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Generation of Kinesthetic Illusion and Tonic Vibration Reflex Response in Trunk Lateral Bending Motion with Mechanical Vibration Stimulation

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Abstract: Mechanical vibration stimulation applied to human muscles induces kinesthetic illusions (KI) and tonic vibration reflexes (TVR) which affect human motor behavior. These effects have attracted increasing attention in the field of rehabilitation, particularly for individuals with impaired motor functions. Lateral trunk bending, a crucial component of postural control, is involved in many daily activities. However, the effects of vibration stimulation on trunk muscles involved in lateral bending have not studied sufficiently. This research explores the potential of mechanical vibration stimulation as a rehabilitation approach by targeting trunk muscles associated with lateral bending. Induced KI and TVR responses are experimentally evaluated, and the effects of varying vibration frequencies are compared to assess differences in motor responses.

Keywords: Mechanical Vibration Stimulation, Kinesthetic Illusion, Tonic Vibration Reflex, Trunk Lateral Bending.

1. INTRODUCTION

Mechanical vibration stimulation has been applied in various contexts related to the nervous system, including perception assist [1], tremor suppression [2][3], proprioceptive enhancement [4], as well as various other neuro-related interventions. In support of these diverse applications, growing research evidence suggests that mechanical vibration stimulation can modulate the interaction between sensation and movement. Among these applications, motor rehabilitation has become a key focus, as vibration stimulation is increasingly recognized for its potential to promote functional recovery via mechanisms such as kinesthetic illusions (KI) and tonic vibration reflexes (TVR) [5]. This approach is especially relevant for addressing motor impairments resulting from neurological conditions such as strokes and spinal cord injury, which often limit individuals' ability to perform essential daily activities.

KI is an extensively studied phenomenon characterized by the perception of movement resulting from sensory stimulation, typically induced by vibratory stimulation applied to the surface of muscles and tendons. When KI occurs, individuals experience a sensation that the stimulated muscle is lengthening or moving, despite there being no actual physical movement [6]-[11]. First described in 1972 by Goodwin et al., who used 100 Hz vibration on the biceps and triceps to elicit elbow-extension and -flexion sensations [6], KI has since been shown to depend on vibration frequency [7]. Roll et al. [8] reported that the greatest illusion occurs at 70 Hz when vibrations of 10–120 Hz are applied to the unloaded biceps and triceps brachii muscles, whereas Naito et al. [9] found the strongest kinesthetic illusion at 70–80 Hz when vibrations of 10–240 Hz are applied to the unloaded elbow joint. Besides, Stimulus location, amplitude, and initial contact force also affect the threshold and intensity of KI [7][10][11].

Additionally, vibratory stimulation of muscle tendons can also trigger a reflexive response known as the TVR. First identified by Eklund et al. in 1966, TVR is characterized by involuntary muscle contractions occurring concurrently with sensory illusions [12]. TVR has been observed over a broader frequency spectrum (20–300 Hz), with reflex intensity generally increasing proportionally with vibration frequency up to a certain threshold [13]. Additionally, variability in physiological conditions and individual differences significantly influence TVR responses, affecting both the magnitude and the consistency of reflexive contractions [14]. Both KI and TVR have been identified as important physiological responses that support the use of mechanical vibration stimulation in motor rehabilitation, each contributing through distinct mechanisms.

Although previous research on KI and TVR has primarily focused on limb joints such as the shoulder, elbow, wrist, knee, and ankle, everyday limb movements often involve concurrent movements of the trunk, highlighting the importance of trunk motor control. Our previous studies have explored KI and TVR responses in trunk movements specifically during forward and backward bending, demonstrating that mechanical vibration stimulation applied to specific trunk muscles can effectively induce these responses [15]. However, research on KI and TVR responses in trunk lateral bending remains limited, despite the frequent and functionally significant occurrence of lateral bending in daily life. To address this research gap, this study investigates the potential of mechanical vibration stimulation to induce KI and TVR responses in trunk lateral bending motion. Various vibration frequencies were applied to relevant trunk muscles to evaluate their impact on the magnitude and characteristics of the induced responses. Findings from this study are expected to provide foundational insights for the development of precise rehabilitation strategies aimed at enhancing motor control and supporting recovery in individuals with trunk movement impairments.

2. METHODS

2.1 Experimental setup

The external oblique is the most superficial muscle of the anterolateral abdominal wall. Bilateral activation produces forward trunk flexion, whereas unilateral activation produces contralateral axial rotation and ipsilateral lateral flexion [16][17]. Owing to its substantial muscle mass and key role in lateral bending, the lateral portion of the external oblique is a suitable position for mechanical vibration designed to evoke KI and TVR in trunk lateral bending motion. This study therefore examines whether vibration applied to the lateral external oblique can consistently elicit KI and TVR. By systematically varying the vibration frequency, we aim to clarify how response magnitude and characteristics depend on frequency.

Figure 1 details the vibration device used, powered by a Carbon Brush Motor (Mabuchi Motor, RS-380PH). The device employs an eccentric shaft coupling with a 1.5 mm offset, providing a peak-to-peak vibration amplitude of 3.0 mm at adjustable frequencies. The oscillator component of the vibrator measures 30 mm in length. The motor's rotational speed is precisely controlled via proportional-derivative (PD) feedback regulation using an incremental encoder (Nidec Copal Electronics, RE12D-300-201) interfaced with a microcontroller (Arduino, Arduino Mega). An initial application force of 3N between the vibrator and skin was monitored with a FlexiForce sensor (TekScan, FlexiForce A205-1). Trunk lateral bending angles were measured using an inertial measurement unit (IMU) (Sparkfun Electronics, MPU9250), which was positioned on the subject's back. Five types of vibration stimulation configurations were tested in this study, as shown in Figure 2. Vibration stimulation was applied to the left external oblique muscle at five distinct spatial configurations (Types 1–5). A reference point was defined along the mid-axillary line at the central region of the lateral portion of the left external oblique muscle. The stimulation positions and configurations were as follows:

- Type 1 (Single-point, reference): A single vibrator placed directly on the reference point.
- Type 2 (Single-point, anterior +5 cm): A vibrator positioned 5 cm anterior to the reference point, along the same transverse plane.
- Type 3 (Single-point, posterior –5 cm): A vibrator positioned 5 cm posterior to the reference point, along the same transverse plane.
- Type 4 (Dual-point, 10 cm apart): Two vibrators placed at the Type 2 and Type 3 positions, with a center-to-center distance of 10 cm.
- Type 5 (Dual-point, 5 cm apart): Two vibrators placed symmetrically 2.5 cm anterior and posterior to the reference point, resulting in a center-to-center distance of 5 cm.

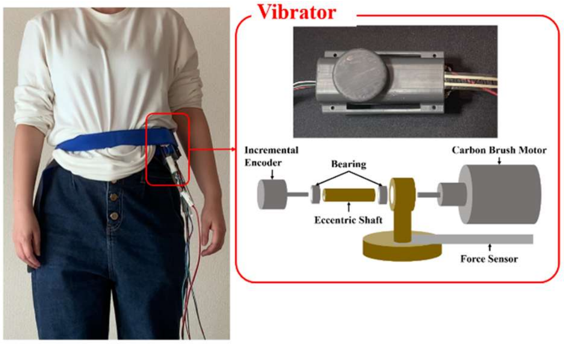

Fig.1 Vibrator outline and structure.

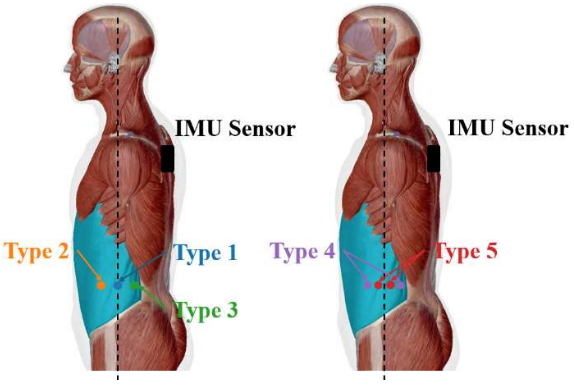

Fig.2 Stimulation positions [18].

To systematically assess the KI and TVR phenomena, vibration frequencies were varied in 20 Hz increments (60, 80, 100, and 120 Hz) for both experimental conditions, with each stimulation trial lasting 10 seconds. The experiments were conducted with three healthy subjects (two males and one female; mean age: 32 years). Detailed demographic information, including gender, age, weight, and height, is presented in Table 1. All participants reported no history of neurological or muscular disorders. To promote focus and minimize external sensory input, subjects wore eye masks and earphones throughout the trials. The experiments have been approved by the research ethics committee of Kyushu University, School of Engineering (H28-04).

Table 1 Information of subjects

Subject	Gender	Age	Weight[kg]	Height[m]
1	Female	31	54	1.60
2	Male	31	70	1.74
3	Male	34	70	1.68

2.2 Experimental procedure

In this study, two experimental conditions (i.e., the KI induction and the TVR induction) were provided to examine the effects of mechanical vibration applied to the left lateral region of the external oblique muscle. Participants adopted an upright standing posture before each trial. During KI induction, they were instructed to maintain their perceived sense of uprightness throughout the stimulation; any observable postural adjustments were interpreted as evidence that the vibration shifted their perception of body orientation. During TVR induction, they were asked to avoid any voluntary responses to the stimulation so that any resulting deviations in posture could be ascribed solely to TVR. Each combination of stimulation type and vibration frequency was tested three times to ensure reliability, and the detailed experimental procedures are described below.

1. Vibrators were secured at the Type 1 position using a rubber band, with the initial contact force adjusted to 3 N.
2. Subjects were instructed to stand upright with their waist relaxed.
3. Trunk lateral deviation angles were recorded using an IMU sensor, beginning 2 seconds before and continuing until 10 seconds after the onset of vibration.
4. The procedure was then repeated for stimulation Types 2 through 5, with each type tested across the four designated vibration frequencies.

3. RESULTS AND DISCUSSION

To assess the impact of vibration stimulation on trunk lateral bending motion, changes in trunk postural angle deviation were calculated. This deviation comprises two components: the Left-Right deviation angle and the Forward-Backward deviation angle. For each trial, the deviation angle was determined by measuring the trunk angle at the onset and at the conclusion of a 10-second vibration stimulation period. The changes in deviation angle across all trials were computed for each stimulation position and frequency, providing a quantitative measure of the effects of vibration stimulation. This analytical method enables a detailed comparison of trunk posture before and after stimulation, offering insight into how vibration input may influence trunk lateral bending motion.

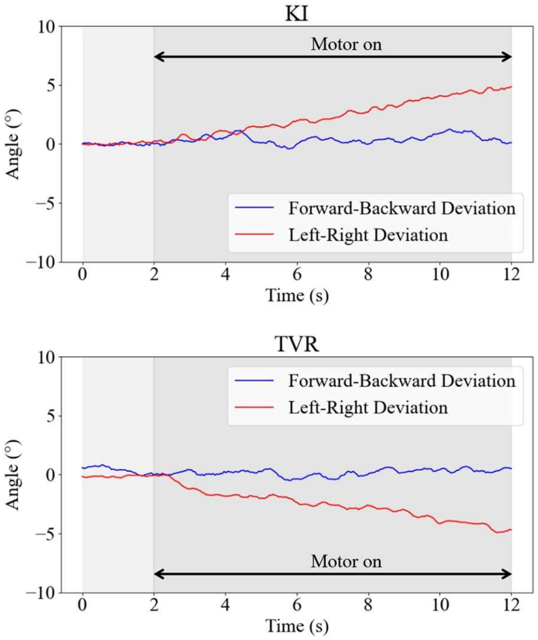

Fig.3 Deviation angles in response to KI and TVR stimulation in Subject 3 (Type 5, 80 Hz).

Figure 3 illustrates the trunk deviation angles induced by KI and TVR stimulation in Subject 3, specifically under stimulation position Type 5 at a frequency of 80 Hz. The x-axis represents time, and the y-axis denotes angular displacement. Deviations are quantified as trunk angle displacements in the Left-Right and Forward-Backward directions. In the figure, the red line indicates the left-right deviation angle, while the blue line represents the forward-backward deviation angle. The light gray shaded region denotes the baseline (resting) period before the onset of vibration, whereas the darker gray shaded area indicates the duration of vibratory stimulation. The observed trunk postural changes occurred shortly after the onset of vibration, attributable to the evoked TVR and KI responses. Figure 4 presents the magnitudes of trunk lateral bending deviations induced by TVR and KI responses, elicited by vibratory stimulation at different stimulation positions and frequencies, across three participants. Deviations are quantified as trunk angle displacements in the Left-Right and Forward-Backward directions. The x-axis represents left-right deviation angle, where negative values indicate leftward bending and positive values indicate rightward bending. The y-axis represents forward-backward deviation angle, with negative values indicating backward bending and positive values indicating forward bending. Each condition is defined by a specific vibration frequency (60, 80, 100, or 120 Hz) and stimulation position (Types 1–5). Individual trial outcomes are shown as translucent markers, while larger, opaque markers represent the mean across three trials within each condition. The deviations on the left side of each plot illustrate trunk posture changes resulting from evoked TVR, while those on the right correspond to changes induced by KI. Figure 5 summarizes the average deviation angles induced by TVR and KI, averaged across all subjects for each stimulation position and frequency condition. Results are shown separately for the Left-Right and Forward-Backward directions. Solid lines represent TVR responses, while dash-dot lines correspond to KI.

As demonstrated in the results, vibration-induced TVR consistently elicited leftward trunk lateral bending across all participants, with deviation magnitude increasing with

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† Yue Hou is the presenter of this paper.

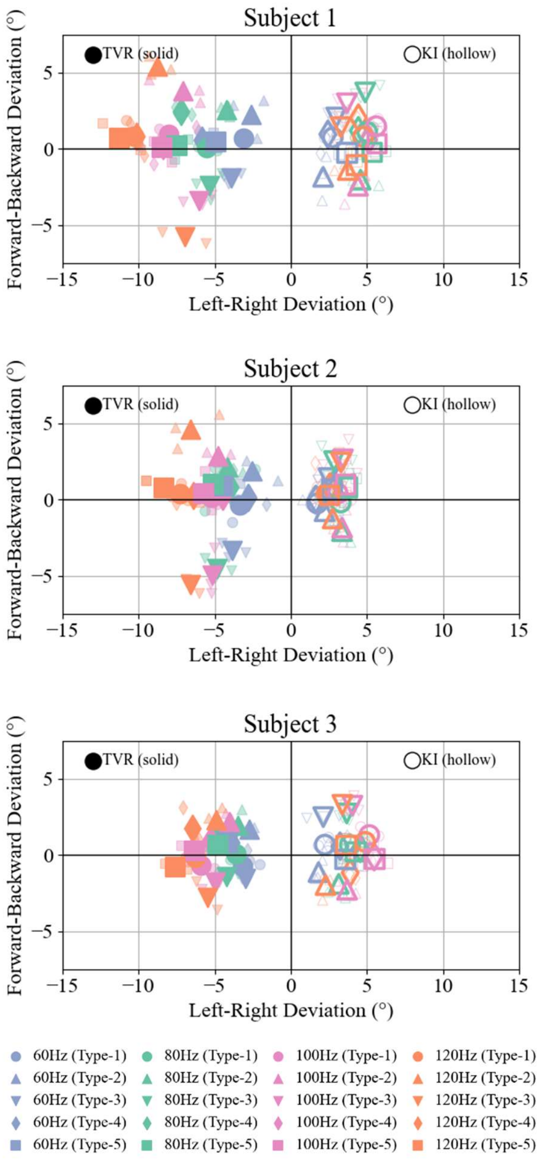

Fig.4 Left–Right and Forward–Backward postural deviations in three subjects.

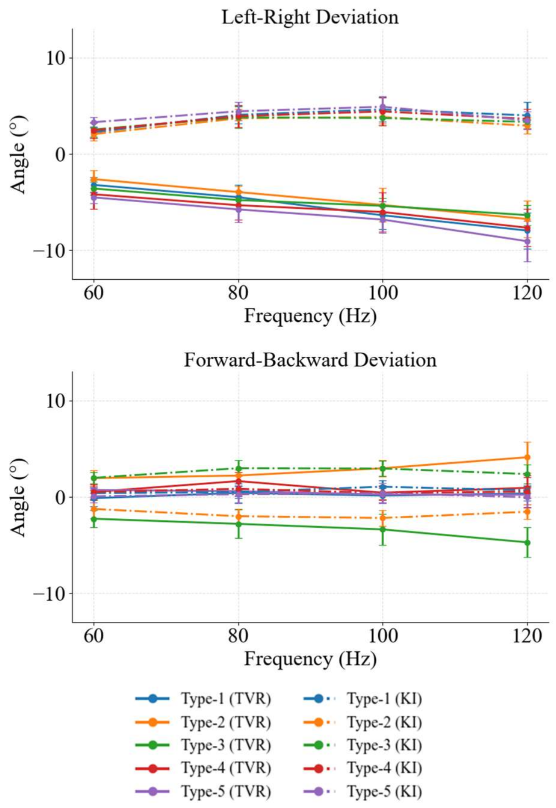

Fig.5 Deviation angles in response to KI and TVR across frequencies and stimulation positions.

Table 2 Time Delays of TVR and KI Responses Under Stimulation Position Type 5

Subject	Type	Time Delay [s] at Frequency [Hz]				
		60	80	100	120	Mean
1	TVR	0.36	0.32	0.26	0.36	0.32
	KI	1.19	0.82	0.72	0.91	0.91
2	TVR	0.21	0.27	0.37	0.32	0.29
	KI	1.46	1.87	1.88	1.36	1.64
3	TVR	0.29	0.37	0.32	0.26	0.31
	KI	0.79	1.17	1.35	1.25	1.14

stimulation frequency, consistent with previous findings [13]. Types 1, 4, and 5 primarily induced lateral bending with minimal anterior-posterior displacement. In contrast, Type 2 (anterior) and Type 3 (posterior) stimulations often resulted in lateral deviations accompanied by forward or backward shifts, depending on the stimulation position. Notably, Type 5 stimulation, characterized by closely spaced dual-point vibration at 120 Hz, produced the largest lateral deviations among participants. KI responses, in contrast, consistently resulted in trunk lateral bending opposite the stimulation position. Similar to the results of TVR, Types 1, 4, and 5 primarily caused lateral bending, whereas Types 2 and 3 induced combined lateral and anterior-posterior trunk movements. The strongest lateral KI responses were generally observed under Type 5 stimulation at 100 Hz across all three subjects. Although Subject 2 exhibited a slightly stronger KI response at 80 Hz than at 100 Hz under the same stimulation position, the response magnitudes at these two frequencies were very close. To better understand the timing characteristics of these postural responses, response latencies were analyzed under stimulation position Type 5, which elicited the largest deviations across conditions. The results are summarized in Table 2, showing the average time delays for TVR and KI across participants. The time delay was defined as the moment when the trunk lateral bending angle first exceeded baseline fluctuations after vibration onset. In this study, the average delays were approximately 0.3 s for TVR and 1.2 s for KI. Other studies on TVR delays have typically used EMG signals and have reported limb muscle responses as early as around 30 ms [19]. The longer delays observed here reflect the use of motion-based measures, which involve additional movement-related latencies, highlighting the need for further analysis based on EMG for direct comparison. Regarding KI, earlier studies investigated other body regions, primarily limb movements, and the delay observed here in lateral trunk bending is broadly consistent with those previously reported latencies [1][4]. Although the findings are based on a limited number of participants (n = 3), they offer a consistent pattern of within-subject responses that supports the feasibility of using vibration stimulation to evoke trunk postural responses. These observations provide a foundation for future studies involving more participants, which would help improve the generalizability of the findings.

4. CONCLUSION

This study demonstrated that mechanical vibration stimulation applied to the lateral trunk, specifically targeting the external oblique muscle, can effectively elicit KI and TVR in trunk lateral bending motion. Variation in stimulation frequency and position produced frequency- and location-dependent effects on response magnitude, enabling the identification of suitable combinations for maximizing lateral KI and TVR. These findings highlight the potential of mechanical vibration stimulation as a novel strategy for motor rehabilitation [5], offering a promising approach to enhancing trunk movement control and supporting functional recovery in individuals with motor impairments.

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REFERENCES

[1] K. Honda and K. Kiguchi, "Control of Human Elbow-Joint-Extension-Motion Change Based on Vibration Stimulation for Upper-Limb Perception-Assist," *IEEE Access*, vol. 8, pp. 22697-22708, 2020.

[2] W. Liu, T. Kai and K. Kiguchi, "Tremor Suppression With Mechanical Vibration Stimulation," *IEEE Access*, vol. 8, pp. 226199-226212, 2020.

[3] K. Kiguchi, T. Kai, and W. Liu, "A fundamental study on tonic vibration reflex in forearm pronation/supination to suppress essential tremor movements," *IEEE Int. Conf. Syst., Man, Cybern. (SMC)*, Toronto, Canada, pp. 2668–2673, 2020.

[4] T. Yamasaki, S. Nishikawa and K. Kiguchi, "Generation of Two-Dimensional Kinesthetic Illusion in Ankle Joint with Vibration Stimulation," *2022 World Automation Congress (WAC)*, San Antonio, TX, USA, 2022, pp. 324-329.

[5] K. Kiguchi and K. Maemura, "Simultaneous Control of Tonic Vibration Reflex and Kinesthetic Illusion for Elbow Joint Motion Toward Novel Robotic Rehabilitation," *2021 43rd Annual Intl. Conf. of the IEEE Eng. in Medicine & Biology Society (EMBC)*, Mexico, pp. 4773–4776, 2021.

[6] G. M. Goodwin, D. I. Mccloskey, and P. B. C. Matthews, "Proprioceptive illusions induced by muscle vibration: Contribution by muscle spindles to perception?" *Science*, vol. 175, no. 4028, pp. 1382–1384, 1972.

[7] M. W. Taylor, J. L. Taylor, and T. Seizova-Cajic, "Muscle Vibration Induced Illusions: Review of Contributing Factors, Taxonomy of Illusions and User's Guide," *Multisens. Res.*, vol. 30, no. 1, pp. 25–63, 2017.

[8] J. P. Roll and J. P. Vedel, "Kinaesthetic role of muscle afferents in man, studied by tendon vibration and microneurography," *Exp. Brain Res.*, vol. 47, no. 2, pp. 177–190, 1982.

[9] E. Naito, H. H. Ehrsson, S. Geyer, K. Zilles and P. E. Roland, "Illusory arm movements activate cortical motor areas: a positron emission tomography study," *J Neurosci.*, vol. 19, no. 14, pp. 6134-6144, 1999.

[10] F. Ferrari, F. Clemente, and C. Cipriani, "The preload force affects the perception threshold of muscle vibration-induced movement illusions," *Exp. Brain Res.*, vol. 237, no. 1, pp. 111–120, 2019.

[11] Y. Umesawa, K. Doi, and H. Fujimoto, "Development and evaluation of a device for inducing kinesthetic illusion of dual joint movements," *J. Adv. Comput. Intell. Intell. Informatics*, vol. 21, no. 4, pp. 737–743, 2017.

[12] G. Eklund and K. E. Hagbarth, "Normal variability of tonic vibration reflexes in man," *Exp. Neurol.*, vol. 16, no. 1, pp. 80–92, Sep. 1966.

[13] A. Kavounoudias, R. Roll, and J.P. Roll, "Foot sole and ankle muscle inputs contribute jointly to human erect posture regulation." *J. of Physiology*, vol. 532, no. 3, pp. 869-878, 2001.

[14] R. M. Johnston, B. Bishop, and G. H. Coffey, "Mechanical vibration of skeletal muscles.," *Phys. Ther.*, vol. 50, no. 4, pp. 499–505, 1970.

[15] Y. Hou, S. Nishikawa, and K. Kiguchi, "Generation of Kinesthetic Illusion and Tonic Vibration Reflex Response in Trunk Flexion and Extension Motion with Mechanical Vibration Stimulation," *2025 IEEE/SICE Intl. Sym. on System Integration (SII)*, Munich, Germany, pp. 410-413, 2025.

[16] S. Kumar, Y. Narayan and D. Garand, "Isometric axial rotation of the trunk in the neutral posture," *Eur J Appl Physiol.*, vol. 86, pp. 53-61, 2001.

[17] J. K-F Ng, V. Kippers, M. Parnianpour and C. A. Richardson, "EMG activity normalization for trunk muscles in subjects with and without back pain," *Med Sci Sports Exerc.*, vol. 34, no. 7, pp. 1082-1086, 2002.

[18] "Visiblebody, 'Human Anatomy Atlas." Accessed: May. 8, 2025. [Online].

[19] E. Kalaoglu, O. F. Bucak, M. Kokce, M. Ozkan, M. Cetin, M. Atasoy, L. Ayture and I. Karacan, "Whole body vibration activates the tonic vibration reflex during voluntary contraction," *J Phys Ther Sci.*, vol. 35, no. 6, pp. 408-413, 2023.