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Comparison of Three Feedback Modalities for Haptics Sensation in Remote Machine Manipulation

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***Abstract*—Previous studies have verified the usefulness of visual haptics for achieving the appropriate grasping force and task success rate to operate remote machines. However, its capabilities have not been evaluated objectively and quantitatively. We comprehensively compare three feedback modalities (i.e., sound, vibration, and light) for providing pseudo-haptic information on contact with an object, which we apply to grasping an object with a remotely operated robot arm. Experimental results verify that the light modality (i.e., visual haptics) minimizes the grasping force and processing load in the operator's brain. We then develop a prototype of a remote machine to demonstrate the feasibility of visual haptic feedback. We consider three implementations (i.e., a light-emitting diode, model-based superimposition, and model-less superimposition) to verify the performance. The results show that visual haptics can stabilize the performance of delicate tasks such as grasping and carrying fragile raw eggs and potato chips. We demonstrate that our visual haptics method (i.e., superimposing haptic information as images on the contact points of the robot's fingertips) can significantly improve the operability of remote machines without the need for highly complex and expensive interfaces.**

***Index Terms*—Haptic and Haptic Interfaces, Dexterous Manipulation, Remote Machine, Feedback Modalities**

I. INTRODUCTION

DEVELOPED countries are dealing with social issues such as a declining birthrate, aging population, and labor shortage [1]. One solution is to increase the number of migrant workers from other countries [2]. However, most workers wish to spend time with their own friends and family in familiar areas rather than living apart from them [3]. In addition, the recent spread of coronavirus (COVID-19) has created a serious barrier to the flow of people across regions. Accordingly, remote machines have received much attention as a viable solution to the problem of labor shortages without reducing the quality of life of the area and workers. As shown in Fig. 1, remote machines can be used for a wide range of purposes, such as maintenance and inspection of facilities in remote and inaccessible areas, response to frequent natural disasters, and telework. In the 1940s, Georges et al. developed a mechanical motion-transmitting manipulation system to handle radioactive materials [4]. In the 1990s, advances in computational processing technology led to the concept of immersion being proposed, where information is transmitted from multiple sensors of a remote machine to give the operator a sense of oneness with the machine [5,6]. While remarkable advances have been made in automation technology with regard to locomotion, fully automated manipulation technology is not yet mature enough to replace human manipulation. Therefore, remote machine manipulation is important for addressing the limits of automated manipulation, advancing virtual/augmented reality (VR/AR) technology, and facilitating sophisticated and globalized communication technologies such as the fifth generation (5G) network and Starlink [7].

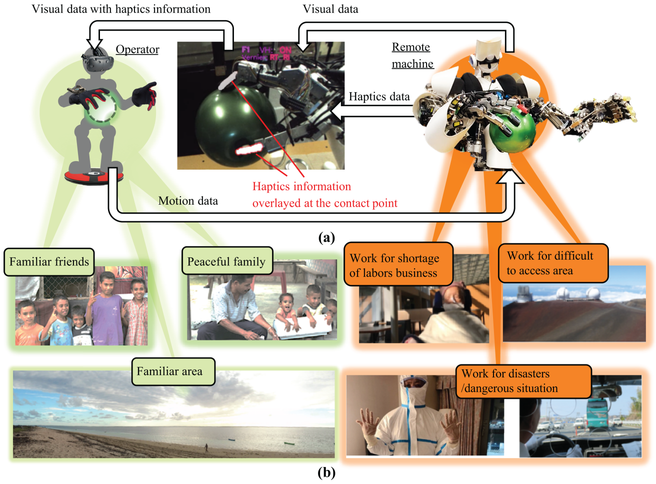

Fig. 1. Developed remote machine system: (a) implementation of the proposed visual haptics on the prototype humanoid remote machine with superimposed images on the fingertips; (b) applications of remote machines.

Haptic transmission is an important element for the manipulation of remote machines. Proposed approaches include physical feedback [8–16] and pseudo-feedback [17–22]. The da Vinci surgical system (Intuitive Surgical) is one of the most advanced remote machine in terms of technology and commercialization [23]. Many surgeons have stated that this system can be used to complete surgeries using only visual information [24]. This suggests that visual feedback may be an ideal approach to haptic transmission.

We previously proposed a method that visually superimposes haptic information on a contact point with the object to minimize the cost and complexity of equipment. It was confirmed through electroencephalogram (EEG) measurements that the visual haptic feedback is effective for remote manipulation in a VR environment [25]. Nevertheless, our previous study lacks in rigorous comparison between visual

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feedback and other non-visual feedback modalities. In addition, the visual feedback modality was not evaluated in a real environment close to the actual conditions for manipulation rather than in a VR environment. Existing studies [20-22] have compared visual haptic feedback with physical haptic feedback in terms of the grasping force and task success rate in real environments using an actual robot. However, these studies did not use EEG to measure the cognitive load on the operator, and the operability was assessed subjectively. In addition, haptic information was superimposed on areas other than the contact point (e.g., beside the contact point or on both edges of a display), which can force the operator to shift their gaze frequently during operation [25]. Also, there is little literature comparing audio as a feedback modality.

The major contributions of our present study are twofold:

- We compare three types of feedback modalities (i.e., sound, vibration, and light) as pseudo-haptic information for a tele-operated arm making contact with an object during a grasping task. Experiments are performed to measure the grasping force and information load on the brain with each feedback modality.
- We build a prototype of a remote machine to implement visual haptic feedback under conditions similar to those of real operation. We consider three methods of visual haptic feedback to evaluate their effectiveness: a light-emitting diode (LED), model-based video superimposition, and model-less video superimposition.

The rest of this paper is organized as follows. Section II presents an overview of haptics research and equipment. Section III gives the equipment and methodology used to compare the three feedback modalities, as well as the results and considerations. Section IV presents the three implementations of visual haptic feedback and the results with the prototype remote machine system. Section V discusses the results of the study, and Section VI concludes the paper.

II. HAPTIC FEEDBACK TECHNOLOGY

A. *Physical Haptic Feedback*

Various functions such as detecting the reaction force at the finger joint, shear force at the fingertip, and temperature have been studied for generating haptic sensations that humans can feel naturally. Three types of devices are available for physically presenting a haptic sensation: the grounding, wearing, and tactile display types. The grounding type transmits haptic sensations physically with six degrees of freedom (DOF) in space [8,9]. While this type of device is advantageous for manipulating a tool with the same shape as the end-effector of a remote machine, such as a pen or forceps, the device tends to be complicated and large. The wearing type is easy to carry because it is attached to the hand. For complicated devices, reaction forces can be generated on individual fingertips using mechanical links and servomotors [10,11]. For simpler and lightweight devices, the contact information of each finger can be transmitted individually to the operator by vibration [12]. HaptX Gloves is an advanced commercial device [13] that realizes physical haptic feedback at multiple points. It uses microelectromechanical systems (MEMS) fluid technology to present 120 points of pressure: 30 points each on three fingers and an additional 30 points on the palm. In addition, various studies have focused on tactile displays to reproduce the feeling of contact on the fingertip [14–16].

B. *Pseudo-Haptic Feedback*

Pseudo-haptic sensations refer to a visual stimulus that expresses physical movement and an appropriately modulated force-tactile stimulus that is not originally given [17]. Kokubun et al. successfully presented haptic sensations by adjusting the amount of mouse movement on a display [18]. Matsumoto et al. developed a system that presents the illusion of moving in a straight passage by expressing curved passages and walls as a linear display in VR space [19]. Interestingly, the operator can perceive pseudo-haptic sensations through modulation of the visual stimuli. Studies have compared and validated the operability of remote machines with physical force feedback (PFF) and visual force feedback (VFF) [20– 22]. Williams et al. compared VFF and PFF for a drill task performed by a remotely controlled humanoid robot. Their results showed that VFF alone reduced the maximum force and torque by 23% compared to no feedback, and subjective results showed that VFF was superior to PFF [20]. Reiley et al. applied robot-assisted VFF to a surgical knot task, where the force sensor information was superimposed as colored circles on the console image except for the instrument tip, depending on the force state [21]. Their results showed that even surgeons without robotic experience significantly improved their performance with VFF in terms of the suture breakage rate, peak applied force, and standard deviation of the applied force. Talasaz et al. compared combinations of VFF and PFF with tele-operated systems [22]. VFF improved the performance without PFF and degraded the performance with PFF. This suggests that VFF is better than PFF for ensuring task performance.

C. *Proposed Visual Haptic Feedback*

The da Vinci surgical system has led to advances in remote machines since the 1980s. The forceps in the patient's body and the forceps operated by the surgeon are not mechanically coupled. Hence, the system is categorized as a remote machine. Despite the effectiveness of haptic feedback in various surgical support robots [26,27], most surgeons have found that this is not really necessary because they could rely solely on visual information when operating the da Vinci surgical system, which has no haptic feedback [24]. This suggests that existing haptic feedback devices are not sufficiently advanced to transmit the feeling of manipulation to the operator and that physical feedback is not required for certain remote manipulation tasks. Thus, visual haptic feedback may be a reasonable option for operating remote machines in terms of simplicity and effectiveness owing to the high level of adaptability of human operators.

In the previous example using VFF, the haptic information was superimposed near the remote machine hand that was manipulating the object or at the edge of the screen. While this presentation method has the advantage of retaining all contact point information, it has the disadvantage of forcing the operator to move their line of sight back and forth from the target object to the haptic information. We previously proposed a method of superimposing haptic information on the contact point with the object and verified its effectiveness [25]. In this study, we perform a more rigorous analysis of our proposed method using experiments, demonstrations, and prototypes.

III. COMPARISON OF THREE FEEDBACK MODALITIES FOR HAPTIC SENSATIONS

A. *Equipment*

To compare feedback modalities for haptic transmission, a simple device was constructed as shown in Fig. 2. The equipment can be operated by a subject within a relatively short time because the arm is constrained in the two-dimensional plane, as shown in Fig. 2(a), and the gripper is constrained in the direction of gravity. The robot arm has 4 DOFs at its joints and 1 DOF for opening/closing the gripper. The wrist position is controlled by the wrist of the operator. The 2-DOF translation of the operator's wrist is measured with a camera-based color tracking technique, and the joint angle command values of each motor are calculated by inverse kinematics using a neural network pre-trained by machine learning. The gap between the grippers is controlled by a dedicated control interface, as shown in Fig. 2(b). The operator can obtain haptic sensations when the robot arm grasps the object with one of three feedback modalities: sound, vibration, and light. A speaker and vibration motor are attached to the gripper control interface worn by the operator, as shown in Fig. 2(b), and the LED is attached to the tip of the robot gripper, as shown in Fig. 2(c). A pressure sensor is attached to the tip of the gripper; when the pressure exceeds a threshold value, the speaker, vibration motor, or LED is activated.

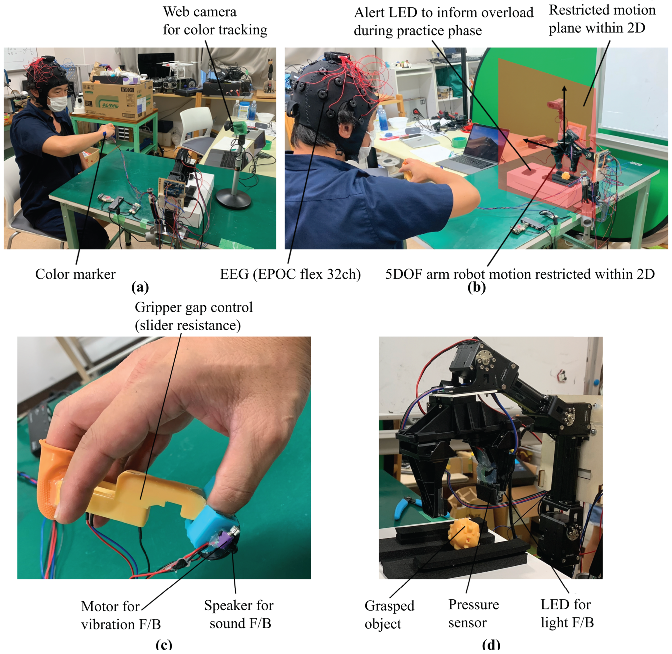


Fig. 2. Evaluation equipment for three feedback modalities: (a, b) experimental scenes; (c) gripper gap controller with vibration and sound feedbacks; (d) robot arm with light feedback.

B. *Method*

Each subject was asked to perform a test according to the process shown in Fig. 3(a). The subjects were instructed to gently grasp and carry as many objects as possible within 1 min. for each case. In session 0, the subjects practiced manipulation for 5 min, and the three feedback modalities were transmitted simultaneously without any data being collected. If the grip was not gentle and the pressure sensor exceeded the upper threshold (40 g, which was difficult but possible), the alert LED lit up as shown in Fig. 2(b). The purpose of this session was for the subject to understand what "gentle" meant and to get used to operating the robot arm. In session 1, four cases were considered to evaluate the feedback modalities, as shown in Fig. 3(b): no feedback (case 1), sound (case 2), vibration (case 3), and light (case 4). To control the influence of the feedback order on the results, three sessions were conducted, as shown in Fig. 3(a).

For subjective evaluation, the subjects were interviewed and asked to answer a questionnaire after each session. The questionnaire asked the subjects to score each feedback modality from 0 to 100 (the higher the score the better). Our questionnaire was based on a simple weighting of the performance, effort, and frustration subclasses of the NASA task load index (TLX) to calculate the subjective operability for manipulation tasks. For each session, two kinds of data were collected with timestamps for later analysis: from the pressure sensor mounted on the gripper and the 32-channel EEG array sensor mounted on the subject. Note that the studies involving human participants were reviewed and approved by the ethics committee of Kansai University as HR2019-13. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

The EEG measurements were visualized as an information flow in the brain based on the Smooth Coherence Transform (SCoT) library [28]. While the original 32-channel electrodes

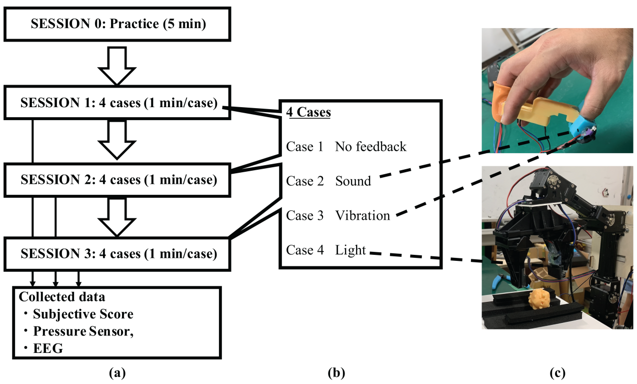
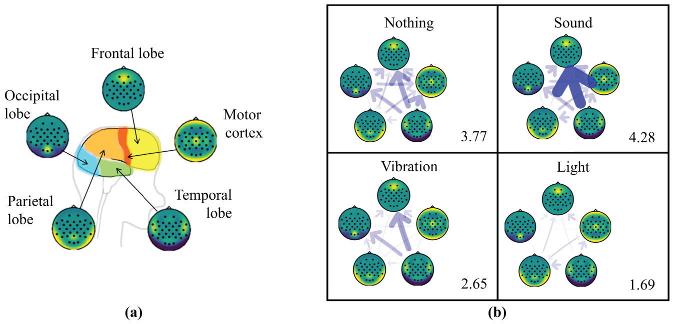


Fig. 3. Evaluation process for one subject: (a) four sessions including practice; (b) procedure for one session; (c) positions of three feedback modality devices.

were spatially mapped to cover most of the scalp as specified by the international 10-10 system, we selected five locations for analyzing the information flow, as shown in Fig. 4: the frontal, occipital, parietal, temporal, and motor regions. The time-series data were sampled at a rate of 128 Hz for about 1 min and then divided into short-time sequences of 0.5 s. The information flow in the brain was analyzed by using a stationary vector autoregressive (VAR) model of the 20th order, which was the minimum value required to pass a statistical whiteness test across all datasets. VAR is widely used for cognitive state analysis in the literature [29–38]. We used a full frequency directed transfer function (ffDTF) as the causality metric to analyze the information flow [39]. The information flow results of three sessions for each subject were evaluated for three frequency bands: the alpha, beta, and theta waves. The arrows in Fig. 4 indicate the direction of information flow in the brain (time order of excitation). The thickness of the arrow line indicates the amount of information flow. The numerical values inside the boxes denote the total information flow in each case.



(a) (b)

Fig. 4. Example results of brainwave analysis by SCoT: (a) spatial arrangement of the brain corresponding to five parts; (b) information flow in the brain and total amount of each feedback.

C. Results

Seven subjects participated in this evaluation test. Two of the subjects were excluded because their EEG measurements deviated from the whiteness test, and they did not understand the task instructions sufficiently. The collected data from three sessions by the five remaining subjects were separated into each case based on the recorded timestamps.

Fig. 5 shows the average grasping force for each case. Compared to the case without sensory feedback, the sound, vibration, and light feedback modalities reduced the grasping force by 18.0% (with a t-test significance level of $p = 0.079$), 17.2% ($p = 0.012$), and 24.1% ($p = 0.034$), respectively. The light feedback modality reduced the grasping force the most, and its statistical significance ($p < 5\%$) was verified in comparison to the case without feedback.

The subjective scores for each feedback modality were normalized against those of the no-feedback case, as shown in Fig. 6. The sound, vibration, and light feedback modalities achieved scores of 1.24 ($p = 0.492$), 1.47 ($p = 0.051$), and 1.85 ($p = 0.108$), respectively. Thus, the visual feedback achieved the highest score. Many subjects mentioned that they could operate the gripper while focusing on the gripper with the light feedback modality. The sound feedback modality may have scored low because of the quality of the sound used in the test. Each feedback modality was turned on continuously when the pressure exceeded the threshold. Some subjects felt that this was noisy, especially with the sound feedback modality. This hypothesis is supported by the fact that the information flow in the brain was highest with the sound feedback modality, as shown in Fig. 6.

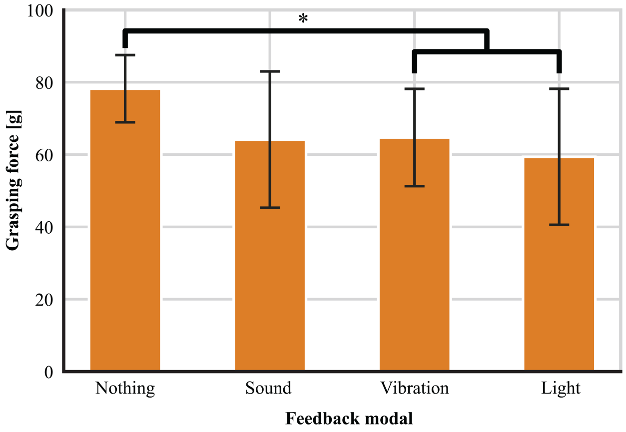


Fig. 5. Grasping forces with three modalities (i.e., sound, vibration, and light) and no sensory feedback (i.e., nothing).

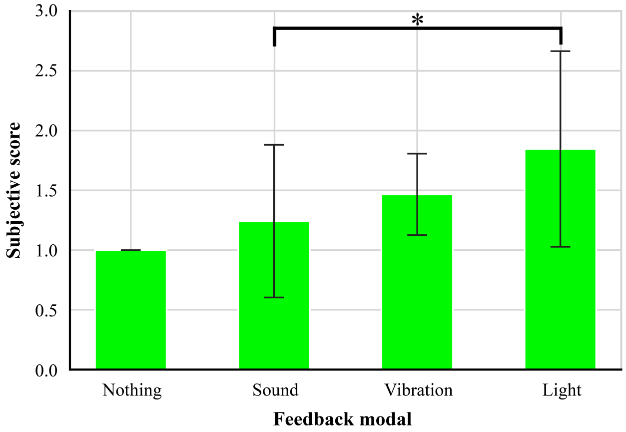


Fig. 6. Subjective scores of operability with three feedback modalities (sound, vibration, and light) normalized against the score for no sensory feedback (i.e., nothing).

Fig. 7 shows the average information flows in the brain for each feedback modality, which were normalized against that of the no-feedback case. Compared to no feedback, the sound feedback modality increased the information flow by 37.8% ($p = 0.279$), while the vibration and light feedback modalities reduced the information flow by 14.0% ($p = 0.264$) and 12.7% ($p = 0.144$), respectively. Both the vibration and light feedback modalities were confirmed to reduce the information flow in the brain.

Fig. 8 shows the relationship between the subjective evaluation and reduction of the information flow in the brain. The translucent range represents a 95% confidence interval. The green, red, and light-orange plots represent the results with the sound, vibration, and light feedback modalities, respectively. There was a positive correlation between the subjective score and reduction of information flow in the brain with a Pearson correlation factor of 0.460 (p-value: 0.055). Thus, the results verified that the proposed visual haptic feedback is superior to other feedback modalities in terms of control of the grasping force, subjective evaluation, and reduction of the information flow in the brain.

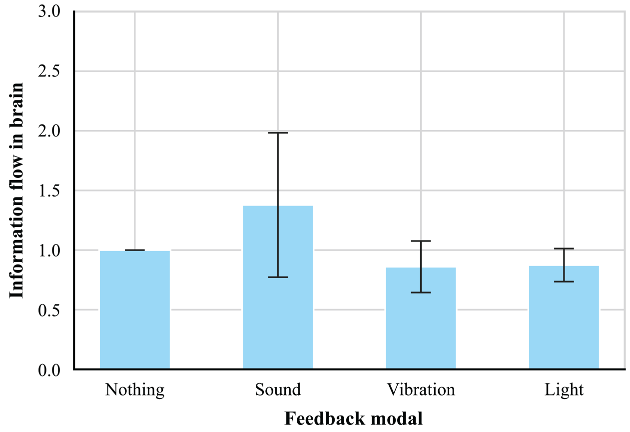


Fig. 7. Information flow in brain according to SCoT results. The flows for each feedback modality were normalized against the flow for no sensory feedback (i.e., nothing).

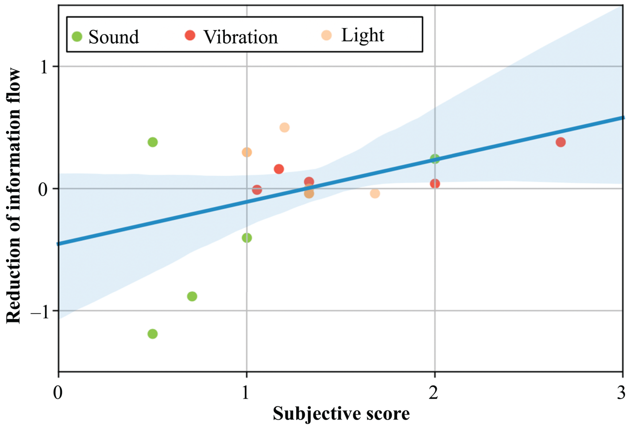


Fig. 8. Subjective score and reduction of information flow in the brain for the three modalities. The color indicates the modality, and a dot indicates the result of a subject.

IV. VISUAL HAPTICS IMPLEMENTATIONS WITH REMOTE MACHINE PROTOTYPE

We developed a prototype of a humanoid remote manipulation system to verify the effectiveness of visual haptics at manipulation tasks under conditions similar to reality. Different implementations of visual haptics were considered. The humanoid robot has 42 DOFs. Each joint of the 11-DOF mechanical hand has a self-locking mechanism with a high-reduction gear and torque adjustment algorithm to enable stable grasping along the shape of the object. In addition, a linear link mechanism was adopted for each joint of the upper body to achieve a high thrust force even with a limited volume and mass. Fig. 9 shows the mechanical structure, drive range, and thrust design values. The technology is based on developments by Mitsubishi Electric Corporation for large telescopes to achieve high-precision motion control of heavy objects. For example, these mechanisms and their control technologies have been applied to the divided mirror replacement robot for the Thirty Meter Telescope (TMT®) [40,41]. Two types of motion transmitters from the operator to the robot were considered, as shown in Fig. 10: a mechanical type with angle detection sensors on each axis, and a wearable type on both hands with a 6-DOF measurement device. Camera images are transmitted to the head-mounted display (HMD), and the waist motion of the robot is controlled by the foot device for the interfaces of both types. The interface of the mechanical type has mechanical encoders controlling 36 DOFs, except for 3 DOFs each for the head and waist. The 36 DOFs of the joint angles are mapped to the remote machine. The interface of the wearable type has spatial measurement devices for both hands and head. The spatial positions of the two hands are mapped to the remote machine by inverse kinematics. The system can intuitively manipulate a wide range of objects from light and soft balls to heavy and hard parts, as shown in Fig. 11. However, it is difficult to manipulate fragile objects with little deformation without haptic feedback from the remote machine to the operator. We investigated three implementations of visual haptics where haptic information was superimposed on the point of contact with the object in the HMD image viewed by the operator. These are described below.

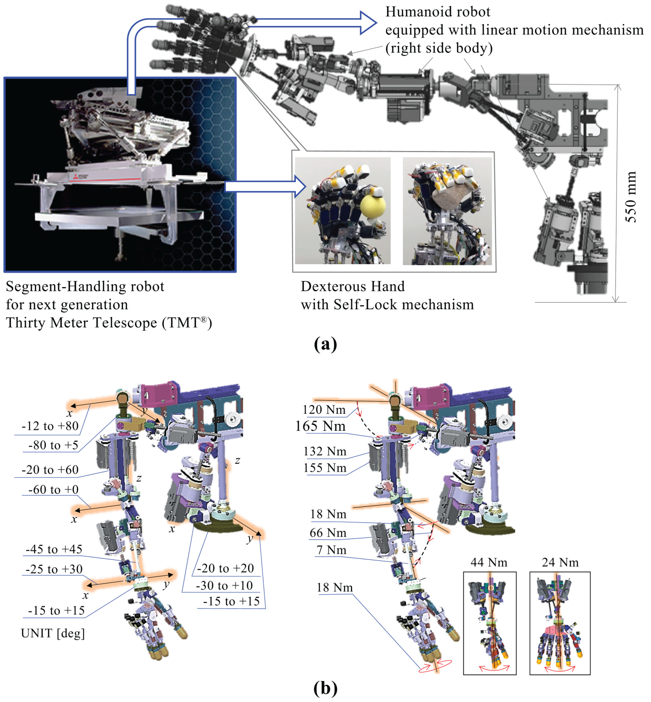


Fig. 9. Prototype of a humanoid remote machine: (a) mechanical properties and (b) specifications of the joint angles (left) and generated torques (right).

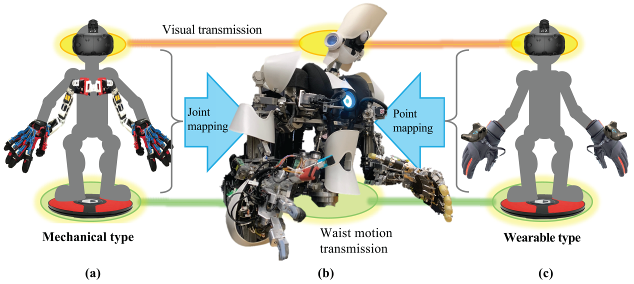
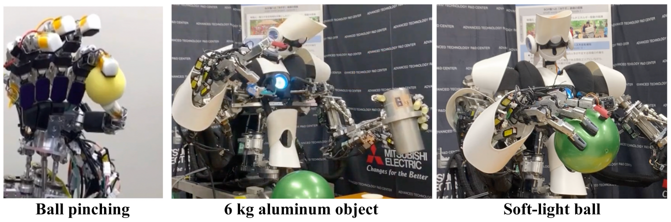


Fig. 10. Prototypes of the operation interface: (a) 36-DOF mechanical encoders excluding 3-DOFs for each of the head and waist. 36-DOF joint angles are mapped to the remote machine. (b) Prototype remote machine. (c) Spatial measurement devices for the hands and head. The spatial positions of the two hands are mapped to the remote machine by inverse kinematics.



Ball pinching **6 kg aluminum object** **Soft-light ball**

Fig. 11. Examples of grasping tasks.

A. Visual Haptics with LED

An LED was mounted on the fingertip and lit up according to the pressure. This visually indicates that pressure is being applied to the workpiece, and it improves the operability of the system. This method does not require any image processing and is the simplest way to achieve visual haptic feedback. However, it cannot be visualized when there is an obstructing object.

B. Visual Haptics Based on Machine Model

The spatial position of the fingertip was identified from the numerical model of the remote machine, camera and the real-time joint angle. Then, a haptic image was presented at the fingertip of the robot hand according to the value recorded by the pressure sensor. With this method, haptic information can be superimposed even in the presence of an obstructing object. On the other hand, superimposition errors can be caused by rattling and deflection of the machine, which can have a significant influence, particularly during contact with an object.

C. Visual Haptics Based on Camera Image

The spatial position of the fingertip was identified from a camera image, and a haptic image was presented at the fingertip of the machine hand according to the value of the pressure sensor. The position can be identified through several methods, such as feature point extraction, AR markers, or a combination of these methods. This method has the advantage of no superimposition error, but the accuracy and robustness of the identification need to be carefully examined.

D. Results

Fig. 12 shows the base verification of these implementations. While the model-based visual haptics had the advantage of being able to superimpose images even with obstructions, the superimposition error caused by rattling and deflection due to contact with the object significantly hindered operability. In contrast, the absence of superimposition errors with the LED-based and camera image-based visual haptics facilitated the transmission of haptic sensations. This made it possible for the robot to grasp raw eggs and potato chips with these implementations as shown in Figs. 12(a) and (c). For potato chips, although the superimposed image was only slightly visible on the fingertip because the grasping force was very small (several tens of grams), the grasping force could be controlled after several training sessions. The results showed that the camera image-based visual haptics was superior to the other two implementations because of the natural expression, precise identification, and potential extension to the proposed visual haptic feedback. We conducted repeated experiments of grasping and transporting a dummy egg. Seven failures occurred when the visual haptics was stopped, but no failure occurred with visual haptics. Other remote manipulation tasks that were successfully performed included soldering, pulling out Bayonet Neill–Concelman (BNC) cables, and grasping a business card. Correspondingly, the results verified the effectiveness of the proposed visual haptic feedback.

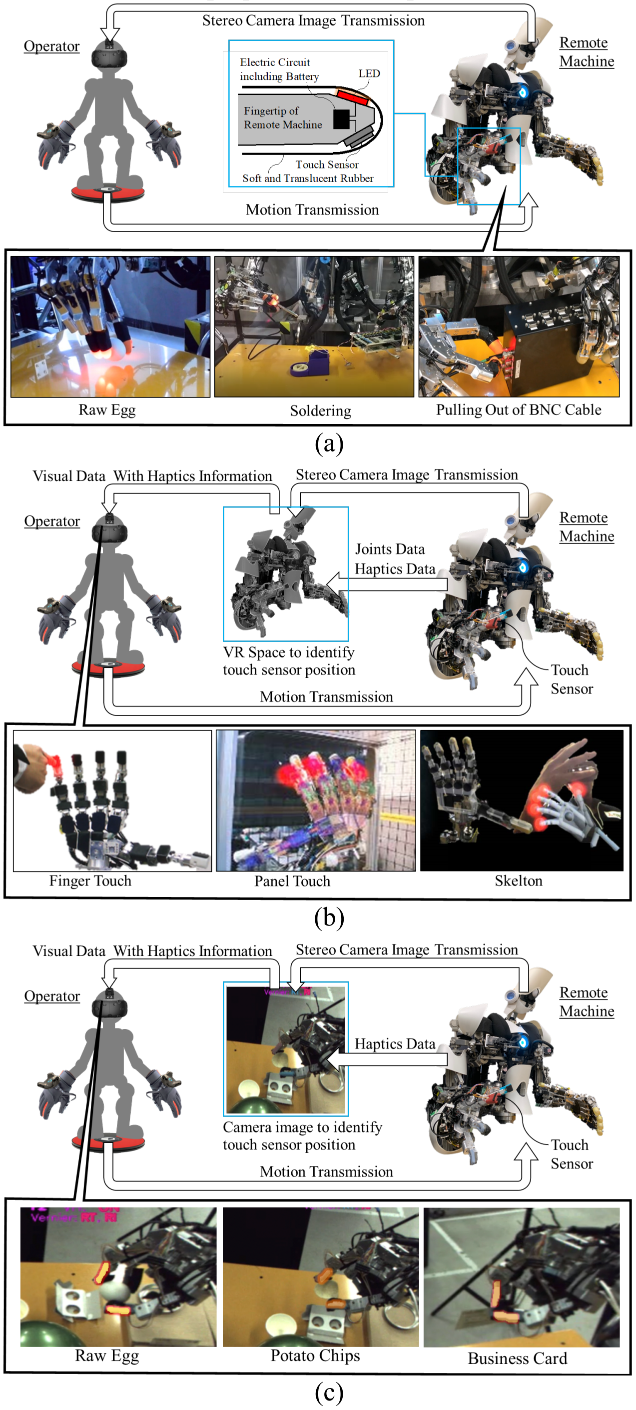


Fig. 12. Prototype implementation of visual haptics: (a) base verification with an LED mounted on the fingertip; (b) superimposition on the robot model; (c) dexterous manipulation with superimposed images based on color tracking.

V. DISCUSSION

Table I presents the subjective ratings of the three feedback modalities based on the post-measurement interviews. In session 1, 80% of the subjects felt that the vibration feedback modality was the best. In sessions 2 and 3, however, the number of subjects who felt like this significantly decreased to 30% and 20%, respectively. In contrast, the number of subjects who preferred the visual feedback modality increased with each session to reach 80% after session 3. When subjects were asked about this change in rating, they expected that the vibration feedback modality would be superior before the experiment. However, they felt discomfort during the actual manipulation because they had switch their focus between their own fingertips and the remote robot hand even though the distance between them and the machine was about 70 cm, as shown in Fig. 2(a). In contrast, with the visual feedback modality, they only needed to focus on the remote robot hand because the haptic information was presented there, and they did not need to switch focus. This may explain the effectiveness of the proposed visual haptic feedback at reducing the cognitive load.

In addition to determining which modality was more effective at presenting haptic information, we were also interested in determining whether the operator would feel more comfortable when feedback modalities were combined. We performed experiments combining the three feedback modalities for a few subjects. In the results, the grasping force slightly decreased, whereas the information flow in the brain increased. Consequently, the subjective evaluation was worse than that for any single feedback modality. Most subjects reported that the feedback from multiple modalities was confusing compared to that from a single modality. This suggests the difficulty of combining multiple feedback modalities for remote machine operation.

The relationship between the number of successes and the grasping force or information flow was interesting to analyze. Success was defined as grasping the object gently (<40 g). However, the threshold was too strict because almost all grasping forces were more than 40 g, as shown in Fig. 5. Although we used an object that did not break in the test, the number of successes would be increased if we used a fragile object.

In this study, we comprehensively evaluated various feedback modalities including their potential developments, by comparing and verifying basic methods of their presentation. However, the feedback modalities were not rigorously optimized. The feedback modalities can be further improved by adjusting the tone and frequency for sound, amplitude and frequency for vibration, and color, shading, and expression for light. A more rigorous analysis of the feedback modalities is left for future work.

TABLE I
SUBJECTIVE RATING OF BEST FEEDBACK MODALITY FOR REMOTE MANIPULATION

Feedback Modality	Session 1	Session 2	Session 3
Nothing	0%	0%	0%
Sound	10%	0%	0%
Vibration	80%	30%	20%
Light	10%	70%	80%

VI. CONCLUSION

Haptic feedback is an important element for remote machine manipulation. We previously proposed a method for visually superimposing haptic information on a contact point with an object and confirmed its effectiveness through EEG measurements in a VR environment [25]. To the best of our knowledge, there has been little in the literature on using EEG measurements as an objective and quantitative evaluation of methods for remote machine operability.

In this study, we comprehensively evaluated the operability of three feedback modalities in terms of the grasping force and cognitive load for an object-grasping task with an actual robot arm. The visual feedback modality was found to be most effective at reducing the grasping force by 24.1% without increasing the amount of information flow in the brain. A positive correlation was identified between the subjective assessment and the reduction of information flow in the brain, which indicates the usefulness of the EEG measurements. Second, we prototyped a remote machine for actual operation, and we investigated different implementations of the proposed visual haptic feedback. The results confirmed that visual haptics stabilized the grasping and carrying performance of fragile objects. Based on these results, the proposed visual haptic feedback is expected to contribute to the development of a highly operable remote machine without the need for a highly complex and expensive interface.

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