REVIEW ARTICLE

The effect of illusory kinesthesia by vibratory tendon stimulation on musculoskeletal pain disorders

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Abstract
"Vibratory stimulation" is a form of physical therapy in which a vibratory stimulus is applied to muscles, tendons, or the whole body to reduce muscle tension and pain. This therapeutic approach is mainly used in a clinical practice setting. Notably, vibratory stimulation of tendons can produce an illusory sensation of limb movement (illusory kinesthesia). In a previous study, my research group revealed that the illusory kinesthesia induced by vibratory tendon stimulation can reduce pain in postoperative patients. This review summarizes the present knowledge regarding the illusory kinesthesia arising from vibratory tendon stimulation, and then describes the indications for the use of vibratory tendon stimulation in patients with orthopedic diseases, with a focus on my own clinical research.

ILLUSORY KINESTHESIA BY VIBRATORY TENDON STIMULATION

The application of a vibration stimulus at an appropriate frequency (around 80 Hz) to a tendon as if stretching the muscle can create a clear sensation of illusory kinesthesia, as the motionless limb is actually moving (Naito, 2004). This illusory kinesthesia by vibratory tendon stimulation is attributable to the activation of Ia afferent sensory fibers from muscle spindles in skeletal muscle, which send information about muscle length to the brain (Figure 1). These afferent inputs from the muscle spindles are largely responsible for the perceived direction of the illusory limb movements.

Two important conditions must be met to induce illusory kinesthesia. First, the stimulated limb should be completely relaxed. Vibratory tendon stimulation of an unrelaxed limb can easily induce a sustained reflex (i.e., a reflex in the opposite direction of the illusory kinesthesia) (Burke, 1976). Second, the subject's eyes should be closed during the stimulation and illusory kinesthesia. Because the limb does not actually move during the illusory kinesthesia, visual information about the true status of the limb can attenuate the illusory effect, and closing the eyes prevents this (Hagura, 2007).

Functional brain imaging studies have shown that motor-related areas on the side of the limb contralateral to the stimulated side are activated by during illusory kinesthesia induced by vibratory tendon stimulation, and the level of activation is equivalent to that observed during actual movement. (Naito, 2004; Imai, 2014). The brain areas that are active during the transfer of illusion have also been clarified. As an example of such transfer of illusory kinesthesia, when the hands are in contact and the illusion of the vibrated right hand transfers to the non-vibrated left hand, not only the left motor-related area but also the right motor-related area are significantly activated. (Naito, 2002). Since the right wrist joint was not stimulated directly, afferent information was not transmitted to the brain. However, the information is integrated in the brain to make sense of the tactile information and the kinesthesia information of the left wrist joint. Another well-known example of such transfer is the "Pinocchio illusion" (Lackner, 1988). A blindfolded participant receives vibratory stimulation on his biceps while touching the tip of his nose with his fingers. The illusory extension of the arm generates the illusion that his nose, his fingers or both are elongating.

Interestingly, illusory kinesthesia can be experienced even when the joints of the extremities are completely immobilized in a cast. In the study of Roll (2012), healthy subjects were divided in two groups, experiment and control groups. The fingers and joints of both groups were immobilized for five days, during which time vibratory stimulation was applied to induce illusory kinesthesia in the experiment group. The brain activities were measured during the hand movements before and after the removal of the immobilization and compared to those of the control group. The results showed that there was no decrease in the activity of

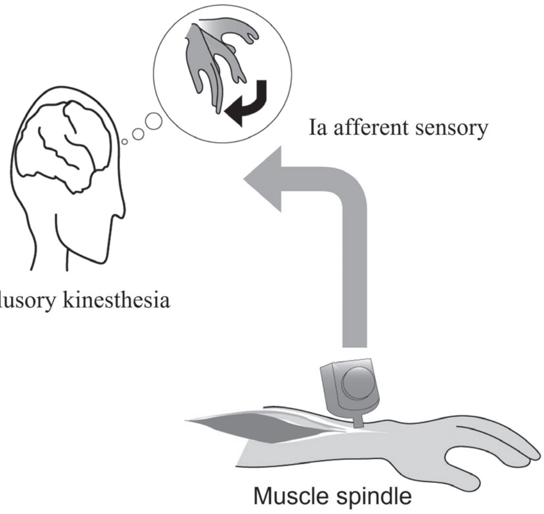

Figure 1. Illusory kinesthesia by vibratory tendon stimulation. Tendon vibration of a limb excites the muscle spindle afferents that contribute to the elicitation of illusory movements of the limb.

the sensorimotor cortex in the experiment group while there was a decrease in the control group. In other words, illusory kinesthesia induced by vibratory tendon stimulation prevented neuroplastic changes in the brain caused by immobility and fixation.

TENDON VIBRATORY STIMULATION FOR POSTOPERATIVE ORTHOPEDIC DISEASE

There are three advantages for using vibratory stimulation to induce illusory kinesthesia. The first is that activity in motor-related regions is involved in the descending pain inhibitory system (Bachmann, 2010; Fregni, 2006b; Fregni, 2006a). Activity in motor-related regions has been observed during illusory kinesthesia, suggesting that the descending pain inhibitory system may be activated. The second advantage is that vibratory tendon stimulation can induce illusory kinesthesia even in a limb immobilized in a cast and can thereby be used to prevent plastic changes in the nerves of the immobilized limb (Roll, 2012). Third, vibratory tendon stimulation does not induce pain or evoke anxiety or fear, but it still stimulates the perception of movement (Imai, 2016; Imai, 2017b).

Why is illusory kinesthesia by vibratory tendon stimulation effective for pain reduction in postoperative patients? To answer this question, I will shift our focus to pain and discuss the definition and the mechanism of chronic postoperative pain.

The definition of pain has been revised for the first time in 40 years by the International Association for the Study of Pain (IASP) as follows: "An unpleasant sensory and emotional experience associated with, or resembling that associated with, actual or potential tissue damage" (Raja, 2020). In regard to chronic pain, the IASP now includes chronic post-surgical pain (CPSP) in the International Classification of Diseases for the first time (Treede, 2019). CPSP was also redefined in 2019 as "pain that has developed or worsened after surgery," and "pain that has exceeded the tissue healing period and has been present for at least 3 months postoperatively."

THE MECHANISM UNDERLYING CPSP

The "fear-avoidance model" (Vlaeyen, 2000) and "learned non-use" (Punt, 2013) were introduced as models for chronic pain. The fear-avoidance model is described as follows: "If pain, possibly caused by an injury, is interpreted as threatening (pain catastrophizing), pain-related fear evolves. This leads to avoidance behaviors, and hypervigilance to bodily sensations followed by disability, disuse and depression. As a result, patients will maintain the pain experiences thereby fueling the vicious circle of increasing fear and avoidance." In this model, distorted perceptions of pain, such as catastrophic thinking, lead to a negative spiral, which induces fear and develops functional disability, decreased activity, and social adjustment disorder (Vlaeyen, 2000). In the "learned non-use" model (Punt, 2013), pain is experienced in parallel with (1) a decreased frequency of use of an affected limb, (2) the acquisition of fear-avoidance behavior, and (3) the acquisition of compensatory movements, resulting in learned disuse of the affected limb. This behavioral pattern is the result of the patient's own decision-making and selection of a behavioral pattern that does not induce pain. Therefore, this decision-making (pain-free behavior or fear avoidance) gradually contributes to the learned non-use of the affected limb. In addition, by the time this learned nonuse is acquired, plastic changes in brain regions (such as reduction of the sensorimotor cortex) have occurred. "Pain-free behavior" becomes a temporary positive reward for patients, and reinforcing this behavioral pattern leads to a chronic model which is learned non-use.

Based on the above-described findings, Chimenti (2018) proposed exacerbation of three types of pain: nociceptive pain, neuropathic pain, and nociplastic pain. These three types of pain can be difficult to classify, and often overlap. Nociceptive plastic pain is "pain that is caused by alterations in the nociceptive system despite the absence of clear damage to peripheral tissues or nerves that cause activation of peripheral nociceptors" (Kosek, 201; Nijs, 2021). It is important to note that in addition to these pain, motor and behavioral factors as well as psychological factors are thought to considered to exacerbate pain. For example, the psychological situation of excessive fear of pain leads to compensatory movements (motor control that places a burden on the musculoskeletal system), and exacerbates pain. This is exactly equivalent to the "fear-avoidance model" described above.

As mentioned above, motor and psychological factors are very closely related to the development of chronic pain and the mechanism of its occurrence and exacerbation (Merkle, 2018). Because motor control changes by pain are a body defense reaction, "fear" can lead to a conceptualization that "movement = pain." In other words, "fear of movement" is an important component in the model of chronic pain, as well as the mechanisms underlying the occurrence and exacerbation of pain and ultimately the therapeutic approach to pain rehabilitation.

EFFECT OF ILLUSORY KINESTHESIA BY VIBRATORY TENDON STIMULATION ON POSTOPERATIVE PAIN

With this background, I conducted a quasi-randomized controlled trial to examine the effects of illusory kinesthesia in postoperative patients with distal radius fractures by applying vibratory tendon stimulation for one week starting the day after surgery. The outcomes demonstrated that the patient group exhibited significant improvements in pain intensity, psychological factors such as anxiety, and motor function compared to a control group who received conventional physical therapy. The beneficial effects were also sustained at the 2-month postoperative follow-up (Imai, 2017b; Imai, 2016). In other words, illusory kinesthesia induced by vibratory tendon stimulation did not induce pain even in the acute postoperative period when pain intensity was high, but it actually reduced pain.

In order to clarify the neurophysiological mechanism of the analgesia, I measured the brain activity of postoperative patients with distal radius fractures using electroencephalography (EEG) on the day after surgery when they were exposed to the illusory kinesthesia induced by vibratory tendon stimulation. The results showed that, as in previous studies (Naito, 2004; Imai, 2014), neural activity in the sensory-motor cortex was increased in the patients who underwent illusory kinesthesia. I also observed that the level of neural activity in the sensorimotor cortex was related to the degree of analgesia at one week after surgery (Imai, 2017a) (Figure 2). The illusory kinesthesia induced by vibratory tendon stimulation may thus have activated the descending pain inhibitory system through activity in the sensorimotor cortex and reduced the patients' pain intensity, leading to psychological improvement along with these reductions. These are considered to be innovative and original clinical results for the prevention of chronic pain.

However, it has not yet been established in which patients the illusory kinesthesia induced by vibratory tendon stimulation is effective. As a first step in clarifying the appropriate patient population, I focused on a specific phenomenon in postoperative patients—namely the tendency of postoperative patients to be required a long period of time to change their direction of movement. In addition, I quantified the time required to switch movement direction. This kinematic abnormality was defined as "movement hesitation" (Imai, 2018) (Figure 3). Additional experiments were conducted after the quantification of the switching time. The kinematic characteristics of the patient group showing delayed improvement in motor function compared to healthy subjects were clarified (Figure 4). The patients with both prolonged movement hesitation times on the first postoperative day and decreased velocity of movement on the seventh postoperative day had stagnant or delayed improvement in motor function (Imai, 2020) (Figure 5).

In future experiments, it will be important to determine whether tendon vibration stimulation and the resulting illusion of movement are effective in reducing the movement hesitation time in patients with long

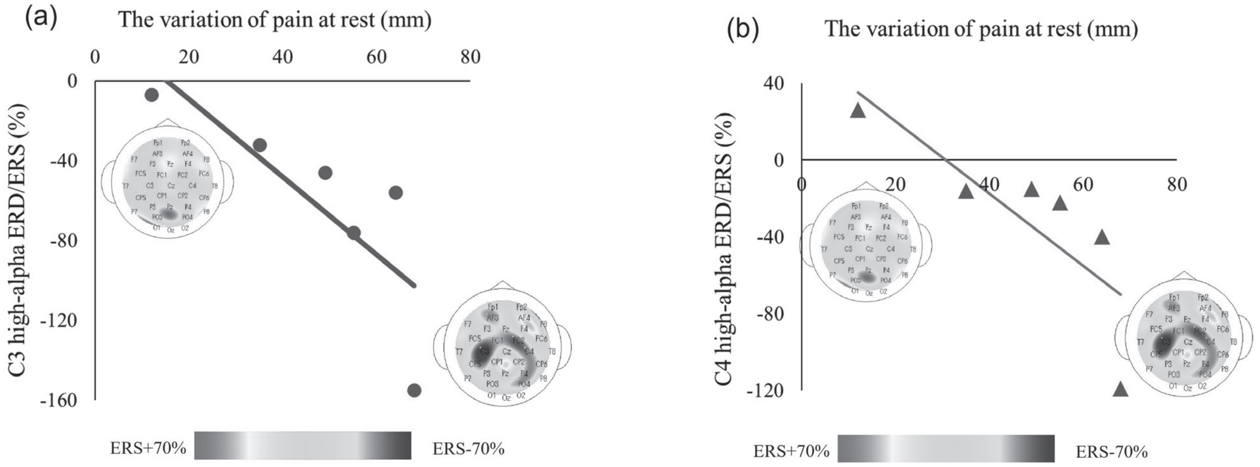

Figure 2. The C3 and C4 channels of event-related desynchronization/event-related desynchronization synchronization % (ERD/ERS%) showed significant negative correlations with the variation of pain at rest. Two-dimensional depiction of scalp topography based on the grand average value of high-alpha ERD/ERS% during vibratory stimulation. The spatial distribution of the ERD/ERS% of the high-frequency alpha band during vibratory stimulation is shown. In the high-frequency alpha band, there is a significant negative correlation between the variation of pain at rest for peculiarity and ERD/ERS% C3 channel [a]) and ERD/ERS% of the C4 channel [b]).

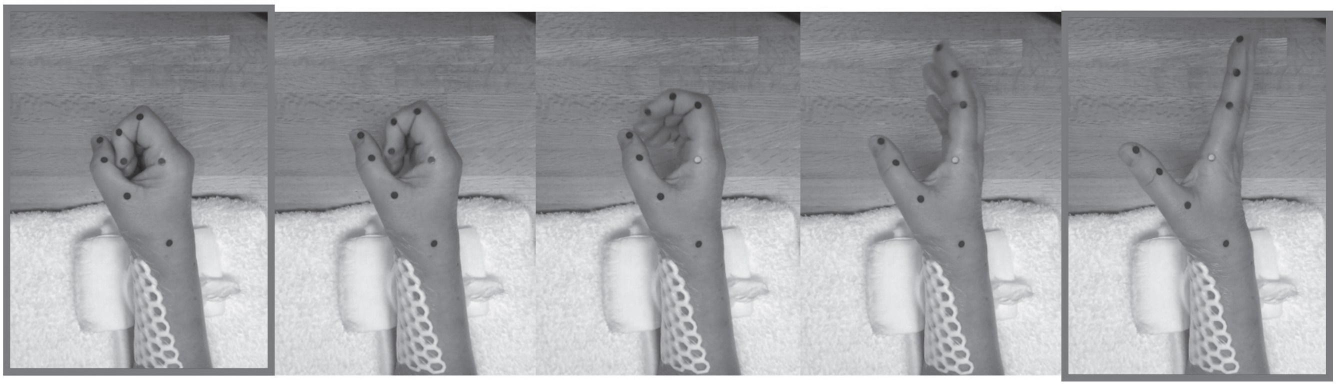

Figure 3. Recording hesitation time. The patient's performance on the finger-tapping task was recorded with an iPhone video camera (sampling rate: 30 Hz). The recorded movie was divided into individual frames, and the number of frames were counted.

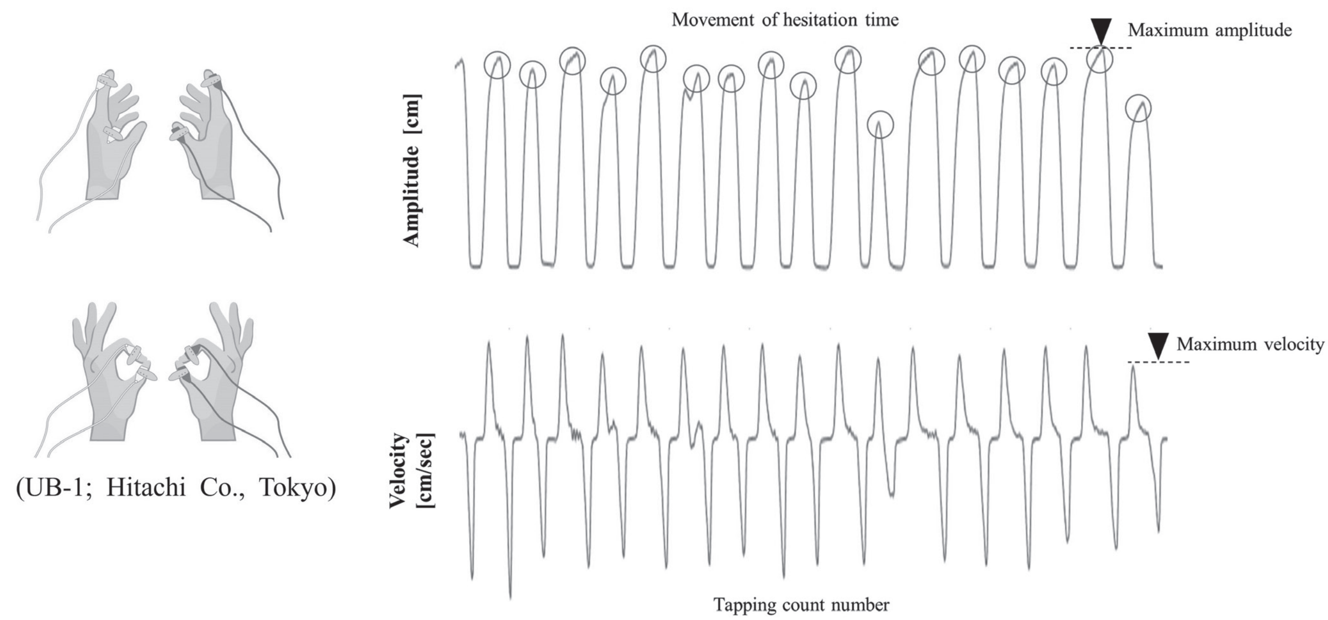

Figure 4. Kinematic data during the finger-tapping task by using UB-1. The upper panel shows the amplitude, and the lower panel shows the velocity. *Red circles* indicate the movement hesitation time.

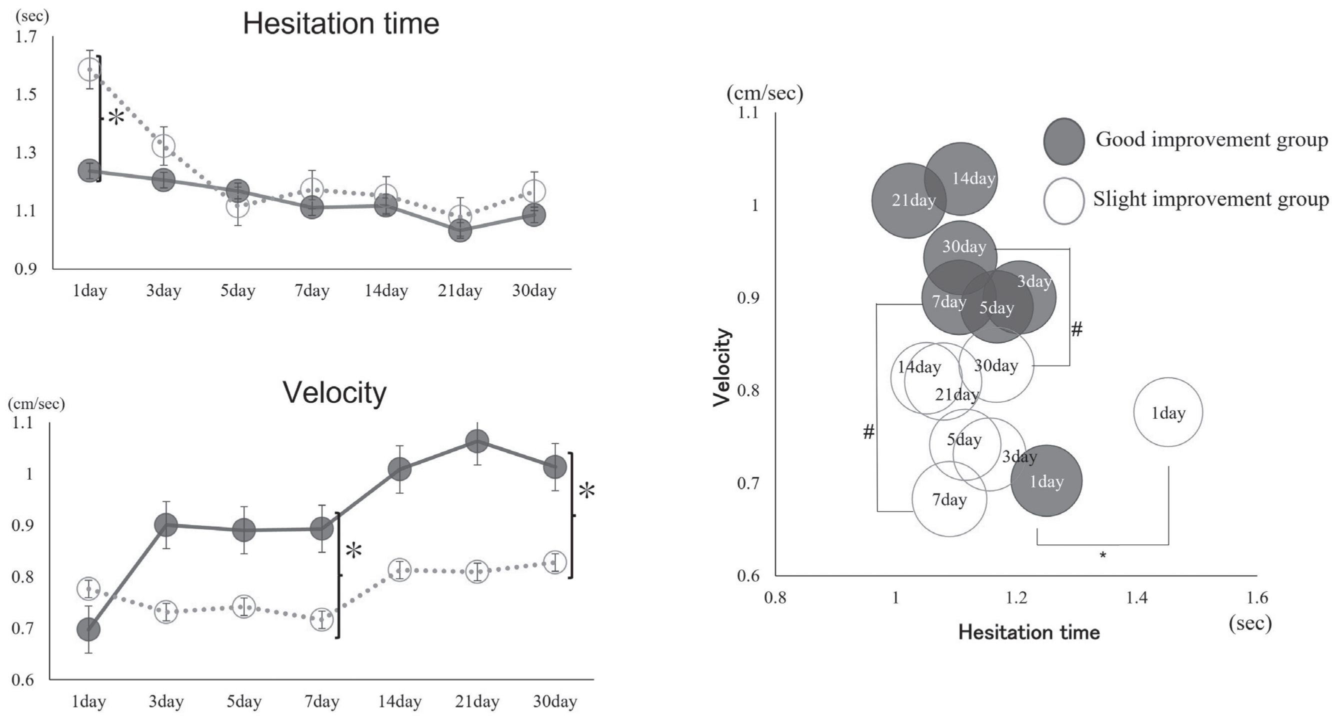

Figure 5. Hesitation time and Velocity. *Red circles* represent results for the good-improvement group, and *blue circles* are results for the slight-improvement group.

movement hesitation time (i.e., patients with a high fear of movement). I will continue to conduct clinical research to assess pain, the psychological aspects of pain, and pain-related movements. Appropriate physical therapy can then be provided based on these assessments.

CONCLUSION

This review article showed the salutary effects of illusory kinesthesia induced by vibratory tendon stimulation in patients with musculoskeletal pain disorders. The mechanism of chronic pain was also introduced, including two chronic model. Finally, focusing on my own research, I described improvements in pain and the psychological effects of pain resulting from the induction of illusory kinesthesia, and the neural mechanism of the analgesic effect. Because it is not yet known whether this approach would be effective for all patients, additional research will be needed to identify the most appropriate populations.

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