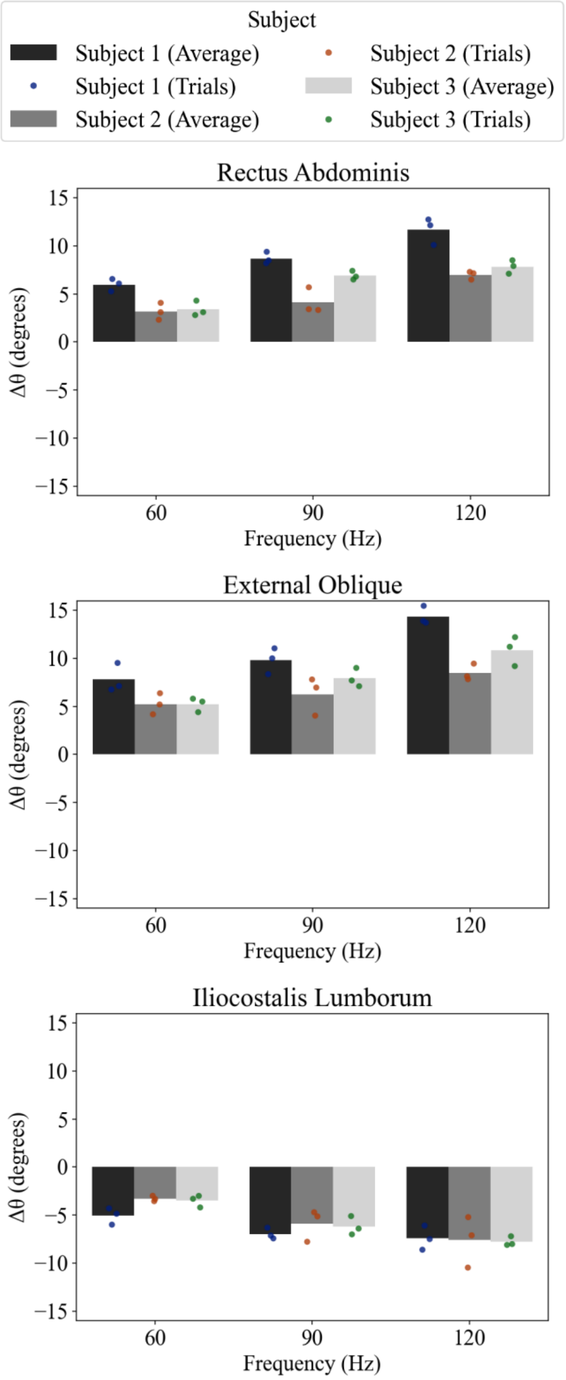


Figure 4. Change angles in the trunk flexion/extension from TVR.

$$v = P_{cs} - P_{ls} \tag{1}$$

This vector represents the spatial relationship between the two points in three-dimensional space and serves as the basis for the angle calculations. This vector was then projected onto the sagittal plane, defined by the *y*-axis (forward-backward) and *z* axis (up-down) directions, by setting its *x*-axis (left-right) component to zero:

$$\boldsymbol{v}_{sagittal} = [0, v_y, v_z] \tag{2}$$

The inclination angle θ, representing the trunk's flexion or extension, was calculated as the angle between $\boldsymbol{v}_{sagittal}$ and the vertical direction. Using the dot product and vector norms, the cosine of the angle was determined as:

$$cos\,\theta = \frac{\boldsymbol{v}_{sagittal} \cdot \boldsymbol{z}}{\left\|\boldsymbol{v}_{sagittal}\right\| \|\boldsymbol{z}\|} \tag{3}$$

where $\boldsymbol{z} = [0,0,1]$ is the vertical unit vector. The angle θ was then calculated using the arccosine function and converted to degrees:

$$\theta = arccos(cos\,\theta) \cdot \frac{180}{\pi} \tag{4}$$

$\Delta\theta$ was determined for each trial by calculating the trunk angle, which was approximately 0 at the onset of the vibration stimulation (θ_{start}) due to the initial upright posture and at the conclusion of the 10-second interval (θ_{end}). This value represents the change in angle over the entire duration of the vibration stimulation:

$$\Delta\theta = \theta_{end} - \theta_{start} \tag{5}$$

Subsequently, the change in the trunk flexion/extension angle ($\Delta\theta$) was calculated for each stimulation site and frequency to quantify the effects of vibration. This approach allows for a clear comparison of trunk posture dynamics before and after stimulation, providing insights into how vibration influences joint behavior. In this study, positive angles ($\theta > 0$) are defined as trunk flexion, while negative angles ($\theta < 0$) are defined as trunk extension.

The levels of KI and TVR induced by each subject's response following vibratory stimulation are depicted in Figures 3 and 4. These two graphs displaying the angular transitions in trunk flexion and extension under each frequency condition were obtained. Figure 3 presents the results of Experiment 1, demonstrating that KI in the direction of trunk flexion and extension were induced in all subjects by applying vibratory stimulation to the selected muscles. Figure 4 displays the results of Experiment 2, showing that the TVR in the direction of trunk flexion and extension was similarly induced in all subjects through vibratory stimulation to the selected muscles. When vibratory stimulation was applied to the rectus abdominis and external oblique muscles, it produced KI toward trunk extension and TVR toward flexion. Conversely, stimulation of the iliocostalis lumborum resulted in KI toward flexion and TVR toward extension. In the graphs presented, each bar represents the average angular change across all trials for each subject, muscle, and vibration frequency, resulting from KI or TVR. These bars offer a concise summary of the overall trends in the data, highlighting variations in muscle response at different frequencies. In Figure 3, it can be observed that vibratory stimulation at all applied frequencies induced KI in the subjects, but as in previous studies, the greatest illusion occurred at 80 Hz [9]. In Figure 4, it is shown that vibratory stimulation at all applied frequencies induced TVR. As the frequency of the vibration stimulation increases, TVR also increases. Additionally, for TVR that induces trunk flexion, the TVR induced by stimulation of the external oblique muscle was greater than that induced by stimulation of the rectus abdominis in all subjects.

CONCLUSION

This study has demonstrated that mechanical vibration stimulation applied to the trunk muscles, specifically the rectus abdominis, external oblique, and iliocostalis lumborum, can effectively induce both KI and TVR in trunk flexion and extension movements. By applying vibration stimulation at different frequencies, we observed distinct variations in the magnitude of induced movements, with optimal effects occurring at certain frequencies. The results confirm that both KI and TVR can be consistently elicited across all subjects, with vibration frequency playing crucial roles in the intensity of the response. These findings highlight the potential of mechanical vibration stimulation as a novel approach for motor rehabilitation, offering a promising method to enhance trunk movement control and support recovery in patients with motor impairments.

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