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Analysis of Human Weight Perception for Sudden Weight Changes during Lifting Task Using a Force Display Device

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Abstract—**The main purpose of this study is to apply the mechanism of human weight perception to multimedia applications. When a start and the goal points are given in the human motion, the velocity profile has an unimodal profile including the acceleration and deceleration zones. In such case, it is widely said that the motion control becomes more accurate in the deceleration zone for the final approach. Hence, it is assumed that the sensing ability also improves. This study challenges to confirm the hypothesis with weight stimuli generated by a force display device. As a preliminary experiment, this study confirms that our device enables the evaluation of human perception by tracing Weber's experiment in virtual reality; the obtained difference threshold (DL: Differenz Limen) almost agrees with the previous results. The difference threshold is a very important factor, which means perceptual threshold for weight changes. We further attempt to clarify the mechanism of the human weight perception for sudden weight changes during the lifting process. Based on individual lifting profiles, this study suddenly changes the load force in the two zones, and examines the difference thresholds of each subject. The results demonstrate that the human weight perception tends to become more sensitive in the deceleration zone during the lifting process. These results also imply the effectiveness of force display devices for physical experiments.**

I. INTRODUCTION

RECENTLY, there has been a rapid advancement in multimedia services including audio/visual display technologies with the remarkable proliferation of computers and information technology. The applications of cellular phones, in particular, have been rapidly increasing in this information age; it can be said that leading-edge technologies are integrated in this small box. In addition to these technologies, the applications of force display technology are expected as a next generation service. If force sensations were easily communicated between users at remote locations, they would obtain and share three-dimensional services with the sense of weight, touch, and deformation in the physical world. Thus, the force information has a potential to expand the application field of multimedia services. However, it is very difficult to present force sensations to match with the human perceptual mechanism because force sensations are very qualitative and are communicated through the exclusive interface in such services. Hence, it cannot be completely guaranteed without a subjective evaluation whether human beings can receive force sensations that are the same as those in the real world even if the displayed force is numerically correct. To realize multimedia applications with a force display, it is essential to appreciate and understand the mechanism of force sensations when using the force display device or the haptic interface in practice. Further, it is desired that the force display applications should be appropriately designed based on the abovementioned mechanism.

With regard to human force sensations, various studies in psychology and neuroscience have been conducted. Weber has discovered that the minimum change in the weight stimulus—the difference of which is noticeable by human beings—is proportional to the magnitude of the standard stimulus (Weber's law) [1]. McCloskey has mentioned that the weight perception is disturbed when the muscles of the arm is excited by providing an oscillation stimulus or by blocking the myoneural junction with drugs [2]. Recently, Turvey has verified that the inertia tensor associate with the perception of the length or the direction of an object when it is being swung [3]. Flanagan and Beltznar have attempted to clarify the weight perceptual mechanism through the size-weight illusion (Charpentier effect) [4] [5]. Most of these studies consider the force/weight sensations in the static force change. However, in our daily life, we often encounter dynamic and sudden force changes rather than static force changes. In fact, dynamic force changes significantly affect human perception. Therefore, multimedia applications with a force display must consider the mechanism of force sensations for a sudden force change during a task. With respect to a dynamic force change, Uno et al. have attempted to clarify the brain model through a reaching task in the two-dimensional plane with a change in the force field by using a mechanical spring [6]. Our previous study also discusses human weight perception for a sudden weight change in the supported weight generated by the force display device, which is under the static motion [7]. Expanding our previous study, this study attempted to evaluate the weight perception for sudden weight changes during a dynamic task,

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in particular, lifting motion of an object. We investigated the difference threshold in the weight perception by providing sudden weight changes in both the acceleration and deceleration zones in the lifting process by using a force display device. Situations in which the given weight/force stimulus dynamically changes arise often in our daily life. However, it is very difficult to examine the force sensation in such a situation because it is nearly impossible to provide a dynamic changeable stimulus to the subject on a regular basis in the real world. Hence, only virtual reality experiments with the force display device would help achieve a breakthrough in these attempts.

The fundamental purpose of this study is to establish the weight perceptual model in our brain from the relationships between the given stimuli (input) and the human responses (output). Further, this study examines the mechanism related to weight perception with the aim of its applications in multimedia services with the force display. We believe that the force display device provides more real force sensations by taking advantage of perceptual mechanisms; this may be achieved by deluding the users with the mechanism even if the force information provided is incorrect. The attempts of this study would contribute to the realization of unique applications with the force display in multimedia services.

II. EXPERIMENTAL SYSTEM

A. Hardware System

This study employed a very simple force display device with 1'DOF; it is believed that precise perception is disturbed by the complicated mechanical structure. Fig. 1 shows a schematic diagram of the experimental system. As shown in Fig. 1, our force display device is driven by an actuator (model: Maxon RE-25) which comprises a gearbox and an optical encoder. A three-directional force sensor is provided at the tip of the force display device. The capacity of the force sensor is 10 N in each direction. In this experiment, the subjects pinch and lift the tip of the device with their dominant thumb and index finger. Hence, the attitude of the hand is forced to change due to the lifting height, as shown in Fig. 2 (a); this situation is unnatural and undesired from the point of view of virtual reality. To avoid this situation, we attached the handgrip shown in Fig. 3 on the top of the force sensor. The subjects can then maintain their hand attitude owing to the handgrip as shown in Fig. 2 (b). Further, a grip force sensor can be attached at the handgrip. Both the force and grip force sensors are of the strain gauge type; the data are transmitted to a computer via each exclusive amplifier.

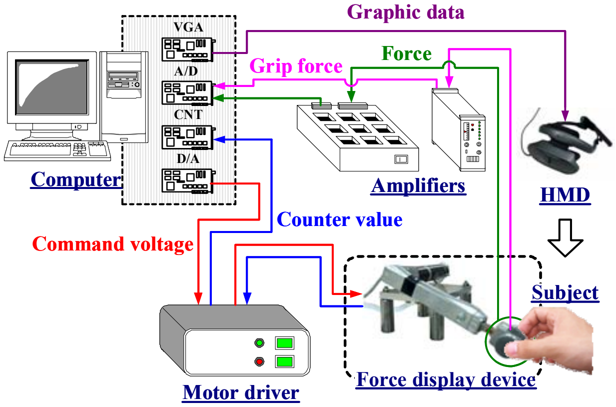
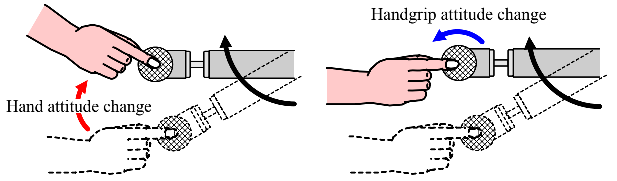


Fig. 1. Schematic diagram of the experimental system.



(a) Without free rotation handgrip (b) With free rotation handgrip

Fig. 2. Difference in lifting manners due to device attitude.

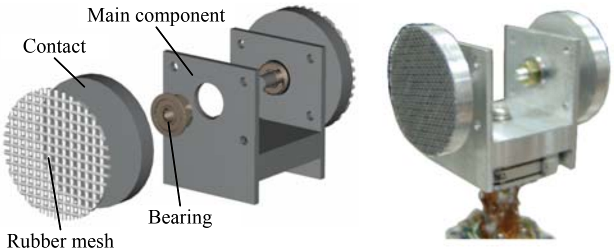


Fig. 3. Architecture of the handgrip attached at the force display device.

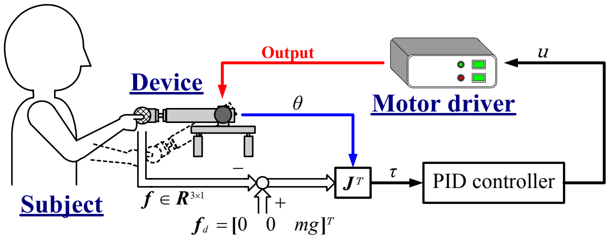


Fig. 4. Control system of the force display device with force servomechanism.

B. Software System

In this study, exclusive GUI applications were developed for conducting the experiments in chapters III and IV. All experimental conditions can be changed on the basis of a few key hits. The operator can numerically observe the experimental conditions and status of the subjects, such as the lifting force; in this paper, the operator refers to the person who conducts the experiment. On the other hand, the subjects lifted the force display device while viewing the three-dimensional graphics displayed on an HMD (model: *i*-visor DH4400-VP). The object displayed on the HMD moves simultaneously with the force display device manipulated by the subjects. Thus, the visual cue offered by the three-directional graphics and the interception of exterior visual information by the HMD help to improve virtual reality when the object is lifted. In this study, the force display is realized by a very simple force servomechanism; the corresponding schematic block diagram is shown in Fig. 4. In such a physical experiment, the stability of the control system significantly affects human perception. Hence, this study

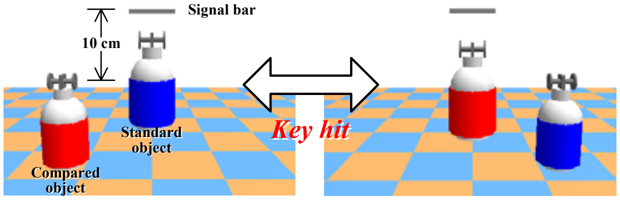


Fig. 5. 3D graphics displayed during Weber's experiment.

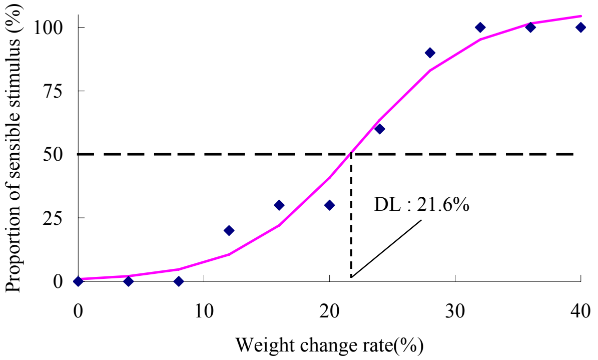


Fig. 6. Representative result of Weber's experiment in virtual reality.

employed a very simple control system in order to, as far as possible, avoid an unstable phenomenon. The sampling time of the control system is 1 ms. The computer processes the robot control, measurement of human responses, and drawing of the graphics on the HMD within the sampling rate.

III. PRELIMINARY EXPERIMENT

A. *Weber's Experiment*

This study reexamined Weber's experiment in virtual reality to verify whether our force display device enables a physical experiment. In the previous study, Weber investigated the magnitude of the stimulus that causes just noticeable difference (jnd) for various sensations, which is the difference threshold [1]. In other words, the difference threshold means the minimum stimulus for which human beings can perceive the difference between given two stimuli. In this study, we instructed six subjects who had no preliminary information to lift the force display device on viewing the three-dimensional graphics shown in Fig. 5 instead of lifting real weights. Mobile virtual objects can be selected and displayed at the center of the HMD monitor by a key hit; only the selected object moves simultaneously with the manipulation of the device. The subjects pinched the device with their dominant thumb and index finger and lifted it until the color of the signal bar displayed above the selected object changed to green. Moreover, in the beginning, the subjects regularly lifted the standard object on the right. After lifting a pair, the subjects judged whether they could perceive the difference between given two weights; they answered only when they sensed an obvious difference. In this experiment, we changed the weight of the compared object from 0 to 40% in steps of 4% of standard 300 g weight; each stimulus was randomly presented 10 times. The typical result of a subject is shown in Fig. 6. This study defined the difference threshold as the stimulus at which the proportion of sensible stimulus is 50%. The horizontal and vertical axes are the weight change rate and proportion of sensible stimulus, respectively. This result shows that the difference threshold in the weight perception is about 20%, which is almost the same as that obtained in previous works [8]. This implies that our force display device enables a physical experiment.

B. *Lifting Profile*

To divide the lifting process into the acceleration and deceleration zones, this study investigated the lifting profile of each subject. We instructed the subjects to lift a 300 g object 10 times until the color of the signal bar changes; the signal bar enables the unification of the movement range of the subjects and formulation of a preliminary plan for the trajectory from a start point to the goal point in their brains. During the experiment, we recorded the responses of the subjects, e.g., the lifting velocity. The typical result is shown in Fig. 7. Fig. 7 shows the relationships between the lifting velocity and force; the blue and red lines indicate the lifting velocity and force, respectively. With respect to the lifting velocity, it should be noted that a short-term unimodal profile including the acceleration and deceleration zones is present in the early stage of the lift; other subjects also respond to this velocity profile at a high frequency. Such a phenomenon does not occur for a free task without any constraints such as the reaching task. In fact, the velocity profile shown in Fig. 8 was observed when the device was lifted without the load force. Fig. 8 indicates the result obtained by the same subject. In general, human beings form a preliminary trajectory from a start point to the goal point in the brain by using a visual cue before transmitting the motor commands to the limbs. It is assumed that the short-term unimodal profile was caused due to the sudden lifting force that was required on account of an incorrect estimation of the weight of the object, i.e., the overestimation produces the error between the estimated and the actual trajectories. In other words, we assumed that this type of a short-term profile in the early stage appears as a result of the effort taken to rectify the swerved trajectory to the original trajectory estimated in the brain. This conjecture

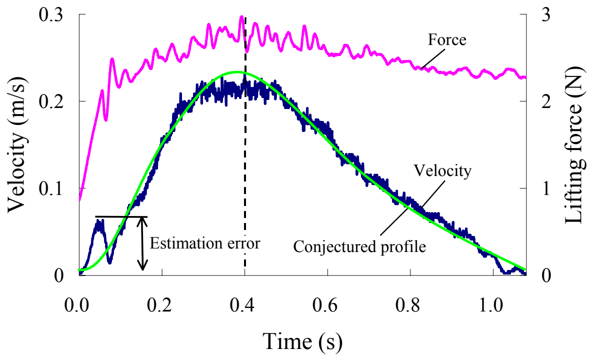


Fig. 7. Relationship between the lifting velocity and force.

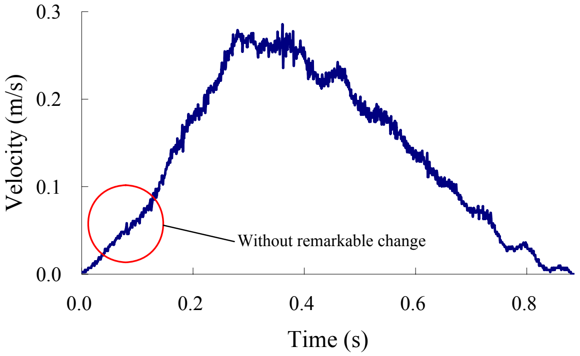


Fig. 8. Lifting velocity profile in the free lift without load force.

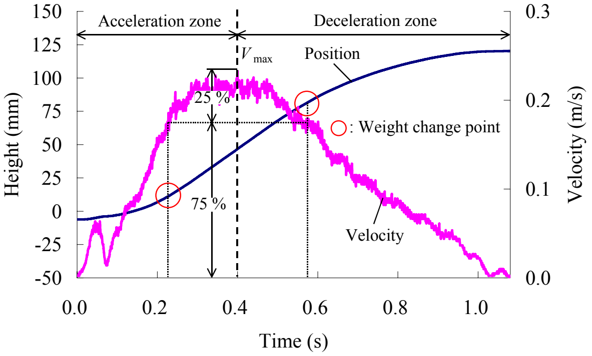


Fig. 9. Division of the acceleration and deceleration zones.

implies that weight estimation is included in the preliminary trajectory planning and has an effect on the actual motor command; repetitious lifts may possibly improve the profile. This phenomenon is not the main subject in this study; however, it is a very noteworthy human response. Hence, we wish to examine it in a future study. Nevertheless, if the short-term unimodal profile in the early stage is ignored, it is confirmed that the lifting velocity appears with a unimodal profile, which almost agrees with the free task profile.

Fig. 9 indicates the relationships between the lifting height and velocity. In this study, the lifting process was divided into the acceleration and deceleration zones by the peak in the lifting velocity, i.e., the region from the start of lifting to the peak is the acceleration zone, whereas the region after the peak is the deceleration zone. This study defined the heights at 75% of the peak value V_{max} as the weight change points in the two zones as shown in Fig. 9; we avoided the heights at the peak of acceleration where the lifting motion becomes most vigorous. The representative weight change points in each subject were defined in this study by averaging 10 results. Based on these results, we attempted to examine the weight perception for sudden weight changes during the lifting task. The details are described in the next chapter.

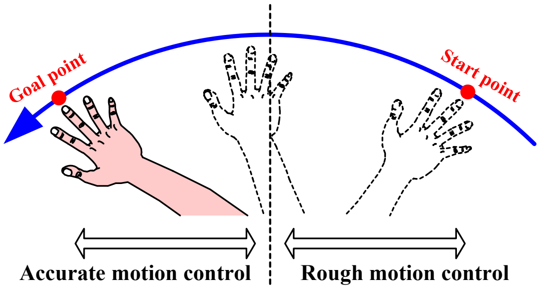
IV. SUDDEN WEIGHT CHANGE DURING THE LIFTING TASK

A. Hypothesis

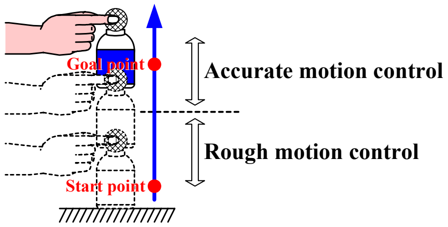
When performing the free motion that connects two points in a two-dimensional plane, it is well known that human beings estimate the trajectory in their brains to minimize the jerk or torque-change by using a visual cue from a start to the goal (minimum jerk model and minimum torque-change model) [6] [9] [10]. The brain then commands the body to follow the estimated trajectory. When practically implementing the task after the issue of the motor commands, it is believed that the motion of the forearm is roughly controlled in the early stage of the task as an open loop; the final approach and adjustment is performed in the later stage by accurate motion control with a feedback loop as shown in Fig. 10 (a). The lifting motion is the simple task that changes the movement to the direction in which gravity acts and adds the weight stimulus. Hence, it is also assumed that similar control characteristics appears when the object is lifted as shown in Fig. 10 (b) although the gravity effect may alter the profile to some extent. In fact, the preliminary experiment in chapter III exhibits almost the similar velocity profile to the lift (see Fig. 7 and Fig. 8). Therefore, given this background, we were interested in human weight perception in two control regions, i.e., the acceleration and deceleration zones. We hypothesized that the accuracy of the weight perception in the deceleration zone becomes more sensitive because the feedback loop becomes stronger for the final adjustment as shown in Fig. 11. Specifically, it is thought that the function of the observer becomes highly accurate. To verify this hypothesis, the difference thresholds of the weight perception in the acceleration and deceleration zones were compared in this study by providing sudden weight changes in both zones with the force display device. It is very difficult to produce such stimuli on a regular basis in the real world.

B. Experimental Method

This study investigated the difference threshold in the weight perception for sudden weight changes during the lifting task by following the experimental procedure shown in



(a) Reaching task



(b) Lifting task

Fig. 10. Difference of control accuracy during the task

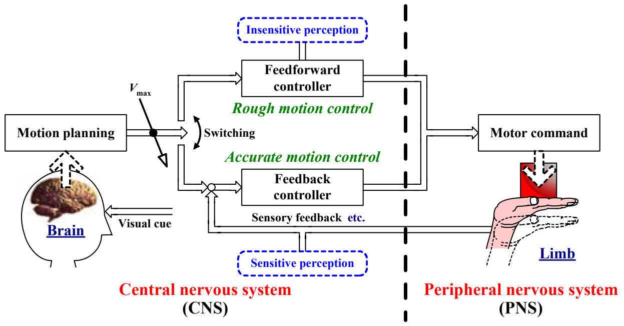


Fig. 11. Assumed weight perceptual model during the lifting task.

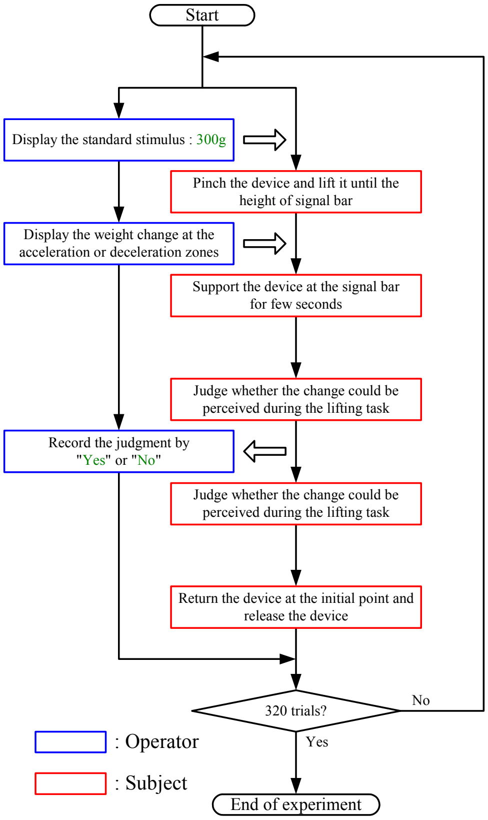


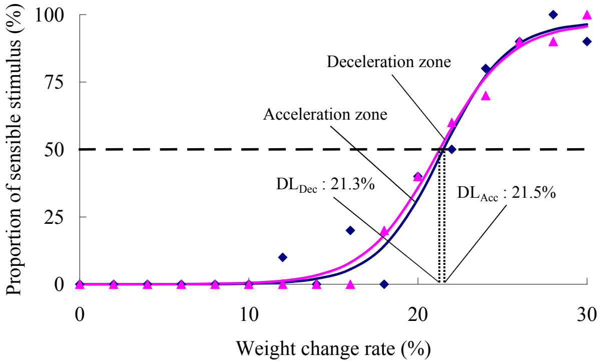
Fig. 12. Flowchart of the experimental procedure related to the weight perception for a sudden weight change during the lifting task.

Fig. 13. Practical picture of the experimental scene.

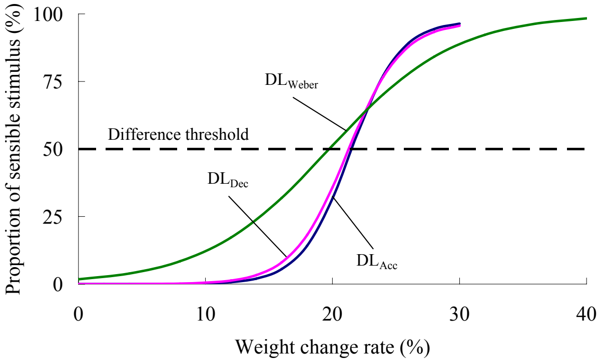
Fig. 12. The subjects lifted the force display device on viewing 3D graphics of an object until the color of the signal bar, which is 10 cm away from the initial position, changed. The subjects strived to stop the device at that height. Until the end of the motion, the force display device automatically loaded the weight with the standard 300 g weight at the individual weight change points. We selected a standard weight so that unfamiliar weight (density) does not prevent the subjects from perceiving the weight as usual [11]. 16 patterns of the weight change rates were displayed from 0 to 30% in steps of 2% of the standard weight; in this experiment, the patterns were displayed 10 times at random. In other words, we instructed the subjects to lift the device a total of 320 times which included the weight change in the acceleration and deceleration zones. Subsequently, the subjects judged whether they could sense the weight change during the lifting process, and the operator verified and recorded their judgments. A practical experimental scene is shown in Fig. 13. The subjects could essentially freely lift the device, but they were instructed to maintain their backs upright and use only their dominant forearm to lift the device.

C. *Difference Threshold*

The representative graphical results are shown in Fig. 14, which are the results of subject C; Table I displays all the results. The blue and red lines indicate the results in the cases of weight changes in the acceleration and deceleration zones, respectively. As shown in Table I, the difference threshold in the acceleration zone is definitely larger in the results of subjects A and E; this implies that their weight perception becomes less sensitive in the acceleration zone. However, these results do not exhibit the obvious evidence that supports our hypothesis. With regard to these results, there is a key



(a) Results of subject C



(b) Comparison with the difference threshold in Weber's experiment

Fig. 14. Representative difference threshold in the weight perception in the lifting process

TABLE I
TABLE OF RESULTS BY ALL SUBJECTS

	A	B	C	D	E	F
Difference threshold in the weight perception						
DL_{Weber} (%)	17.0	15.3	19.8	21.6	20.1	21.1
DL_{Acc} (%)	25.3	14.9	21.5	12.15	26.9	15.3
DL_{Dec} (%)	22.2	16.2	21.3	13.3	21.1	15.5
Lifting profile in the preliminary experiment						
V_{max} (m/s)	0.43	0.26	0.20	0.26	0.23	0.25
SD (%)	2.3	1.8	4.0	7.5	4.3	4.5

・V_{max} : Averaged peak value of lifting velocity
・SD : Standard deviation of V_{max}

TABLE II
ACCELERATION AND DECELERATION ZONES

	A	B	C	D	E	F
A_{min} (m/s^2)	−0.84	−0.54	−0.60	−0.80	−0.60	−0.74
A_{max} (m/s^2)	1.29	0.83	0.65	0.94	0.92	0.91
A_{pro} (%)	65.5	65.1	93.1	84.6	65.4	81.1

・A_{min} : Averaged minimum acceleration in the acceleration zone
・A_{max} : Averaged maximum acceleration in the deceleration zone
・A_{pro} : $A_{rate} = |A_{min}|/|A_{max}|$

factor in the ratio of the acceleration and deceleration zones. Table II indicates the relationship between the minimum and maximum accelerations in the preliminary lifting profiles that are averaged over 10 trials; it implies a typical lifting manner of each subject. In Table II, A_{pro} means the proportion of the deceleration zone to the acceleration zone. According to our hypothesis, A_{pro} must become far less than 100% because A_{max} becomes larger than A_{min} due to rough control in the early stage of the lift. Namely, the difference between the control characteristics in two zones is lost as A_{pro} approaches 100%. In this case, our hypothesis does not hold true. As shown in Table II, it should be noted that subjects C, D, and E lifted the device by A_{pro} near the 100% level, i.e., they lifted the device in both zones in a similar control manner. Consequently, it is supposed that their results were not applied to our hypothesis. The results of subject B are currently under investigation. Further, it is implied that the control characteristics during the lifting task may relate to the human weight perception.

V. CONCLUSION

In this paper, we examined human weight perception by using a force display device with the aim of investigating its applications in multimedia services. In particular, this study focused on human weight perception for sudden weight changes during a lifting task and attempted to reveal the difference between the weight perceptual strategies in the lifting process. As a preliminary experiment, we demonstrated the effectiveness of our device by analyzing the difference threshold in virtual reality. Further, we investigated the individual lifting profiles of the subjects to decide the weight change points in the lifting process. The results indicate that the velocity profile has a short-term unimodal profile in the early stage, which does not appear in the free lift in the absence of a load force. This phenomenon implies that weight estimation is related to the preliminary trajectory planning in our brain. Referring to the profiles, this study attempted to define the weight change points. At the points, we investigated the difference threshold for both the subliminal and supraliminal weight changes. The result indicates that our hypothesis—that human weight perception becomes more sensitive in the deceleration zone of the lift—is partly correct. This is a breakthrough for the weight perception during a dynamic task. So, we will reexamine the hypothesis in our future works by unifying the lifting speed or including the case of weight elimination. In addition, we will attempt to trace the key factor that brings weight perception during a dynamic task by analyzing the subliminal and supraliminal responses divided by the difference threshold.

Our results demonstrated the possibility and some benefits of using the force display device in the physical experiment. In fact, we could substantially reduce the experimental periods by changing the conditions immediately. We believe that virtual reality technologies including force display can lead to a breakthrough in the investigation of the perceptual mechanism that is difficult to examine in the real world. Further, it is expected that the clarified perceptual mechanism may shed further light on multimedia applications; we thought that illusion phenomena, in particular, have large potential for such applications. In our future works, we will try to find applications through a more detailed analysis of the human force/weight perceptual mechanism.

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