Motion Guidance Using Translational Force and Torque Feedback by Induced Pulling Illusion

Takeshi Tanabe[1](✉), Hiroaki Yano[2], Hiroshi Endo[1], Shuichi Ino[1], and Hiroo Iwata[2]

[1] Human Informatics Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Central 6, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8566, Japan
{t-tanabe,hiroshi-endou,s-ino}@aist.go.jp

[2] Faculty of Engineering, Information and Systems, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8577, Japan
yano@iit.tsukuba.ac.jp, iwata@kz.tsukuba.ac.jp
https://unit.aist.go.jp/hiri/hi-fitness/index.html,
http://eva.vrlab.esys.tsukuba.ac.jp

Abstract. It is known that humans experience a kinesthetic illusion similar to a pulling sensation in a particular direction, when subjected to asymmetric vibrations. In our previous study, we developed a device that can apply a translational force and a torque to induce this illusion. The illusory translational force might induce a reaching motion of the upper limb, and the applied torque might induce a flexion–extension motion of the wrist. In the present study, we experimentally verified whether these motions can be induced. The results confirmed that the device could guide the upper limb with a success rate of 94.3% when switching between the application of the translational force and the torque. The results suggested that torque application could be a cue for the user to determine the movement direction intuitively.

Keywords: Illusory force perception · Asymmetric vibration · Non-grounded haptic interface · Motion guidance · Skill transfer

1 Introduction

Conventional methods of motion guidance include a verbal method, in which an expert verbally teaches a motion to a trainee, and a non-verbal method, in which the expert directly touches the trainee's body to induce a targeted motion. In particular, non-verbal methods are used in a wide range of fields, such as rehabilitation, craftsmanship, medical techniques, and sports. These instructions are called extrinsic feedback and are known to be effective in motor learning [1]. In recent years, motion guidance methods using haptic interfaces were proposed for high reproducibility and quantitative training [2,3]. These devices guide the

I. Nisky et al. (Eds.): EuroHaptics 2020, LNCS 12272, pp. 471–479, 2020.
https://doi.org/10.1007/978-3-030-58147-3_52

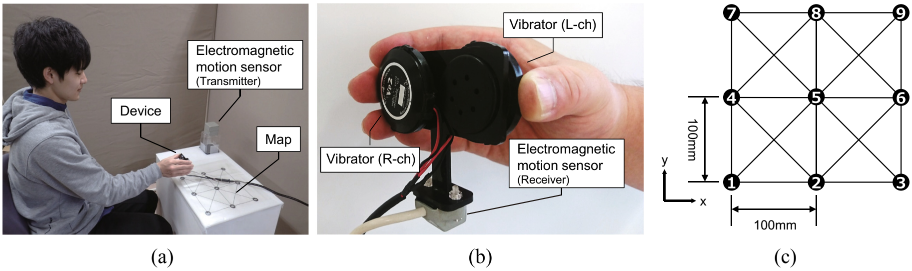

Fig. 1. Upper-limb guidance system: (a) overview, (b) enlarged view of the device, and (c) map of the navigation system.

user in performing the target motion by applying a force or torque to the user's body. However, these haptic interfaces need a large workspace because they must be grounded. Other studies [4,5] proposed a motion guidance method using vibrotactile cues, in which vibrators can be worn on the body because these actuators are smaller. This method has been applied to training for violin playing [5] and snowboarding [6]. Moreover, the application of a vibrotactile cue to an end effector, such as the hand [7] or wrist [4], is more effective than the application to a joint because the motion of the upper limb depends mainly on the hand position. However, the vibration stimuli have no directional cue such as a force or torque. The motions corresponding to vibrotactile cues, such as the movement of an arm in the direction in which vibration was perceived [4], must be mapped in advance. Such mapping of motions is difficult for trainees with a high degree of freedom of motion [8]. Therefore, to achieve efficient motion guidance, the actuator must be able to provide compelling directional information easily to the end effector.

In recent years, haptic interfaces that utilize a kinesthetic sensory illusion have been proposed. It is known that the sensory properties of humans are nonlinear. When strong and weak stimuli are applied sequentially, the user perceives the former but does not clearly perceive the latter. Based on this finding, Amemiya et al. proposed a method of applying vibrations with asymmetric acceleration to induce the perception of force toward a single direction in the user's hand [9]. Furthermore, we previously proposed a method of inducing pulling illusion by using a small voice-coil-type vibrator [10]. In addition, we developed a holdable device that presents an illusory translational force and torque by combining the two force vectors [11]. A new motion guidance method can be developed based on this pulling illusion for applications such as rehabilitation and skill transfer because compelling directional information can be easily provided to the fingertips by only vibration stimuli.

Reaching is a basic motion of the upper limb, in which the hand extends to a target position. Thus, the pulling illusion can be induced to guide the upper-limb motion of reaching. The application of a translational force might be effective for the guidance of reaching because the user's arm can be led by the translational force. However, when applying a translational force in one dimension, only the pushing and pulling motions of the upper limb can be induced. Reaching requires motion guidance in two or three dimensions, which can be achieved by the vector synthesis of translational force. On the other hand, translational force can be applied to guide only large movements of the user's arm to in the forward–backward, upward–downward, and leftward–rightward directions. To guide more complex movements, which are required for applications such as rehabilitation and skill transfer, it is necessary to combine the reaching motion with the motion of an end effector, such as the flexion–extension movement of the wrist. The application of a torque might be effective to induce a rotational motion of the wrist joint. In other words, if the reaching of the upper limb by a translational force and wrist flexion–extension movement by a torque can be combined, a wide range of motions from large to complex movements can be induced. In particular, torque application is important because it can provide a directional cue to perform reaching by changing the angle of the wrist. Therefore, it is hypothesized that torque application can provide intuitive feedback for the direction in which the upper limb should be moved.

In the present study, we experimentally verified whether the motion of upper limb can be induced based on the pulling illusion by using a combination of a translational force and torque. An upper-limb guidance system was developed, and a guidance experiment was performed for a reaching task in two dimensions as a basic study. The characteristics of guidance with and without torque application were investigated.

2 Method

2.1 Participant

Seven right-handed males aged 22–24 years participated in the experiment. The experimental procedure was in accordance with the Declaration of Helsinki. Informed consent was obtained from all participants.

2.2 Upper-Limb Guidance System

Figure 1 shows the upper-limb guidance system, which consists of a device that can apply a translational force and torque to induce the pulling illusion, an electromagnetic motion sensor (Polhemus Inc., 3SPACE FASTRACK), and a printed map. The device consists of two voice-coil-type vibrators (Acouve Lab Inc., Vibration Transducer Vp210). Two vibrators were placed in a side-by-side configuration. When a user holds these between the thumb and index finger, as shown in Fig. 1 (b), the force generated by the adjacent vibrator is primarily perceived by each digit. When the direction of the force exerted by each vibrator is controlled, a user can perceive both a translational force and torque. If forces are applied in the same direction on the participant's thumb and index finger, the participant perceives a translational force in this direction. In contrast, if forces in opposite directions are applied by the vibrator, the participant

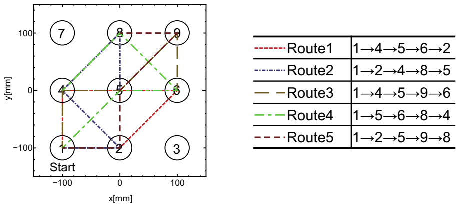

Fig. 2. Routes used in the experiment.

perceives a torque. In other words, this device can apply forces in four directions, in which a forward or backward translational force and a clockwise (CW) or counterclockwise (CCW) torque, by combination of the force vectors. These directions are controlled using an asymmetric-amplitude signal with a two-cycle sine wave that is inverted for a half-cycle [10]. Each signal was amplified with an amplifier circuit using a power amplifier IC (Texas Instruments Inc., LM386) with a maximum output voltage of ±4.5 V. The frequency of the input signal was 75 Hz. More details of this device can be found in Ref. [11].

The transmitter of the motion sensor and map were set on the table in front of the participants (Fig.1 (a)). The receiver of motion sensor is attached to the device (Fig. 1 (b)), and the position and posture of the device on the map were measured. The upper limb of the participant was induced by switching and presenting the translational force and the torque. The map and the device are not fixed, and participants can move the device freely on the map. Numbered circles on the map indicate nodes, and solid lines indicate routes (Fig. 1 (c)). The map has three nodes in the x direction and three nodes in the y direction. A total of nine nodes are arranged at 100 mm intervals. Each node and adjacent nodes in 45° steps were connected by routes. Routes in up to eight directions are connected at one node.

Next, the guidance algorithm is described. In this system, a translational force was applied if the posture of the device faced the direction of the next target node, and a torque was applied to face the target direction otherwise. The target angle θ_P between the position of the device $D(D_x, D_y)$ and the next target node $P(P_x, P_y)$ is

$$\theta_P = \tan^{-1} \frac{P_y - D_y}{P_x - D_x}. \tag{1}$$

The posture around the vertical axis of the device θ_D was measured, and a CW or CCW torque was applied when $\theta_D > \theta_P$ or $\theta_D < \theta_P$, respectively. Considering the range of motion of the wrist and the measurement accuracy, when the difference between the posture of the device and the target angle was less than ±15°, switching from torque to translational force was performed. When the target node was in the positive translational direction from the device, a forward translational force was applied, and when the target node was in the negative direction, a backward translational force was applied. When the device was within a certain distance from the center of the target node (set to

10 mm in this system), the target node was switched to the next node. In this algorithm, even if the position of the device deviates from the predetermined route, the torque and translation force are applied in accordance with the angle and distance to the target node. This system is intended for use with the right hand, and the posture of the device was set to 0° when facing the front (see Fig. 1 (b)), 45°, −45°, and −90° (CW is positive). The upper limb of the participants was guided in eight directions by applying a forward or backward translational force in the above four postures. The angle of the turning motion (difference between the device postures at the start and end of turning, hereinafter referred to as the rotation angle) was 0° at minimum and 135° at maximum.

The route was set to five types, each passing through five out of nine nodes with one stroke (Fig. 2). The start position was fixed at node 1. These routes were selected to make the number of occurrences of each rotation angle approximately equal.

2.3 Procedure

Under the hypothesis that the torque application can provide intuitive feedback for the direction in which the upper limb should be moved, the experiment was conducted with (w.) and without (w/o) torque application. Because the wrist posture could not be guided in the w/o torque condition, the participants performed active exploration for the next target posture by rotating the device. In the w. torque condition, the posture was guided by torque application as explained in Sect. 2.2. Under both conditions, a forward or backward translational force was presented when the device was guiding to the next node.

The experimental tasks are as follows. Participants moved their upper limbs as guided by the device to trace a solid line when traveling along a route and to perform rotation within a node. In total, 30 trials were performed for each participant, with 3 trials for each condition (2 levels) and each route (5 levels), and each condition and each route was randomized. To minimize fatigue during the experiment, the trials were divided into three blocks of 10 trials each, and the participants were given a two-minute break between blocks. In this experiment, audiovisual information was not blocked because actual motion guidance was assumed. Before the trial, the experimenter verbally guided the participant about the condition of torque application. A sound effect was output from the speaker only when the goal was achieved, indicating that the trial was completed. A 5-min practice period was set up so that participants could learn how to operate the device before the experiment.

3 Results

Figure 3 shows typical examples of the device's trajectory. The solid lines show the trajectories in which the device was moved by the participants, and the broken lines show the target routes. The task was determined as successful when the device passed the nodes in the set order.

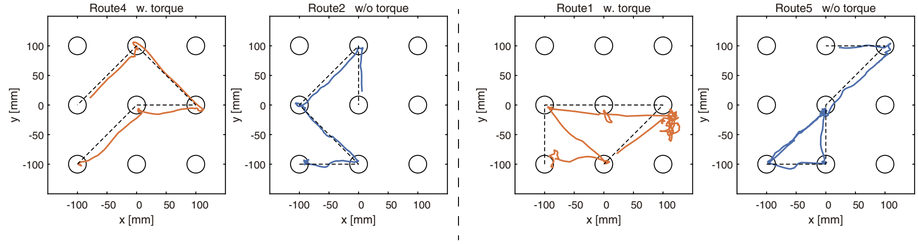

Fig. 3. Typical examples of the device's trajectory: (a) successful task; (b) failed task.

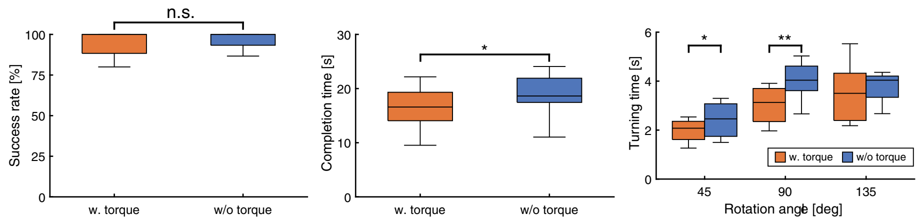

Fig. 4. Experimental results: (a) success rate of guiding along routes, (b) task completion time, and (c) turning time (n.s.: not significant, *: $p < 0.05$, **: $p < 0.01$).

Figure 4 (a) shows the success rate for guiding routes. The average success rate in the w. torque condition was 94.3%, and the rate in the w/o torque condition was 96.2%. In a paired t-test between the conditions, no significant difference was found [$t(6) = 1.00$, $p = 0.37$, $d = 0.28$].

The task completion time and turning time were analyzed for only successful trials. Figure 4 (b) shows the task completion time. The completion time indicates the time from the start signal provided by the experimenter to time at which the fifth node is reached. In a paired t-test between the conditions of torque application, a significant difference was found [$t(6) = 2.49$, $p < 0.05$, $d = 0.53$].

The turning time indicates the time from the moment when a node is reached to the time at which the turn at the node is completed. Figure 4 (c) shows the turning time at each rotation angle. Since the change in turning time was small with respect to the rotation direction, the rotation directions were merged for each rotation angle. Furthermore, the rotation angle was not considered a factor, because the turning time increased as the rotation angle increased. In a t-test between the conditions of torque application, significant differences were found for 45° [$t(6) = 2.67$, $p < 0.05$, $d = 0.68$] and 90° [$t(6) = 3.96$, $p < 0.01$, $d = 1.32$], whereas no significant difference was found for 135° [$t(6) = 0.57$, $p = 0.59$, $d = 0.24$].

4 Discussion

Because the success rates of guidance were high under both conditions, it was shown that the upper-limb motion could be guided by the pulling illusion. This result suggests that the user can be guided to perform large and complex movements by combining the reaching and wrist motions. However, although no significant difference was found between the conditions, the success rate was lower under the w. torque condition. This might have been caused by the adaptation to stimuli induced by the long-term application of asymmetric vibration. We confirmed that the subjective sensitivity of illusory force decreased with the continuous presentation of asymmetric vibration [12]. In the w. torque condition, the asymmetric vibration was always presented, whereas in the w/o torque condition, the stimulus during the turning motion was not presented. The sum of the vibration-stimulation times was larger in the w. torque condition, and the adaptation might be induced earlier. Therefore, an application method that considers adaptation is required.

The completion time and turning time were significantly shortened on applying the torque. Thus, it is considered that the participants intuitively determined the direction in which the wrist must be flexed with the torque application. On the other hand, although the difference in turning time between the torque conditions was remarkable when the turning angle was small, such as 45° or 90°, the effect of the torque application was smaller for a turning angle of 135° ($d = 0.24$). When the turning angle was 135°, either the CW rotation from the −45° posture or the CCW rotation from the 45° posture was performed. Thus, the participant could determine the next direction to rotate to without directional information when the turning angle was 135°. In other words, this result supports the hypothesis that the torque application is effective when it is necessary to determine the direction. Therefore, the illusion may be useful as a trigger of motion.

This method is expected to be effective in an environment where visual information can also be presented because the task is to guide the user along routes on a map. Moreover, it is difficult to induce high-speed motion by using this method because the user needs to move the upper limb by using a force or torque cue. Therefore, guidance for slow motions, such as rehabilitation using a pegboard, welding, and calligraphy, might be feasible. Particularly in the field of rehabilitation, it has been reported that reaching assisted by a robot contributes to the recovery of motor function [13]. Motor learning might be promoted by supporting reaching using our device. However, although this study showed that the pulling illusion could guide reaching and wrist motions, the effects on motor learning were not clarified. In the future, long-term verification of motor learning using our device is required.

5 Conclusion

In this study, we verified whether the motion of upper limb can be induced by using the translational force and torque presentation based on the pulling illusion. As a result, it was confirmed that this device could be guided with a success rate of 94.3% in the condition of switching the presentation of the translational force or the torque. It was also suggested that torque presentation could be a cue to intuitively determine the direction. In the future, we investigate the relationship the pulling illusion and motor learning, and develop the applications, such as rehabilitation or skill transfer.

Acknowledgments. This work was supported by JSPS KAKENHI Grant No. 19K24374.

References

1. Tani, H.: Are Instructions and Feedback by a Therapist Effective in the Motor Learning?. Rigakuryoho Kagaku, vol. 21, no. 1, pp. 67–73, 2006. (in Japanese)
2. Yem, V., Kuzuoka, H., Yamashita, N., Ohta, S., Takeuchi, Y.: Hand-skill learning using outer-covering haptic display. In: Auvray, M., Duriez, C. (eds.) EUROHAPTICS 2014. LNCS, vol. 8618, pp. 201–207. Springer, Heidelberg (2014). https://doi.org/10.1007/978-3-662-44193-0_26
3. Feygin, D., Keehner, M., Tendick, F.: Haptic guidance: experimental evaluation of a haptic training method for a perceptual motor skill. In: Proceedings of 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator System (HAPTICS 2002), pp. 40–48 (2002)
4. Salazar, J., Okabe, K., Murao, Y., Hirata, Y.: A phantom-sensation based paradigm for continuous vibrotactile wrist guidance in two-dimensional space. IEEE Robot. Autom. Lett. **3**(1), 163–170 (2018)
5. van der Linden, J., Schoonderwaldt, E., Bird, J., Johnson, R.: MusicJacket-combining motion capture and vibrotactile feedback to teach violin bowing. IEEE Trans. Inst. Meas. **60**(1), 104–113 (2010)
6. Spelmezan, D., Schanowski, A., Borchers, J.: Haptic guidance: experimental evaluation of a haptic training method for a perceptual motor skill. In: Proceedings 4th International ICST Conference Body Area Networks, pp. 1–8 (2009)
7. Basu, S., Tsai, J., Majewicz, A.: Evaluation of tactile guidance cue mappings for emergency percutaneous needle insertion. In: Proceeding of IEEE Haptics Symposium 2016, pp. 106–112 (2016)
8. Bark, K., et al.: Effects of vibrotactile feedback on human learning of arm motions. IEEE Trans. Neural Syst. Rehabil. Eng. **23**(1), 52–63 (2015)
9. Amemiya, T., Ando, H., Maeda, T.: Lead-me interface for a pulling sensation from hand-held devices. ACM Trans. Appl. Percept. **5**(3), art. 15, 1–17 (2008)
10. Tanabe, T., Yano, H., Iwata, H.: Evaluation of the perceptual characteristics of a force induced by asymmetric vibrations. IEEE Trans. Haptics **11**(2), 220–231 (2018)
11. Tanabe, T., Yano, H., Iwata, H.: Proposal and implementation of non-grounded translational force and torque display using two vibration speakers. In: Hasegawa, S., Konyo, M., Kyung, K.-U., Nojima, T., Kajimoto, H. (eds.) AsiaHaptics 2016. LNEE, vol. 432, pp. 187–192. Springer, Singapore (2018). https://doi.org/10.1007/978-981-10-4157-0_32
12. Tanabe, T., Yano, H., Iwata, H.: Temporal characteristics of non-grounded translational force and torque display using asymmetric vibrations. In: Proceedings of IEEE World Haptics Conference, pp. 310–315 (2017)
13. Takahashi, K., et al.: Efficacy of upper extremity robotic therapy in subacute poststroke hemiplegia. Stroke **47**(5), 1385–1388 (2016)