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Pseudo Force Display that Applies Pressure to the Forearms

Abstract

Conventional force display systems provide a force sensation by applying force to the operator's body via actuators such as electric motors. These systems can potentially harm the operator, especially when providing a large force sensation. This study shows that constrictive pressure on the distal part of the forearms provides a force sensation such as holding a heavy object or pushing a wall when the pressure changes in accordance with the hand motion. This force display provides a large force sensation of ~10 N without applying real force to the operator's hand, which makes the system intrinsically safe and suitable as a wearable force display system. Experimental results show that the discrimination thresholds are consistent with Weber's Law. It was demonstrated that an operator could sort virtual objects by weight using this system.

1 Introduction

Conventional force displays provide a force sensation by applying force to the operator's body via actuators such as a robot manipulator (Brooks, Young, Batter, & Kilpatrick, 1990; Kazerooni & Guo, 1993; Bergamasco et al., 1994), a motor-driven wire system (Ishii & Sato, 1994; Kawamura, Ida, Wada, & Wu, 1995), and pneumatic cylinders (Burdea, Zhuang, Roskos, Silver, & Langrana, 1992). For example, PHANToM (Massie & Salisbury, 1994), one of the most popular commercially available force displays, provides a force to an operator's hand through a handle attached to a robot manipulator. The magnitude of the force provided to the operator's hand depends on the power of the robot manipulator. Therefore, in designing a force display that uses a robot manipulator, it is essential to carefully consider safety requirements, especially when providing a large force. The same is necessary of other force displays that directly provide a force to an operator's hands via actuators.

To overcome this problem, some alternative methods have been proposed. One approach is to provide force in a passive manner. Colgate, Peshkin, and Wannasuphoprasit (1996) developed a force display that exerts a reaction force on a hand through a handle with a wheel that rotates against the direction of movement. Sakaguchi, Furusho, and Takesue (2001) developed a force display that provides a reaction force to a hand via the braking torque of a manipulator. Mitsuda, Kuge, Wakabayashi, and Kawamura (2002) developed a wearable force display with a pneumatic passive element that they called a particle mechanical constraint. The particle mechanical constraint is a soft plastic tube con-

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taining Styrofoam beads, and the shape of the tube can be freely transformed. Evacuating the air inside the tube fixed on the operator's body makes the tube rigid and restricts the operator's motion. These passive force display systems do not create any power by themselves and are therefore intrinsically safe. However, they are inherently limited in their functionality: because they provide only a reaction force, they do not provide any sensation when the operators do not move.

Another approach is to provide a force sensation through the use of an illusion. Amemiya, Ando, and Maeda (2008) developed a handheld force display in which mechanical oscillation provides the sensation of pulling or pushing because of the nonlinearity of human perception. This device can be used for mobile interfaces such as a navigation display; however, it cannot provide a force sensation when the operators interact with objects because they have to hold the device with their hands.

Minamizawa, Fukamachi, Kajimoto, Kawakami, and Tachi (2007) developed a force display that provides a sensation of holding an object under the force of gravity by deforming the finger pads. This device provides a force sensation to fingers when pinching an object. The above-described methods provide a force sensation using smaller mechanisms than those used in conventional force display systems; however, their applications are limited, and the forces displayed by them are small.

This study describes a novel force display that uses an illusion of force sensation that is generated by constrictive pressure on the forearms. The author found this illusion empirically, and the mechanism is still being investigated. This method provides a force sensation to operators without providing a real force. Therefore, it is intrinsically safe in a manner similar to passive force displays, although there exists a risk of injury due to constrictive pressure. The advantages of this method are as follows:

- It is intrinsically safe.
- It provides a large workspace because the system can be wearable.
- It is soft and lightweight. Only an air cuff is attached to the forearm.
- The device does not disturb arm motion.
- It provides a large force sensation of $\sim$10 N compared to the device weight.

First, this paper presents the system configuration of the force display. Then, it describes a discrimination threshold for the force sensation as determined through a psychophysics experiment. Next, the performance of the force display is examined through a task involving sorting virtual objects by weight. The amount of force sensation is examined by a task in which subjects compared the force sensation generated by the pressurized cuff with the actual force sensation produced by holding a real object. This paper also describes how a force display system that simultaneously applies pressure to both the forearms and the palms provides a more natural force sensation. Finally, the potential mechanisms of this illusion are discussed.

The original concept of this force display that applies constrictive pressure on the forearm and the experimental results have already been published in Japanese (Mitsuda, 2007). Furthermore, the concept and experimental results of simultaneously applying pressure to both the forearms and the palms have been briefly described in the proceedings of a domestic conference in Japanese (Mitsuda, 2008). This paper is a translated and revised version of these two papers that includes additional analyses and new considerations. The reprint of the original papers has been permitted by the relevant societies.

2 Experiment 1-1

2.1 System Configuration of a Force Display Applying Pressure to the Forearm

Figure 1 shows the configuration of a force display system that applies pressure to the forearm. A blood pressure cuff (width = 12 cm, mass = 120 g, HEM-762 Fuzzy, OMRON, Japan) is fixed on the distal part of the forearm of an operator, as shown in Figure 2. We empirically found that the distal part was a suitable fixation point for providing a force sensation. When the cuff was fixed on the proximal part of the forearm, which is the usual fixation point for blood pressure measurements, it did not provide any force sensation. The cuff is loosely

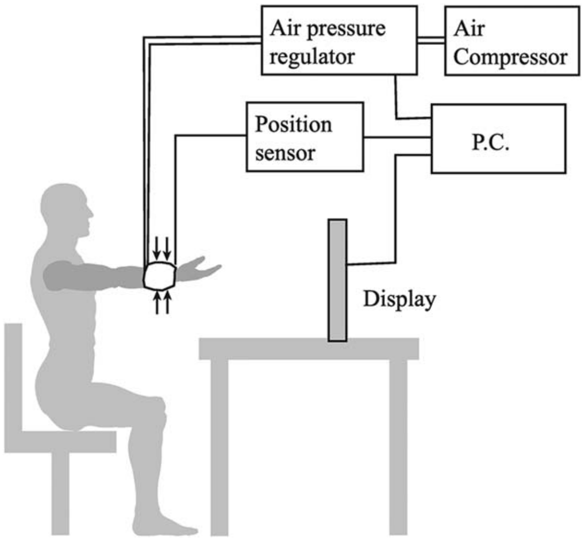

Figure 1. *System configuration of force display to the hand.*

Figure 2. *Blood pressure cuff used for force display.*

fixed to avoid putting any constrictive pressure on the forearm when no air pressure is provided through the cuff. The air pressure of the cuff is controlled by a computer through an electropneumatic regulator (EV-2500, CKD, Japan). The hand position is measured at 120 Hz by a FASTRAK computer-controlled electromagnetic sensor. The hand and a virtual environment are displayed on a computer screen in front of the operator. Figure 3 shows the step responses of the air pressure inside the cuff when it is increased from 0 kPa (atmospheric pressure) to 5 kPa (Figure 3[a]) and again decreased to 0 kPa (Figure 3[b]). The response for the decrease was slower than that for the increase because the inside air was released to the atmosphere without any pump; the response for the decrease can be improved by using a vacuum pump.

2.2 Discrimination Threshold Test

To characterize the sensation caused by the cuff pressure, a discrimination threshold was examined by using the descending method of limits (Gescheider, 1997), a classical psychophysical method, as follows. Subjects sat on a chair and put their dominant hand on a table in front of them. The pressure cuff was fixed on the distal part of the dominant forearm. The cuff pressure was initially set to a base pressure and maintained at this pressure for 3 s. It was then increased or decreased to a comparative pressure. Subjects were asked to identify which pressure was greater. When the subjects answered incorrectly, the cuff pressure was returned to atmospheric pressure and the trial was repeated with the same base pressure and a new comparative pressure that was increased or decreased by 0.1 kPa. When the subjects answered correctly, the trial was repeated with the same pressures. The discrimination threshold was determined when the subjects answered correctly twice in a row. Six base pressures (1.0 kPa, 2.0 kPa, 3.0 kPa, 4.0 kPa, 5.0 kPa, and 6.0 kPa) were examined for the lower discrimination threshold test and three base pressures (2.0 kPa, 4.0 kPa, and 6.0 kPa) were examined for the upper discrimination threshold test. The order of the base pressures was randomized. Ten male students, ranging in age from 21 to 25 years, participated in this experiment. Nine of the subjects were right-hand dominant.

2.3 Results

Figure 4 shows the results of the discrimination threshold test. The upper thresholds were proportional to the base pressure, which is consistent with Weber's Law (Fechner, 1966), that is, the ratio between the just noticeable difference in stimulus intensity and the reference stimulus intensity is a constant. The relationships

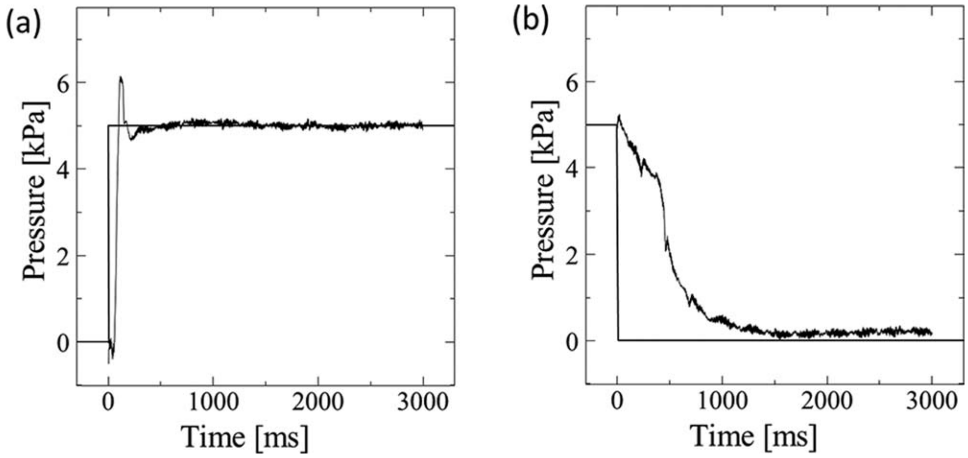

Figure 3. *Step responses of air pressure inside the cuff (a) when air pressure was increased from 0 kPa (atmospheric pressure) to 5 kPa, (b) when air pressure was decreased from 5 kPa to 0 kPa.*

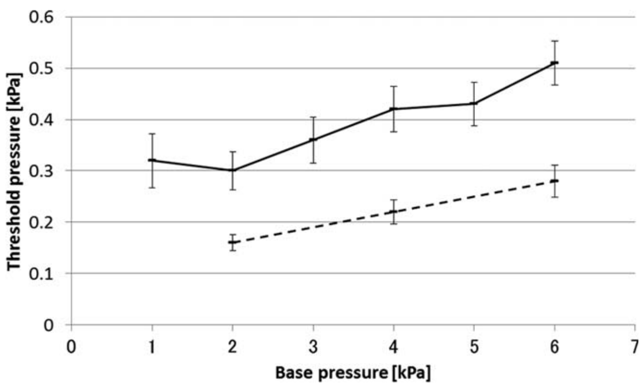

Figure 4. *Discrimination thresholds of a sense of constrictive force. Solid line indicates the upper threshold pressure and dotted line, the lower threshold pressure. Error bars show the standard error.*

between the discrimination thresholds and base pressures were approximated by the least-squares method as

$$D_u = 0.030p + 0.10$$
$$D_l = 0.049p + 0.21$$

where D_u, D_l, and p denote the upper discrimination threshold, lower discrimination threshold, and base pressure, respectively, and the units used are kPa.

3 Experiment 1-2

3.1 Method

The performance of the force display system was examined through a task involving sorting objects by weight. Figure 5 shows the virtual environment developed for this task. Virtual objects such as dice are placed on a virtual table. The operator's hand is displayed as a horizontal line. Operators can virtually hold up and move the virtual objects from side to side using a hand on the touch screen. When operators hold up an object, the system increases the cuff pressure according to the weight of the object and provides a force sensation. When the hand holding the virtual object is lowered below the table, the object remains on the table and the cuff pressure is decreased to atmospheric pressure. The inertia of the virtual objects was ignored, and the cuff

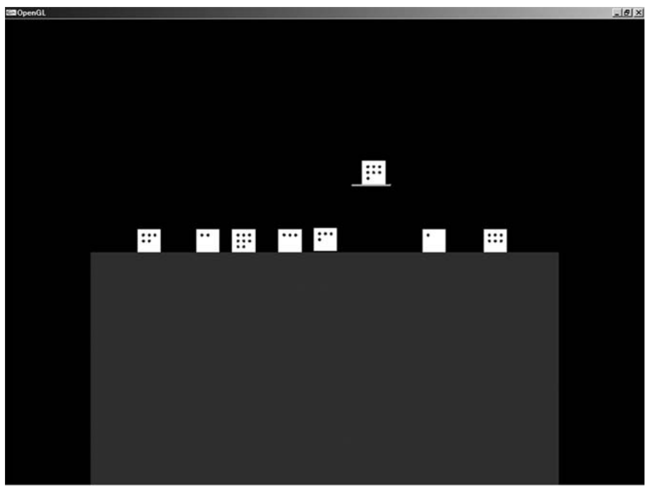

Figure 5. *Virtual environment for manipulating objects.*

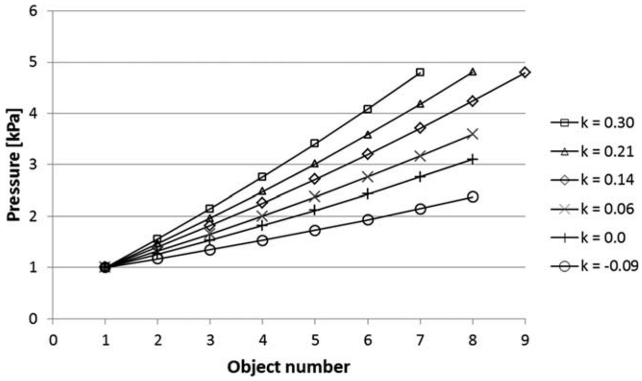

Figure 6. *Pressure configuration for a task involving sorting virtual objects.*

pressure when holding a virtual object was set to a constant value. The cuff pressure for the *i*th virtual object was set to

$$P_i = P_{i\text{-}1} + (0.049\ P_{i\text{-}1} + 0.21 + k)$$

where k is a parameter that is adjusted based on the difficulty of the task. P_1 was set to 1.0 kPa. When k is zero, $P_i - P_{i\text{-}1}$ is the lower discrimination threshold pressure described in the previous section. A larger k implies an easier task.

The 10 male students who participated in Experiment 1-1 also participated in this experiment. First, three conditions ($k = 0.30$, 0.21, and 0.14) were examined. The number of virtual objects was 7, 8, and 9 in the respective conditions. The maximum cuff pressure was 4.8 kPa in all conditions. Because all subjects sorted the virtual objects twice in each condition without any mistakes, more difficult conditions ($k = 0.06$, 0.0, and -0.09) were examined by seven of the 10 subjects. The number of objects was set to 8. The maximum cuff pressure in these conditions was 3.6, 3.1, and 2.4 kPa, respectively. The pressure configuration in each condition is shown in Figure 6. Subjects performed eight trials (two trials for each condition) in a randomized order.

3.2 Results

Table 1 presents the experimental results. In the table, the horizontal bars indicate that the subjects did not make any mistakes in the trial and the serial numbers indicate the sorted order results where the subject made mistakes. It shows that four subjects made more mistakes when k was set to -0.09 than in the other conditions. The numbers in parentheses in the table show the mean of the lower discrimination threshold pressure for each subject. Subjects who had a small discrimination threshold pressure tended to not make mistakes when k was set to 0.06 and 0.0. Table 2 presents the results of each condition as a confusion matrix, where a cell number in the *i*th row and *j*th column shows the number of trials in which subjects identified the *i*th virtual object as the *j*th virtual object. Two-way analysis of variance shows that the number of missed trials differed with the parameter k ($p = .03$) but not with the order of virtual objects ($p = .59$).

4 Experiment 1-3

4.1 Method

The amount of force sensation was examined by a task in which subjects compared the force sensation generated by the pressure cuff with the actual force sensation produced by holding a real object. The pressure cuff was fixed on the dominant forearm, and a box containing gravel (0.7 g) was hung on the nondominant forearm by a 12-cm-long fabric ring. The subjects closed their eyes while sitting on a chair and extended their arms, as shown in Figure 7. Subjects were asked to compare the sensations of weight in both arms and to select one of the following responses: (1) add gravel, (2) decrease gravel, or (3) stop (i.e., they felt that both arms were equally heavy). The experimenter adjusted the amount of gravel in the box according to the subjects' responses and measured the weight when the subjects felt that both arms were equally heavy. Seven among the 10 male students who participated in Experiments 1-1 and 1-2 participated in this experiment. All participants were right-hand dominant. Three cuff pressures (2.0 kPa, 4.0 kPa, and 6.0 kPa) were examined three times each. Each subject performed nine trials in a randomized order.

4.2 Results

Figure 8 shows the experimental results. All subjects perceived a greater sensation of weight with a larger

Table 1. *Result of a Task Involving Sorting Virtual Objects by Weight*

	$k = 0.06$		$k = 0.0$		$k = -0.09$	
	1st trial	2nd trial	1st trial	2nd trial	1st trial	2nd trial
sub.A (0.3 kPa)	—	—	—	—	—	—
sub.B (0.4 kPa)	—	12345687	—	—	—	—
sub.C (0.5 kPa)	21435678	—	—	—	12346578	13245678
sub.D (0.5 kPa)	12347568	—	—	31245678	12435678	12346587
sub.E (0.2 kPa)	—	—	—	—	—	12346758
sub.F (0.3 kPa)	—	—	—	—	—	12346578
sub.G (0.4 kPa)	—	—	—	—	—	—

cuff pressure, although the amount of perceived weight differed substantially among the subjects. The perceived weight was approximated by the least-squares method as

$$w = 1.41p + 1.27$$

where w and p denote the perceived weight in Newtons and cuff pressure in units of kPa, respectively. The intercept (perceived weight when cuff pressure is zero) was similar to the weight of the cuff (1.18 N).

5 Experiment 2

5.1 Method

The above-described force display provides a force sensation to the forearms but not to the palms. To provide a more natural sensation of holding an object, a force display that also provides a force sensation to the palms was developed by simultaneously applying pressure to the palms and forearms. An operator wears gloves that apply pressure to the palms through air-inflated balloons. Figure 9 shows the structure of the glove. An outer leather glove contains an inner rubber glove. The inner glove is inflated by air and applies pressure to the hand between the inner glove and the outer glove. The center of the inner glove has a rectangular hole (width = 2 cm, length = 3 cm) that flattens its shape; without this hole, the glove would become spherical and produce the sensation of a ball touching the palms. The pressure cuffs were fixed on the distal part of the forearms as in the previous force display. The hand position was measured at 120 Hz by a computer-controlled FASTRAK electromagnetic sensor and a screen in front of the operator displayed the virtual environment and the hands. A virtual cube (40 cm on each side) was displayed at a height of 110 cm with virtual hands. When operators push the virtual cube by hand, the cube is compressed in the direction of the hand movement, as shown in Figure 10, and simultaneously, the cuff pressure and glove pressure are increased in proportion to the compressed displacement. The cuff pressure and glove pressure were adjusted individually because the sensitivity against the pressure differed substantially between subjects. Subjects practiced pushing a surface of the virtual cube, and the pressures were adjusted to avoid causing the operators any discomfort. Eight male subjects, from 21 to 25 years of age, who did not participate in Experiments 1-1, 1-2, or 1-3 participated in this experiment. The means ± *SD* of the cuff pressure and glove pressure were 1.2 ± 0.5 kPa/cm and 0.7 ± 0.3 kPa/cm, respectively.

The subjects were asked to evaluate the force display through a questionnaire. First, the subjects pushed and deformed a virtual cube on the screen in six directions: forward, backward, right, left, down, and up. The subjects experienced the pushing task in two conditions. In the first condition, the system applied pressure to only the palms. In the second condition, the system simultaneously applied pressure to both the palms and the forearms. After each pushing task, the subjects assessed the pushing sensation on a three-point rating scale: (1) felt a pushing sensation, (2) felt a sensation similar to that of pushing, and (3) felt no pushing sensation. Finally, the subjects assessed the overall sensation of pushing in the

Table 2. *Confusion Matrix of Result of Sorting Objects*

	Judgment							
Stimulus	1	2	3	4	5	6	7	8
***k* = 0.06**								
1	13	1						
2	1	13						
3			13	1				
4			1	13				
5					13		1	
6					1	13		
7						1	13	
8								14
***k* = 0.0**								
1	14							
2		13	1					
3		1	13					
4				14				
5					14			
6						14		
7							13	1
8							1	13
***k* = −0.09**								
1	14							
2		13	1					
3		1	12	1				
4			1	13				
5					10	4	1	
6					3	13	1	
7					1		12	1
8							1	13

two conditions as follows: (1) felt a better pushing sensation when pressure was applied only to the palms, (2) felt a better pushing sensation when pressure was simultaneously applied to both the palms and the forearms, (3) felt the same pushing sensation when pressure was applied only to the palms in comparison to when pressure was simultaneously applied to both the palms and the forearms, and (4) did not feel a pushing sensation in either condition.

5.2 Results

Figures 11 and 12 show the questionnaire results for the pushing sensation in each condition. When pressure was applied only to the palms, some of the participants did not experience a pushing sensation, especially during the backward or the forward movements. In contrast, when pressure was simultaneously applied to both the palms and the forearms, seven participants experienced the sensation of pushing a cube in all of the direc-

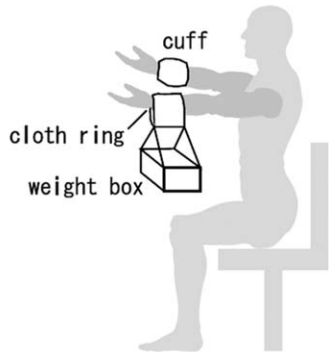

Figure 7. *Weight perception test.*

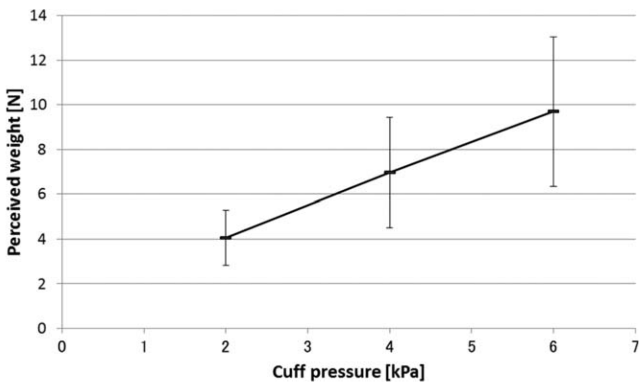

Figure 8. *Weight perceived by constrictive pressure on a forearm. Error bars show the standard deviation.*

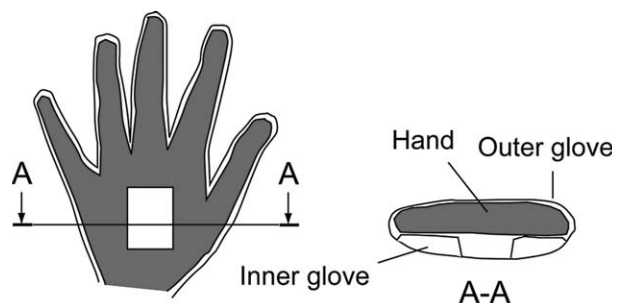

Figure 9. *Structure of glove for placing pressure on a palm.*

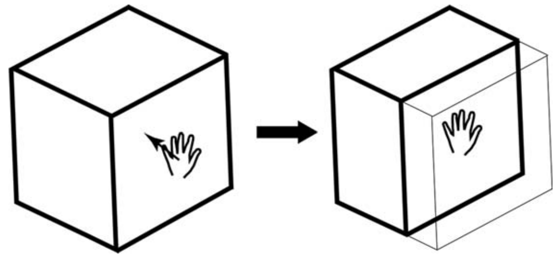

Figure 10. *Deformation of a virtual cube.*

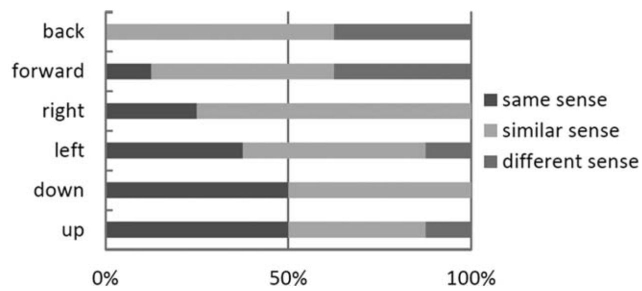

Figure 11. *Questionnaire result when palms were pressured ("same sense," "similar sense," and "different sense" are the participants' response about the sensation they felt compared to a real force sensation).*

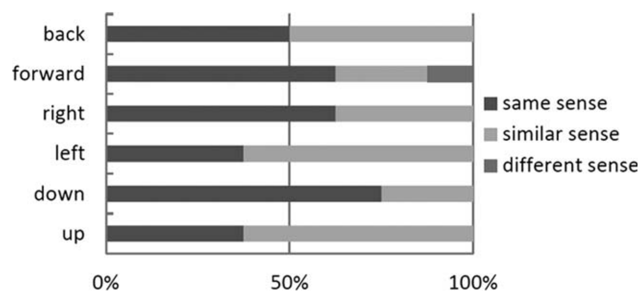

Figure 12. *Questionnaire result when palms and forearms were pressured simultaneously ("same sense," "similar sense," and "different sense" are the participants' response about the sensation they felt compared to a real force sensation).*

tions. Figure 13 shows the questionnaire results for the case of comparing the pushing sensation between the two conditions. In the backward, forward, and rightward movements, seven subjects felt a stronger sensation of movement when pressure was simultaneously applied to both the palms and the forearms than when pressure was applied only to the palms; however, three subjects felt better when pressure was applied only to the palms in the leftward and downward movements. Subjects who provided better assessments when pressure was simultaneously applied to both the palms and the forearms reported that they felt as if they were pushing a heavier object in this case. In contrast, one subject reported that he felt a strange sensation in this case. For the upward

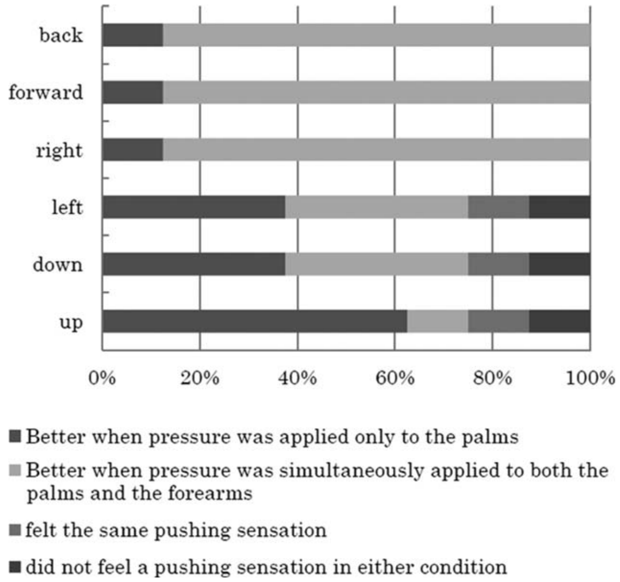

Figure 13. *Questionnaire result of comparing the two conditions.*

movement, five subjects felt better when pressure was applied only to the palm.

The force display system was also assessed for the task of lifting a virtual cube using both hands. Pressure was applied to both palms when both hands touched the virtual cube, and pressure was applied to both forearms when both hands moved upward. The pressures applied to the palms and forearms were set individually based on the pressure determined in the previous experiment, that is, the pressure when the displacement was 1 cm in the previous experiment. Subjects were asked to hold the virtual cube by both hands, lift it, and move it around. As in the previous experiment, subjects compared the sensation of lifting the object between when pressure was simultaneously applied to both the palms and the forearms and when pressure was applied only to the palms. Figure 14 shows the results of the questionnaire. All of the subjects experienced a sensation of lifting or similar to that of lifting an object when pressure was simultaneously applied to both the palms and the forearms. In contrast, three subjects did not experience a sensation of lifting an object when pressure was applied only to the palms; instead, they reported a sensation of holding an object by both hands but not a sensation of lifting up the object.

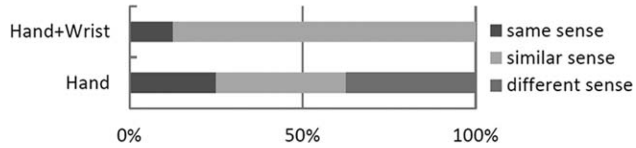

Figure 14. *Questionnaire result about a sense of lifting an object.*

6 Discussion

The results of Experiment 1-2 show that the constrictive pressure of 6 kPa on the forearm provides a weight sensation of ~10 N. The maximum force provided by the constrictive pressure is limited by the maximum pressure that does not cause the operators any discomfort. However, the amount of force is relatively large considering the weight of the device, compared to existing force displays. As described in the introduction, conventional force displays that provide a force sensation via actuators require a large device. A force display that uses illusions produced by mechanical oscillations (Amemiya et al., 2008) or the deformation of finger pads (Minamizawa et al., 2007) also requires a heavy device on the body to provide a large force sensation. In contrast, this method requires only an air cuff on the forearm, although a source of air pressure and a controller are also required.

One limitation of this force display is the lack of design guidelines, because the generated force sensation has been examined only subjectively and the mechanism of the illusion has yet to be clarified. In the previous experiment, the pressure applied to the palms and the cuffs was adjusted individually. A suitable ratio of both pressures was critical to provide a natural force sensation. When operators push a real wall by hand, the amount of force can be perceived by a sensation on the palm or by the muscle activities of the arm. The force of pushing (i.e., pressure on the palm) is determined by the muscle activities. Therefore, the pressure on the palm and the muscle activities usually vary in a coordinated manner. This could explain why the ratio of both pressures was critical to provide a natural force sensation. Indeed, when a large pressure was applied to the palm and a small pressure was applied to the forearm simultaneously, or vice versa, the operator experienced a strange sensation that differed from the usual. Examining the optimal ratio of the pressures on the palm and on the forearm is an important issue for further study to understand the mechanism of the illusion.

In the experiment described in Section 2.2 in which the sensation of weight between two arms was compared, some subjects commented that they experienced different sensations between the arm with a pressurized cuff and the other arm with a real weight. Because the dominant arm was only compressed and no downward force was applied to the arm, the sensation of weight is just an illusion. Therefore, subjects could compare the constrictive pressure on the forearms and not the sensations of weight in the experiment. In contrast, the subjects did not comment on any strange sensations during the experiment involving the sorting of virtual objects by weight. It is possible that a concurrent change in the constrictive force with the visual information or with the arm motion is essential to provide a force sensation. It is known that visual information affects the sensation of weight (Nicolas, Ross, & Murray, 2012). The sensation of pressure, which is not produced in daily activities, might be related to the force sensation produced by visual information. Another possible mechanism of this illusion is the change in muscle activities by the constrictive force. In the experiment described in Section 2.4, in which the sensation of weight was compared, some subjects moved their hands up and down slightly. The sensation of weight is produced not only by afferent signals but also by efferent signals (Luu, Day, Cole, & Fitzpatrick, 2011). The inertial force was ignored and the cuff pressure was kept constant in this experiment. However, muscle activities for moving the hands might change with the constrictive force. It has also been reported that muscle stiffness affects the sensation of weight (Koike, Kim, & Duk, 2006). The change in muscle stiffness by the constrictive force is another possible factor that produces the illusion. Occlusion of blood flow might also affect the weight sensation. It has been reported that the occlusion of blood flow significantly increases the integrated electromyogram (Takarada et al., 2000) and reduces dynamic muscular endurance (Wernbom, Augustsson, & Thomeé, 2006). Constrictive pressure on the forearm might change the blood flow, and induced muscle fatigue might affect the muscle activities. However, the constrictive pressure on the proximal part of the forearm or on the upper arm, which occludes blood flow, did not produce a weight sensation. The mechanism of the weight sensation produced by constrictive pressure on the forearm remains unclear, and therefore, further studies are required to clarify the mechanism.

7 Conclusion and Future Work

This paper presented a novel method for providing a force sensation by applying pressure to the distal part of the forearms. The questionnaires showed that the pressure applied to the forearms, which is controlled in accordance with the arm motion and visual information, can create a sensation of weight when pushing an elastic wall.

With the rapid advance of haptic displays (El Saddik, Orozco, Eid, & Cha, 2011; Mihelj & Podobnik, 2013), methods of evaluation have recently attracted attention (Samur, 2012). Not only the physical attributes but also the psychological attributes are recognized as important factors when evaluating the performance of haptic displays. This study evaluated the proposed system by discrimination threshold tests, a measure of perceived weight, and questionnaires. Other attributes such as the minimum or maximum force, influence of the arm posture, and hysteresis characteristics are expected subjects of evaluation in future studies.

In addition, it is important to clarify the mechanism of the illusion. The pressure on the forearms might influence the muscle or the tendon directly, or the reduced amount of blood in the forearms might influence the perception of the muscles or the tendons. Electromyographic analysis is expected to be an important aspect of future studies.

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References

Amemiya, T., Ando, H., & Maeda, T. (2008). Lead-me interface for a pulling sensation from hand-held devices. *ACM Transactions on Applied Perception, 5*(3), Article 15.

Bergamasco, M., Allota, B., Bosio, L., Ferretti, L., Parrini, G., Prisco, G. M., Salsedo, F., & Sartini, G. (1994). An arm exoskeleton system for teleoperation and virtual environments applications. *Proceedings of the 1994 IEEE International Conference on Robotics and Automation,* 1449–1454.

Brooks, F. P., Young, M. O., Batter, J. J., & Kilpatrick, P. J. (1990). Project GROPE—Haptic displays for scientific visualization. *Computer Graphics, 24*(4), 177–185.

Burdea, G., Zhuang, J., Roskos, E., Silver, D., & Langrana, N. (1992). A portable dextrous master with force feedback. *Presence: Teleoperators and Virtual Environments, 1*(1), 18–28.

Colgate, J. E., Peshkin, M. A., & Wannasuphoprasit, W. (1996). Nonholonomic haptic display. *Proceedings of the IEEE International Conference on Robotics and Automation,* 539–544.

El Saddik, A., Orozco, M., Eid, M., & Cha, J. (2011). *Haptics technologies: Bringing touch to multimedia*. Berlin: Springer-Verlag.

Fechner, G. T. (1966). *Elements of psychophysics* (H. E. Adler, Trans.; D. H. Howes, & E. G. Boring, Eds.). New York: Holt, Rinehart and Winston.

Gescheider, G. A. (1997). The classical psychophysical methods. In *Psychophysics: The fundamentals.* (Chapter 3) Mahwah, NJ: Lawrence Erlbaum Associates.

Ishii, M., & Sato, M. (1994). A 3D spatial interface device using tensed strings. *Presence: Teleoperators and Virtual Environments, 3*(1), 81–86.

Kawamura, S., Ida, M., Wada, T., & Wu, J. L. (1995). Development of a virtual sports machine using a wire drive system—A trial of virtual tennis. *Proceedings of the 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems,* 111–116.

Kazerooni, H., & Guo, J. (1993). Human extenders. *Journal of Dynamic Systems, Measurement, and Control, 115*(2B), 281–290.

Koike, Y., Kim, J., & Duk, S. (2006). Role of stiffness in weight perception. *Japanese Psychological Research, 48*(3), 174–187.

Luu, B. L., Day, B. L., Cole, J. D., & Fitzpatrick, R. C. (2011). The fusimotor and reafferent origin of the sense of force and weight. *Journal of Physiology, 589*(13), 3135–3147.

Massie, T. H., & Salisbury, J. K. (1994). The PHANToM haptic interface: A device for probing virtual objects. *Proceedings of the ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 55-1,* 295–300.

Mihelj, M., & Podobnik, J. (2013). *Haptics for virtual reality and teleoperation*. Berlin: Springer-Verlag.

Minamizawa, K., Fukamachi, S., Kajimoto, H., Kawakami, N., & Tachi, S. (2007). Gravity grabber: Wearable haptic display to present virtual mass sensation. *Proceedings of ACM SIGGRAPH 2007, Emerging Technologies,* Article 8.

Mitsuda, T. (2007). Pseudo force display by the use of constrictive pressure on a wrist. *Transactions of the Virtual Reality Society of Japan, 12*(4), 577–583 (in Japanese).

Mitsuda, T. (2008). Pseudo force display by placing pressure on a wrist and a palm. *Proceedings of SI 2008, Society of Instrument and Control Engineers, 3B3-1*, 979–980 (in Japanese).

Mitsuda, T., Kuge, S., Wakabayashi, M., & Kawamura, S. (2002). Wearable force display using a particle mechanical constraint. *Presence: Teleoperators and Virtual Environments, 11*(6), 569–577.

Nicolas, S., Ross, H. E., & Murray, D. J. (2012). Charpentier's papers of 1886 and 1891 on weight perception and the size-weight illusion. *Perceptual & Motor Skills, 115*(1), 120–141.

Sakaguchi, M., Furusho, J., & Takesue, N. (2001). Passive force display using ER brakes and its control experiments. *Proceedings of the IEEE Virtual Reality Conference,* 7–12.

Samur, E. (2012). *Performance metrics for haptic interfaces.* Berlin: Springer-Verlag.

Takarada, Y., Takazawa, H., Sato, Y., Takebayashi, S., Tanaka, Y., & Ishii, N. (2000). Effects of resistance exercise combined with moderate vascular occlusion on muscular function in humans. *Journal of Applied Physiology, 88*(6), 2097–2106.

Wernbom, M., Augustsson, J., & Thomeé, R. (2006). Effects of vascular occlusion on muscular endurance in dynamic knee extension exercise at different submaximal loads. *Journal of Strength & Conditioning Research, 20*(2), 372–377.