Illusion of Motion Induced by Tendon Electrical Stimulation

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ABSTRACT

Kinesthetic illusion is a well-known phenomenon elicited by vibratory stimulation to muscle tendon, which presumably causes muscle spindle activity. It is a candidate for kinesthetic sense presentation by direct receptors stimulation, which may lead to novel compact or immobile haptic displays. However, kinesthetic illusion requires strong mechanical vibrations, which hinders its practical use. I proposed to use electrical stimulation to muscle tendon, in which Golgi tendon organ resides, to generate the illusion. The experimental results revealed that tendon electrical stimulation elicited a similar illusion of motion to the kinesthetic illusion.

KEYWORDS: Golgi Tendon Organ, Haptic Display, Muscle Spindle, Tendon Electrical Stimulation, Virtual Reality

INDEX TERMS: H.5.2 [User Interfaces]: Haptic I/O

1 INTRODUCTION

Haptic interfaces that provide kinesthetic sensation are indispensable for telexistence and virtual reality, because they promote a sense of reality and intuitiveness. However, most haptic interfaces for kinesthetic sensation require large mechanical setups, which are sometimes undesirable due to limited workspace. Furthermore, mechanical devices that support whole-body haptic interactions, from fingers to feet, remain impractically costly.

Successful sensory presentation methodologies are commonly conscious of human sensory receptors. Visual displays use three primary colors (red, green and blue) that correspond to three types of cone cells in the retina. Auditory displays are discussed in terms of frequency characteristics, which correspond to the activity of hair cells in the cochlea. “Receptor selective stimulation” appears to be a key to the success of sensory displays.

In contrast, current haptic technologies try to reconstruct real physical phenomena, such as collisions with spring-damper structures. If we can introduce the methodology of receptor selective stimulation to the design of haptic displays, we may be able to reproduce kinesthetic sensations at lower costs. There is also the possibility of constructing immobile haptic interfaces that do not require users to move, but affluent kinesthetic sensations make them feel like they are moving (Figure 1). Immobile haptic interfaces may also be beneficial to users with limited physical capacities.

There is a well-known phenomenon called kinesthetic illusion that is induced by vibratory stimulation to the muscle tendon, which presumably stimulates kinesthetic receptors. It seems ideal for the purpose of receptor selective stimulation, but the requisite strong mechanical vibrations hinder its practical use.

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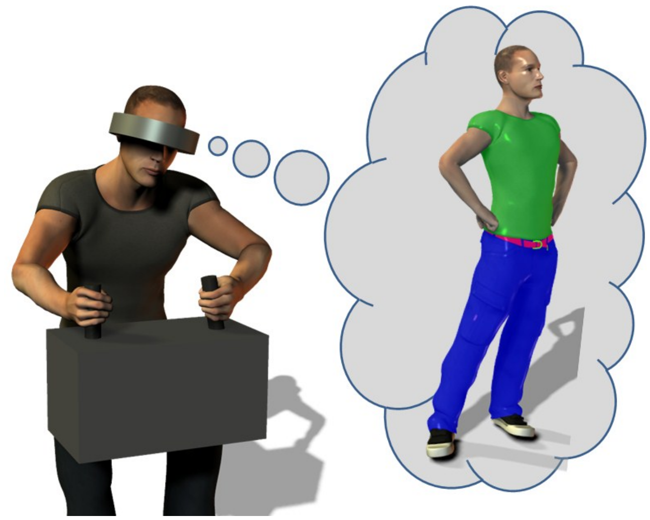

Figure 1 Immobile haptic interface with stimulation of kinesthetic receptors [1]

The purpose of this study was to generate kinesthetic illusion using electrical stimulation. In a previous study, the author observed that electrical stimulation to muscle tendon may induce illusory motion [1]. This paper shows detailed setups of the experiment, revealing that tendon electrical stimulation elicited a similar illusion of motion to the kinesthetic illusion .

2 RELATED WORK

2.1 Kinesthetic Illusion by Tendon Vibration

In 1972, Goodwin et al. and Eklund individually discovered an illusory arm motion, when 100Hz vibration was applied to tendon [2][3][4]. This phenomenon is now called kinesthetic illusion and it was supposedly elicited by activation of muscle spindles. Vibratory input to the tendon propagates to muscle and causes activity of muscle spindles, generating positional and velocity misinterpretation [5][6][7].

Application of kinesthetic illusion to human interface was proposed recently. Roll et al. placed numerous vibrators around the ankle and wrist to elicit virtual 2D motion [8]. Tomota et al. proposed using the illusion as a haptic interface, and evaluated the amount of illusion [9]. Leonardis et al. combined the illusion with visual stimuli [10]. Yaguchi et al. stimulated both ends of a muscle simultaneously so that the illusion becomes clearer [11]. However, strong mechanical vibration is necessary, which requires heavy actuators. Large noise also hinders its practical use.

2.2 Interface Using Electrical Stimulation

Electrical stimulation is a portable and energy-efficient method to deliver many types of sensations. Electrocutaneous display is a typical example, composed of surface electrodes to stimulate nerves that are connected to mechanoreceptors [12][13][14]. By varying polarity, electrode size and frequency, numerous types of sensations can be presented. Another interesting example is galvanic vestibular stimulation [15]. Direct current between two electrodes attached around the ears modulates activity of the vestibular system, causing illusory body tilt.

Kinesthetic display based on electrical stimulation has also been proposed [16][17]. Its main purpose is to stimulate muscles, not sensory organs. Utilizing functional electrical stimulation (FES) technology that was fostered in the field of rehabilitation engineering, muscles are utilized as “ideally wearable actuators”. Incorporating elements of FES technology could reduce the size of the system, but it would remain similar to conventional mechanical haptic displays, from the viewpoint that an external physical environment is presented and the user must move.

3 TENDON ELECTRICAL STIMULATION

I propose to use electrical stimulation to generate the kinesthetic illusion. If successful, problems related to size and noise of vibratory stimulation will be resolved.

Very few works have used electrical stimulation to generate the kinesthetic illusion, possibly because of the proposed mechanism of the illusion. As mentioned in section 2.1, the illusion is thought to be caused by muscle spindle activity, induced by propagated vibration from the tendon. If that is the case, electrical stimulation would be challenging, because electrodes placed over the muscle (which contains muscle spindles) would inevitably stimulate muscle efferent nerves, resulting in undesirable motion.

There is another sensory organ named Golgi tendon organ that is located in the tendons of skeletal muscles. If the Golgi tendon organ is at least partially responsible for the illusion, then electrical stimulation of the organ without stimulating the muscle becomes possible by placing the electrodes on the tendon (see Figure 2 for positional relationships).

There are some previous studies that the author considers suggesting possible involvement of the Golgi tendon organ to the illusion. Gandevia applied electrical stimulation to the ulnar nerve around the wrist and generated the kinesthetic illusion of fingers [18]. Although the authors suggested that muscle spindles might be responsible for the phenomenon, the volume of muscle under the stimulating point seems limited, and hence, receptors other than muscle spindles might have been involved.

Macefield electrically stimulated a single nerve fiber of muscle spindle, joint receptor, Golgi tendon organ and skin mechanoreceptor, and asked subjects to indicate when they perceived something. They found that for a large number of muscle spindle afferents they stimulated (14/16), there was no perceptual response to the stimulation, whereas that of the joint receptor and Golgi tendon organ (3/3), did cause illusion of motion (we must note that the sample number of Golgi tendon organ was quite limited in most literatures) [19]. Furthermore, during the 1980s and 90s, there were many studies stating that the muscle spindle receptor has a much lower threshold than other receptors (see [20]) which is a primary reason why it was considered responsible for the illusion. However, recently Fallon and Macefield found that the threshold among the receptors is actually not very different [21].

Based on the above, I hypothesize that it may be possible to generate illusory motion by tendon electrical stimulation, where the Golgi tendon organ resides.

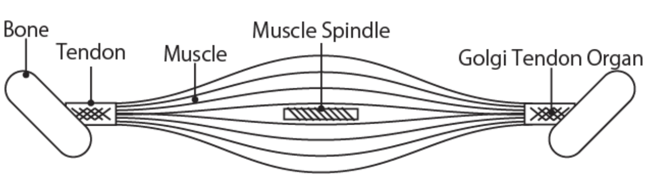

Figure 2 Location of the muscle spindle and Golgi tendon organ.

4 EXPERIMENT

Transcutaneous electrical stimulation of the Golgi tendon organ itself is frequently done to investigate the Golgi tendon reflex [22][23][24]. Based on these studies, experiments were conducted to see if kinesthetic illusion can be elicited by tendon electrical stimulation.

Figure 3 shows the setup of arm tendon electrical stimulation. Two electrodes (Nihon-Kohden Corp., F-150S) were attached to the distal end of the triceps’ tendons of the right arm. The electrodes were positioned about 3cm above the elbow joint, according to previous literature. The electrode size was 18mm×36mm, and the longitudinal axis of the electrodes was aligned parallel to the arm.

There are three convex parts on the elbow when it is bent, which correspond to bone edges, as shown in Figure 3. The two electrodes were placed close to the lateral and middle convex. If the electrodes were placed closer to the medial convex, the electrical current would have stimulated the ulnar nerve, causing strong cutaneous sensations on the lateral side of the lower arm.

The electrical stimulation was a current-controlled rectangular pulse, with 500 μs width, 0-10 mA height, and 100 Hz pulse frequency. The voltage was 0 V to around 150 V, depending on the skin condition. Participants controlled the pulse height themselves, with their left hands. The pulse was set biphasic, meaning that both electrodes alternatively worked as an anode and a cathode. This was achieved by using switching circuit that the author developed [14].

Participants included 10 adults, 22-36 years of age, two females and eight males. Participants were told that the experiment was about illusory motion and after the pulse height adjustment, they were asked to hold both arms out in front of them, close their eyes, relax, and use their left arm to mimic the perceived posture of their right arm (stimulated side). In other words, their left arms were mirror images of the subjective right arms. The stimulation continued for approximately 5 seconds until elicited illusory motion was considered saturated. The procedures were videotaped for analysis.

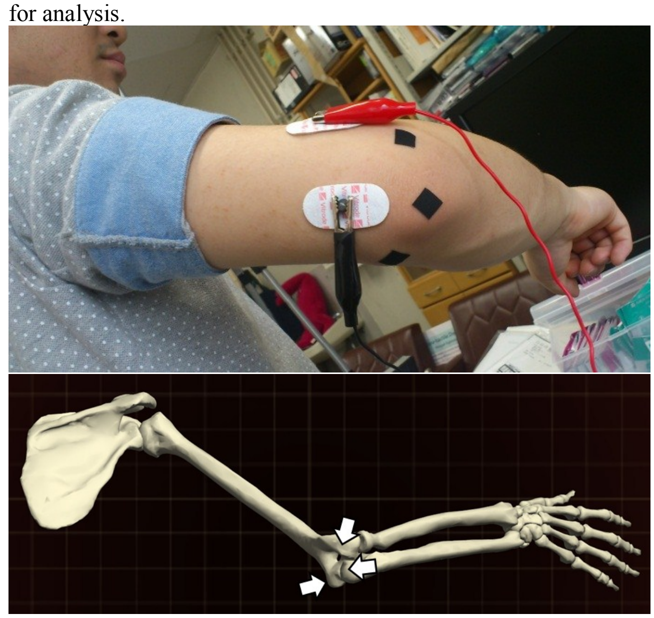

Figure 3 Arm tendon electrical stimulation. Electrodes were attached on the distal end of the triceps tendons. Black tape corresponds to bone edges, as indicated by arrows in the bottom figure.

5 RESULTS

The experimental results were categorized into three groups.

The first group was composed of three participants. They experienced strong illusions, as shown in Figure 4. In this figure, the participant mimicked the posture of his illusory right arm with his left arm. The left arm almost contacted his chest, while the right arm was almost still. One participant commented that it felt like “the right arm’s “ghost” moved inward”. All three participants commented that the motion was accelerated and stopped before hitting their chest.

The second group was composed of five participants. They experienced moderate illusions as shown in Figure 5. In this figure, the participant’s right arm moved inward slightly, but her left arm (mimicking right arm posture) moved 10 cm more than the right arm.

The third group was composed of the remaining two participants. They experienced no illusory motion, but their right and left arms both moved inward slightly. They commented that they felt an external force pushing the arm inward, but positional illusion was not elicited.

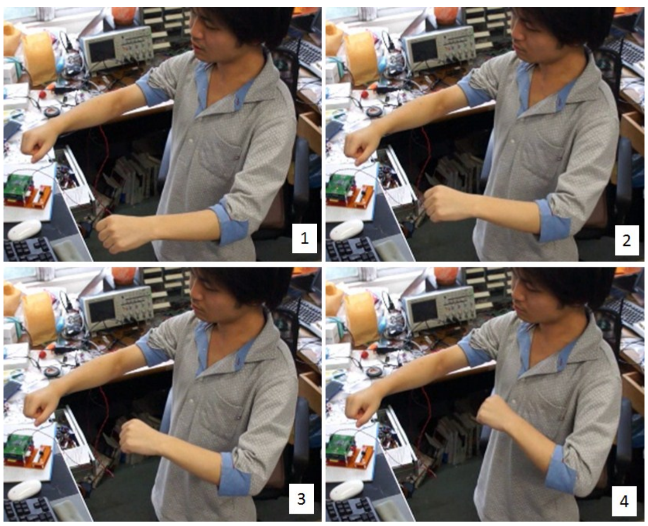

Figure 4 Case of strong illusory right arm motion mimicked by left arm. The right arm remained still, while the left arm almost touched the participant’s chest.

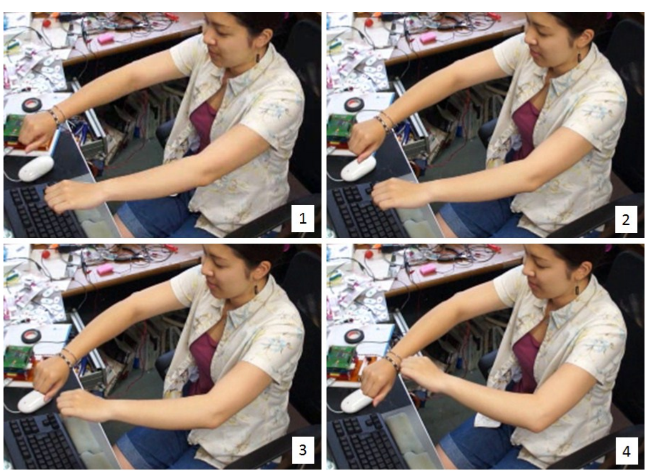

Figure 5 Case of moderate illusory right arm motion mimicked by left arm. Both arms moved inward slightly, while the left arm moved around 10cm more.

6 DISCUSSION

All participants, including those who did not experience illusory motion, commented that they felt an external force pushing the right arm inward. If the electrical stimulation had stimulated the triceps muscle, the exerted force and resultant motion would have been outward and not inward. Therefore, it is highly unlikely that this was a real force generated by muscle activity, but rather an illusory force elicited by the activities of sensory organs.

Because the Golgi tendon organ is a known force receptor, and the stimulating electrodes were placed over the tendon, the author speculated that activation of the Golgi tendon organ might be responsible for the elicited illusion. However, we cannot conclude from the present study that Golgi tendon is responsible for the illusion; because electrical current is diffusive so that it might have stimulated muscle spindles happened to be close to the tendon.

Variations in the strength of the illusory motion were puzzling. One possible explanation for the variations is that the illusory “force” was first elicited, and the illusory “motion” was rendered as a result of calculations in the central process. Comments by three participants in the first group, i.e., that they felt as if the motion was “accelerated”, seem to support this explanation. The long path between illusory force and translated motion, as well as other abundant posture cues such as cutaneous sensation and muscle spindle activity, might have hindered participants in the third group from experiencing any illusory motion.

It is known that the kinesthetic illusion is affected by cutaneous cues. The same tendency was observed in the arm tendon electrical stimulation, but with stronger effect. For example, just placing the stimulated arm to the arm rest eliminated the illusion, making quantitative measurement difficult. Cutaneous cues from sleeves also affected the amount of illusion and sometimes eliminated the illusion. We speculated that in the kinesthetic illusion, strong vibration might have masked the cutaneous cues, while in our case, cutaneous sensation by electrical stimulation was not so strong, relatively emphasizing external cutaneous cues.

7 CONCLUSION

This paper introduces the methodology of “receptor selective stimulation” to the kinesthetic display. Referencing the well-known kinesthetic illusion induced by tendon vibration, electrical stimulation of the tendon was tested to determine if it also causes illusory motion. The experimental results showed that illusory force was elicited for all participants (n=10), and illusory motion was elicited for most participants (n=7). Some participants experienced accelerated motion; one participant even reported experiencing the sensation of a “ghost arm”.

The commonly experienced illusory force implies possible contribution of the Golgi tendon organ to this phenomenon. Furthermore, as the result is similar to the known kinesthetic illusion, it is possible that the kinesthetic illusion is at least partially induced by activity of the Golgi tendon organ. Kinesthetic illusion is commonly thought to be elicited by the activity of muscle spindles.

Future works will include quantitative evaluation of the elicited motion, control of the amount of motion by varying the strength of the stimulation, and application of stimulation to other parts of the body. Nerve recording will be conducted to verify the hypothesis that the Golgi tendon organ plays a major role in this electrical tendon stimulation and may play a partial role in the known kinesthetic illusion.

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