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Virtual Whole-Hand Grasping Feedback for Object Manipulation with a Two-Finger Haptic Interface

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Abstract

In many virtual reality (VR) applications, achieving natural interaction with virtual objects remains a key challenge. In this paper, we present a virtual grasping feedback method based on a whole-hand model avatar in a virtual environment using a two-finger haptic device. To provide engaging visual feedback, we propose a method of rigging a virtual whole hand model of five fingers from two input positions of the gripper, as well as a strategy for determining proxy points adapted to various shapes of the objects in contact. To provide plausible haptic feedback, we investigate virtual force acting on the user's fingers by proposing a dynamic model that includes the main factors influencing grasping force based on the study of the actual grip. We demonstrate the effectiveness of the proposed method by conducting experiments where a user grabs three different shapes of a container to pour the liquid out of the container. Depending on the contact positions of thumb and index fingers of the user, the five-finger avatar hand poses an intuitive configuration concerning the shape of the container. The computed force feedback helps the user to successfully manipulate the container in lifting and tilting actions.

Category: Human-Computer Interaction

Keywords: Haptics; Virtual reality; Human-computer interaction

I. INTRODUCTION

The immersive experience is one of the key aspects of a successful virtual reality (VR). While the visual fidelity of the scene is no longer a major issue these days, there remain many challenges in the interaction with the virtual environment in intuitive and natural manners. Focusing on virtual grasping, as we touch, hold, and move the objects using our hands, first of all, it is desirable to have a hand-shaped object rather than an abstract pointer as an avatar for interacting with a virtual object. It would be even better if the avatar is appropriately articulated according to the user's input. The recent development in bare hand motion tracking from leap motion brings visualization of articulated hand model controls in VR applications. However, it lacks haptic feedback which can greatly improve the sense of immersion.

People appropriately control the applied forces of grasping upon manipulating an object while several external forces change according to the state of the gripped object. For example, the grasping force varies not only with the mass of the object but also with the center of mass, the tilted angle, and the texture. Even in a virtual system, if the force feedback from an input device, which is simply used to deliver the weight of an object or the sense of a collision, reflects these external factors

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properly, the feedback could make the users adjust the grasping force.

A haptic device like a gripper can provide both the ways to manipulate the virtual hand and haptic feedback to users. Unfortunately, due to the limitation of the degrees of freedom for most of the input devices, only one or two points are tracked from the device and the numbers of tracked points are too few to control the dexterous parts of a whole hand model. Most of the previous studies have focused on increasing the degrees of freedom of input devices by solving inverse kinematics or estimating the rest of the points after matching the input positions to certain points. On the other hand, we control a whole hand model using two input points from a two-finger haptic interface, gripper, by pre-defining essential joints following a human hand bone model. We identify each joint location as a contact point for collision detection.

We have developed a method for manipulating the hand model from two input positions in which the inputs are mapped to the major tracing points, thumb and index fingertip, and the movements of the rest of the points are derived based on the predefined trajectories. In this way, even though a user operates a haptic device with a limited degree of freedom, he/she can engage with the virtual world similarly to the operation of the dexterous avatar hand.

Haptic rendering in the virtual world comprises collision detection and force computation. The feedback force is usually computed by the penetration depth and virtual coupling is applied for stable interaction. However, when a user picks up an object, there are two stages to consider—first is in contact and the second is in lifting while holding the object. We are required to explore the appropriate force to be given in each situation. We have measured the input forces from the device as well as the computed feedback force while interacting with the virtual object to investigate how the user accommodates the grasping force in effect. In this paper, using a haptic device, we introduce a method to provide feedback on a force that changes continuously according to the state of the grasp and the object to be grasped. Our main contributions are: (1) we present the whole hand rigging method for grabbing an object based on only two tracked fingertips and (2) we study the influence of base force feedback for a virtual object based on the object's state and the manipulation.

The remainder of the paper is organized as follows. After reviewing the related work in Section II, we present our method for rigging a whole hand model and generating the plausible grasps and we introduce haptic rendering to accommodate the force feedback. Section IV describes our experiments on allowing users to grasp various objects and the outcomes. Subsequently, we provide conclusion in Section VI.

II. RELATED WORK

There have been several studies dealing with the motion of the whole hand given a reduced set on input. While the finger motions are reconstructed with inverse kinematics [1], techniques are also applied in motion tracking [2]. Use of the depth or RGB cameras are the mainstream methods. As hand tracking and segmentation can be performed in real-time with high accuracy [3, 4], methods for generating plausible grip motion have been proposed based on physics-based control [5, 6]. In addition, methods of localizing and regressing joints [7] or labeling motion capture data from multiple cameras [8] based on a convolutional neural network have been presented to resolve the occlusion. There are also growing interests in hand interaction with the recent technological development, and reported data [9] provides a way to use real-life hands to directly interact in augmented reality. In virtual hand-object interaction, the interpenetration problem is also an issue, and study by [10] proposes visual cues of grasping in virtual environment. However, these methods have a fundamental limitation where they can only provide visual feedback.

Wearable devices have also been utilized for inputs because sensors attached to each finger joint can be matched with the degrees of freedom of a human hand model. Several studies have used standard devices such as dataGlove or CyberGlove to measure the movement of the finger joints and map it to a virtual system [11, 12]. Unfortunately, real hand movements are limited and uncomfortable. A few studies proposed the methods to match the insufficient input positions from a device to a whole hand model by estimating the rest of the points. For example, two points tracked from a device are mapped to the major points of the hand model, and the positions of the other points are determined by kinematic constraints [13], or grasp samples from a few primitive objects are additionally used to generate several possible hand poses [14]. Although they show natural grasps for a few objects, their grip types are restricted and only simple force feedback is provided based on collision.

Experiments identifying the differences between virtual and real object grasps have been conducted to provide guidelines for constructing a virtual system in which various grips are used. They analyzed the effect of object features or tasks such as object transport to grip aperture, path, and velocity [15, 16]. But there was no comparison of the grasping force, which is crucial to deliver the sense of the grip. To the best of our knowledge, there exist no literature dealing with a virtual system where the force from a device is adapted according to the user's manipulation of the grasped object, or a study on the influence of such force feedback on the grasping force.

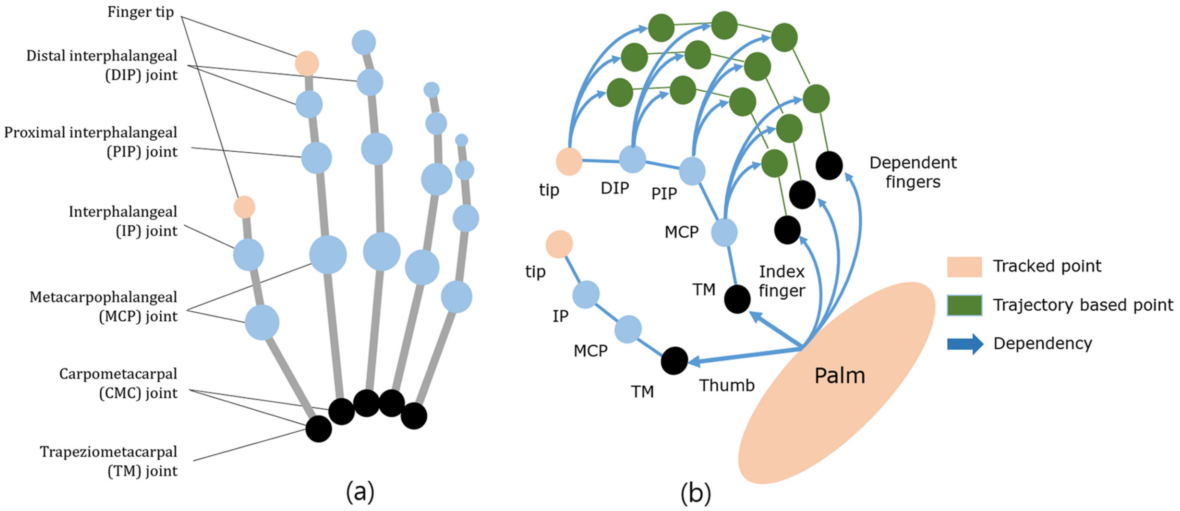


Fig. 1. (a) The contact point is defined at a joint position based on phalanx structure. (b) Depending on a target grasp type, each contact point of the dependent fingers is matched to the contact point of the index finger.

III. METHOD

A. Rigging a Virtual Hand

To freely manipulate a virtual hand, we need a model capable of moving each finger comprehensively. Therefore, we first define the reference hand model based on a human hand skeleton (Fig. 1(a)). We select the essential joints in a human phalanx structure and positioning contact points at each joint location. The model is defined by selecting the essential joints in a human phalanx structure and connecting them to the appropriate length. Typically, 24 joints are selected and contact points are positioned at each joint location. The length between each contact point is defined by the average length and ratio of hand segments measured from adults having no developmental abnormalities [17]. The lengths are appropriately scaled to match with other objects in the experiments.

Because the degrees of freedom of the gripper device are insufficient compared to the hand model, it is important to map the input points to the model. Since we are using a two-finger haptic interface, we matched two tracked points from the gripper interface to the tip points of the thumb and index finger. For the inner points of the thumb, we defined the trajectory to the direction of the thumb abduction movement and for the inner points of the index finger, we chose another trajectory to the direction of the inner palm (Fig. 2). Green points in Fig. 1(b) are moving along with index finger points since we target the grasp type so that the middle, ring, and little fingers move along with the index finger. All points

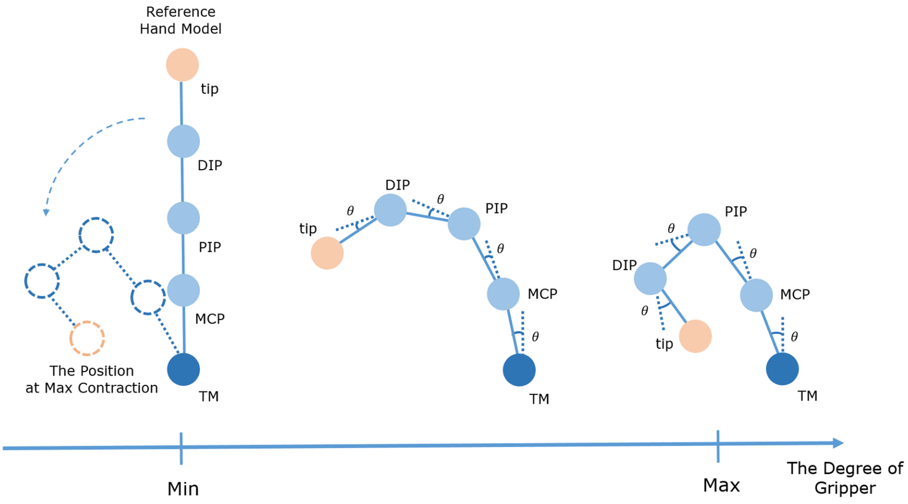


Fig. 2. Each contact point of the index finger is rotated along the trajectory at a certain angle according to the value of the input device.

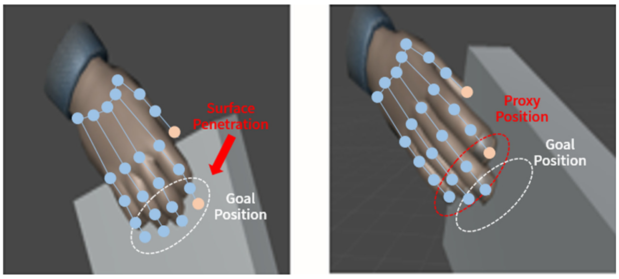


Fig. 3. Before (left) and after (right) applying a virtual proxy generation method. Parts of the rigged hand model corresponding to the collision points are moved to the proxy position to prevent visual penetration.

rotate based on the trajectory according to the varying degrees of the gripper, and the rotation angle for each point was adjusted to resemble the plausible movement of a human hand.

B. Generating a Plausible Grasp

The contact points must determine whether they collide with the graspable virtual objects to prevent visual penetration. Upon determining a point of collision, the collision force is computed and a proxy is created on the surface of the object [18]. When parts of the rigged hand model are inside the object, corresponding collision points that are inside the object are moved to the proxy position on the surface of the object to prevent visual penetration (Fig. 3). When users grasp an object, there can be several different grasp shape because users can grasp the object anywhere, in any direction, and at any angle they want. The virtual hand rigging method from the previous section is not enough since it only rigs the hand to a certain position. Therefore, we need a method to move non-contact points to an appropriate position on the surface of the object. When grasping occurs after the tip points of the thumb and index finger collide with an object, the rotational direction from the tip of the index finger to the tip of the thumb is calculated. Subsequently, using the direction between the other fingers as the axis, the non-contact points of the middle, ring, and little finger are projected to the surface of the object in the range of the maximum angle, and the possibility of collision is checked. Then, if there is a possibility of collision, those non-contact points will move to the appropriate position on the surface of the object (Fig. 4).

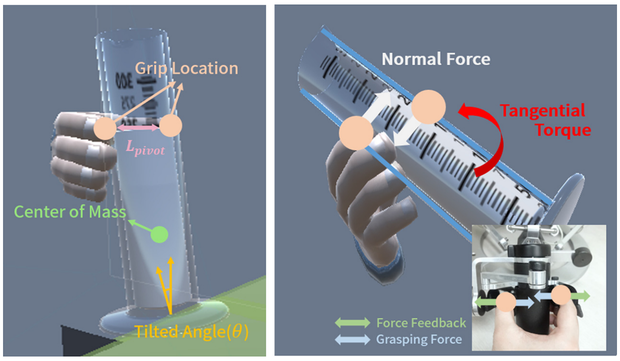
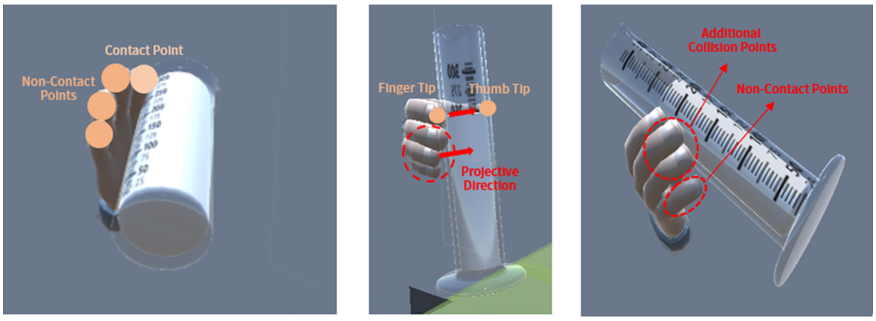


Fig. 5. Each element to calculate the tangential torque (left) is displays with the selected force and torque (right). Also, the direction of force feedback and grasping force at the gripper interface are represented.

C. Pendulum-based Haptic Rendering

People continuously adjust their grasping force when manipulating a grasped object. This force can vary to the grip location, and even if the objects are tilted with the same angle, more force is required to control the object as the center of mass is lower. Thus, the main forces affecting the real grip and the factors influencing these forces have been covered in many studies where the number of fingers used are two (thumb and index finger) [19-21] or five [22-24].

After considering not only grasping, but also subsequent control such as lifting, tilting, and holding of the grasped object, we selected a normal force and a tangential torque as the major elements to change the grasping force (the right image in Fig. 5). Then, the center of mass (CoM), the tilted



(a) (b) (c)

Fig. 4. (a) The positions of the contacted and non-contacted points with the grasped object are shown. (b) The direction of projection is calculated from the tip point of the thumb to the tip point of the index finger, and (c) the additional collision to the non-contact points is determined.

angle (θ) and the grip location were selected as the factors affecting the force and torque (the image on the left in Fig. 5).

A compound pendulum equation of motion (1) is used as a basis for the haptic rendering because the tangential torque (τ) changes according to the position of CoM, the grip location, and the tilted angle of the grasped object. m_{obj} is the object mass, g is the gravitational acceleration, and L_{pivot} is the distance from the CoM to the middle points of the tips of the thumb and index finger. θ is the displacement angle of the object based on the angle at the moment of grasp.

$$\tau = m_{obj} * g * L_{pivot} * sin(\theta) \tag{1}$$

Based on the formulation, τ is the maximum when the object is tilted 90°, but it must be converted to the normal force in order to provide the feedback force to the users using a force type that the input device can generate.

However, since a converted force from τ is not strong when the object is not tilted significantly, we need a base force feedback (F_{base}) to give the feeling of grasp regardless of the object's state. Thus, τ was linearly converted in a range of normal force starting from F_{base}. The range of normal force (F_{range}) was set differently for each object to observe the change in the user's grasping force according to different force feedback.

The appropriate values for F_{base} and F_{range} were chosen by conducting the preliminary experiments to prevent users from applying excessive force on the fingers as well as from feeling too strong a force feedback.

To minimize any fatigue on fingers, we also added a force that changed by the difference in the gripper between the moment of grasp and the present.

IV. EXPERIMENTS

We conducted a series of experiments to verify how successfully our method creates a plausible grasp and achieves effective haptic rendering. We provided three different shapes of beakers: a cylindrical shape (left, Beaker1), a spherical bottom (middle, Beaker2), and a conical bottom shape (right, Beaker3) in Fig. 6. Two guidance points were defined on the surface of each beaker but only one point was displayed at each task to indicate where to grasp. However, the point was only visual guidance, so the beakers could be grasped anywhere. In addition, the CoM of each beaker was set to a distinct position to deliver different force feedback by grip location and subsequent manipulation. A simulation was designed to let a user grasp and manipulate a variety of objects multiple times. It was configured as follows: in a tutorial, a user learns how to control the rigged hand using an input device by grasping an empty beaker and move to the desired destination. After finishing the tutorial, the user grasps a beaker and moves it to the destination. After completing this task, the user tilts the beakers to pour a certain amount of two fluids into a target container. A mixing board displays the current and the target amounts of each fluid so that the user can determine which beaker to use and how much fluid to pour. If the user does not maintain the degree of the gripper within a certain range, the grasped beaker slips and returns to its original position. After the tutorial, various shapes of beakers are provided, and the same work as in the tutorial should be done for all the beakers.

In the experiment, a stable base force and the range of normal force were applied to the model and the variation in the user's grasping force was measured from seventeen participants (11 males and 6 females). We obtained a total of 72 grasps with 22, 32, and 18 grasps for each beaker. We also measured contact points of fingers to object to verify the hand rigging model.

The simulation was based on the Unity game engine (2018.2.8f1) and ran on a laptop (Intel Core i7-7700k, 8 CPU, 16 GB RAM, Geforce GTX 1080). The omega.7 was used as the input device and the users were instructed to insert the thumb and index finger of the right hand into the gripper interface.

V. RESULTS

A. Rigging the Virtual Hand

1) Finger Adaptation

Fig. 7 showcases several snapshots of the grasping results generated by the proposed rigging method described in

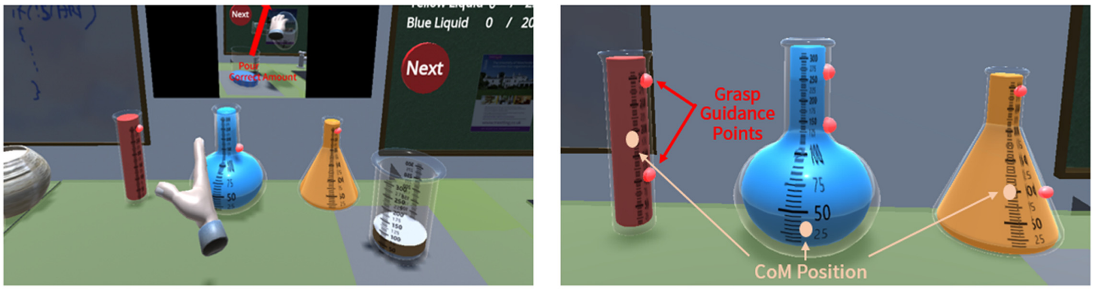
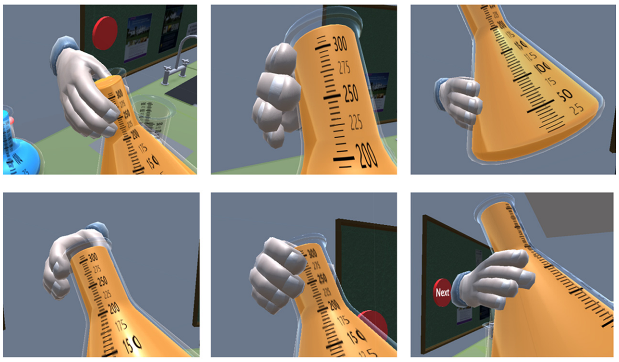


Fig. 6. A simulation overview (left) and the properties of each object (right).



(a) (b) (c)

Fig. 7. The variation of contact points depending on the grasp location. When the upper part of Beaker3 is grasped, only the thumb and index finger are used to grasp (a). Other types of grasp may appear at a similar location, so the middle finger is also used to grasp (b). When the middle or lower part are grasped, all the fingers are used most of the cases (c).

Section III-B. Note that the users have only used two fingers on the gripper device for all cases. While there are variations in grasp visualized by the hand avatar, they do not have any visual penetration and grasps resembling real-life grasping. Also, they have slightly different configurations of the fingers in each variant grip. For example, the number of fingers in contact with the beaker is 2, 3, and 5 in Fig. 7(a), (b) and (c), respectively. We investigated if the number of fingers in contact depends on the position of the reference point relative to the shape of the object in hand.

Each finger is identified as “used” when at least one of the contact points in the finger is used to grasp the object. Because the number of measured data for each beaker was not sufficient to assume normality, the Shapiro-Wilk test was performed to determine the degree of normality. As a result, Beaker1 and Beaker2 were found to have normality ($p < 0.05$). Pearson correlation between the number of used-fingers and the distance from the reference point was calculated. A negative coefficient indicates that more fingers are used as the user grasped location closer to the reference point, and we can say that it is significant if it has a negative coefficient. Beaker2 and Beaker3 were found to be significant with $r = -0.222$ and $r = -0.133$, respectively. But Beaker1 was not found to be significant ($r = 0.063$) (all with $p < 0.001$). We see that it is reasonable given that the shapes of both Beaker2 and Beaker3 are convex towards the bottom. We also compute the point biserial correlation coefficient (r_{pb}) to determine specifically which finger has affected the number of used-fingers. Again, the negative coefficient means the finger is used more frequently, as the grasping location is closer to the reference point. Because the contact of both tips of thumb and index finger is the success condition of the grasp, only the other three fingers are examined. As a result, in the case of Beaker2, the ring finger ($r_{pb} = -0.346$) and pinky ($r_{pb} = -0.475$) are found to be the main factors influencing the number rather than the middle finger ($r_{pb} = -0.095$). For Beaker3, only the pinky has a significant relationship ($r_{pb} = -0.181$). For both Beaker2 and Beaker3, which have a significant relationship between the number of used-fingers and grasp position, the correlation between the number of contact points and the grasp position were also analyzed. There was no relationship to Beaker2 ($r = -0.006$), but Beaker3 showed a correlation ($r = -0.307$) (all with $p < 0.001$). Based on the results, we conclude that, depending on the surface shape of the object, the fingers used for the grasp as well as the number of points in contact could be different.

Table 1. The contact relationship of the joint points according to the grasp position

Joint point	Beaker1	Beaker2	Beaker3
Thumb MCP	-	SN	SN
Finger DIP	SN	-	VSN
Finger PIP	SN	SN	VSN
Finger MCP	VSN	SN	-
Middle tip	P	-	VSN
Middle DIP	-	-	VSN
Middle PIP	SN	SN	SN
Middle MCP	-	SN	-
Ring tip	VSN	-	-
Pinky DIP	-	-	SN
Pinky PIP	VSP	-	-
Pinky MCP	SP	-	-

MCP: metacarpophalangeal joint, DIP: distal interphalangeal joint, PIP: proximal interphalangeal joint, N: negative, SN, strongly negative, VSN: very strongly negative, P: positive, SP: strongly positive, VSP: very strongly positive.

2) Contact Occurrence at Joint Points

To analyze how the object shape affects each contact point, various contact occurrences at points depending on the grasped location are compared. When the point biserial correlation coefficient is calculated, half of the contact points show meaningful results with all types of beakers (Table 1). Not all contact points need a correlation with the grasping position because the contact points are changed according to the types of grasp. Each correlation is calculated based on the relative position to the reference point and whether the contact has occurred. Correlated contact points show negative values in most cases, indicating that the occurrence of contact is increased when grasping occur near the bottom of Beaker2 and Beaker3. The correlations also occur in the contact points of the entire fingers, not in some of the fingers. There are, however, a few exceptional points to Beaker1. In the case of *Middle tip*, the relationship may have occurred because most of the non-contact point projection method is applied to it. We confirm that for some joint points, the surface of the object can affect the contact ratio.

3) Non-contact Point Projection

We analyzed the effect of the non-contact point projection method on each point for evaluation of the proposed method. The method happened at 15 of the 74 grasps, approximately 20.27% and the rates of occurrence per beaker are as follows: 30.43% for Beaker1, 18.75% for Beaker2, and 11.11% for Beaker3. If the surface of the object is flat, the object is mostly obliquely grasped, so the technique would be most applied to Beaker1. When the role of each additional contact point was examined, 52.38% of the additional points were used for the original purpose of the technique which contacts the tip point of a finger when the only the inner points are contacted. And 33.33% of points have increased the number of used fingers and 14.29% of points were used to contact the inner joint points. Thus, the non-contact point projection method mostly satisfied its purpose.

B. Plausible Haptic Feedback

1) Stable Force Feedback

An appropriate force feedback should be used so that the users do not fail to grasp when instant force feedback (F_{base}) is generated and increased according to F_{range}. Thus, a two-step experiment was conducted to find suitable values, and in the first step, only F_{base} was applied to several objects with different values. Then, the distinct F_{range} was added in the second step to make the force feedback change when the user tilted the grasped object, but this time, F_{range} was not changed by the grip location. The combination types of F_{base} and F_{range} were randomly applied to the objects (Table 2).

Table 2. The number of users whose grips fail frequently when F_{base} is fixed and changed (F_{range})

	Number of users with frequent grip failure
F_{base}	
0	0/10
0.4	0/10
0.8	0/10
1.2	5/10
1.6	3/10
2.2	5/10
The range of force (N) (F_{range})	
0–2 (2)	0/10
0.4–2.4 (2)	1/10
0.8–3.8 (3)	1/10
0.8–4.8 (4)	1/10
1.2–4.2 (3)	1/10
1.2–5.2 (4)	2/10
1.6–4.6 (3)	4/10
1.6–5.6 (4)	4/10
2.2–4.2 (2)	4/10

Because two or three times of grasp were sufficient for each beaker to perform the task, if users made too many attempts on each beaker in the first step, we concluded that F_{base} was too strong to maintain the degree of the gripper. Although the users had an acceptable number of grasps for forces less than 1.2 N, 5 of the 10 users could not maintain grasp above that force. In addition, the number of failed users for 1.6 N and 2.2 N was also high,

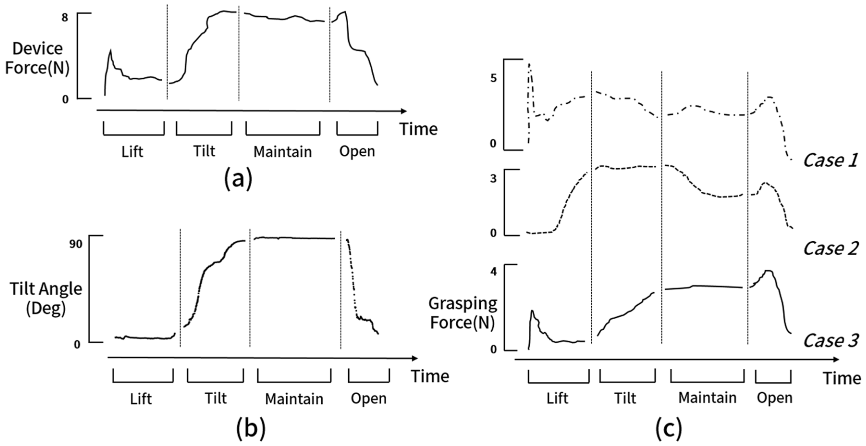


Fig. 8. Graphs of changing forces and the tilted angle of the grasped object. The grasping force of a user (c) was calculated based on the force feedback from a device (a) and the tilted angle, which means a normal force (b). Each of them was divided into four states: lift, tilt, maintain, and open, and the variation of grasping force showed a variety of types in each state like Case 1, Case 2, and Case 3.

3 and 5, respectively. The reason for not showing a linear increase of failure might have been that users were accustomed to strong forces because F_{base} was assigned in the arbitrary order. Thus, we concluded that it was desirable to set F_{base} lower than 1.2 N.

When F_{range} was applied to objects, the grasp could also fail because the force changed suddenly as the object tilted. Three combinations of F_{base} and F_{range} with high failure ratios were found, but they showed that the effect of F_{base} was greater than F_{range} (Table 2). That is, unless users failed to grasp by the force of the grasping moment, the changing force had no significant effect on the failure.

2) Grasping Force Variation

A total of 72 grasping forces were analyzed based on the change in force feedback. When a user manipulated the grasped beaker, the total force feedback and the tilted angle of the object were measured. Therefore, the grasping force was calculated from the total force and the increased normal force, and the variation was divided into four states (Fig. 8). The first state is from the moment of grasping to the lift of the object where F_{base} mainly affects the grasping force. Then, we examined the second state where the grasping force was adjusted according to the increasing normal force when the object is tilted. The third state was to maintain the tilted angle, and the object was let go at the last state, which is called the open state as the user opens his/her fingers to make the object slip out. We did not analyze the open state because the object was set back to its original position when the gripper was sufficiently loosened.

a) Response to instant force feedback: Because the gripper was tightened immediately to the maximum when the force feedback was not provided, we assumed that when a user grasps a virtual object, some amount of force is used in a way similar to an actual object. When the user grasps the object, F_{base} is applied to the direction of extending the fingers of the gripper interface. Therefore, the degree of the gripper is loosened at the moment of grasp, but in most cases, it was stabilized quickly by the user adjusting the grasping force. Among the 71 data items, the response time to F_{base} was 0.106±0.095 seconds (n=60). In the six exception cases, the degree of the gripper was not immediately stabilized, but it oscillated or loosened to a large extent. Three cases where the object began to tilt at the moment of the grasping were not used in the analysis.

When we analyzed the variation in the grasping force, the users stopped tightening the gripper until their force reached 3.76±0.08 N and the shape of the beaker did not affect the grip force ($p > 0.5$). Thus, we demonstrated that the user could maintain the grasp of the object by a stable response to immediate force feedback with a certain grasping force.

Table 3. Analysis of factors affecting the grasping force when the object is tilting

	Mean±SD	**Correlation coefficient**
The increased normal force		
Beaker1	0.56±0.29	-0.251
Beaker2	1.02±0.54	-0.223
Beaker3	2.33±0.34	0.098
The grasping force before tilt		
Beaker1	3.84±1.84	-0.184
Beaker2	3.38±1.33	
Beaker3	4.63±1.96	

The increased value of normal force and the grasping force before tilt are identified as major factors and analyzed for each beaker.

b) Force types with tilting of the object: When a user tilted a object, the force feedback increased by normal force and the grasping force also increased in 62 out of 71 data items to prevent the gripper from releasing more than a certain amount. This means that the users maintained a gap between the fingers as the force acting on the fingertips increased. Although the condition of failure of the virtual grasp was not given, it was controlled based on actual experience.

Nine cases out of 71 were excluded because the object was not rotated sufficiently (30°) or the gripper was continuously loosened after grasping.

The data were classified into four groups according to the change in grasping force compared with the normal force, and a change of less than 0.1 N was regarded the same as an increase: the grasping force varied close to the increase of the normal force (G1), higher (G2), lower (G3), or changed in a more complex way (G4) (Fig. 9). We analyzed G1–G3 groups where the object was tilted for a sufficient time at 3.647±1.392 seconds (min=1.340 seconds).

The effect of varying the force feedback by the normal force on the grasping force was investigated. The ANOVA showed a significant difference in the beaker type ($p < 0.001$), and there was a negative correlation in Beaker1 and Beaker2 (Table 3). This means that the gripper was loosened when the force feedback changed significantly because the user had not increased the grasping force sufficiently. However, no significant relationship was observed for Beaker3 which had a large change of force.

The magnitude of the grasping force before the beaker tilts can also affect the change in grasping force. There was no difference in force before tilting, depending on the beaker type ($p > 0.1$). The correlation over all the cases was a negative value, which indicated that the greater the

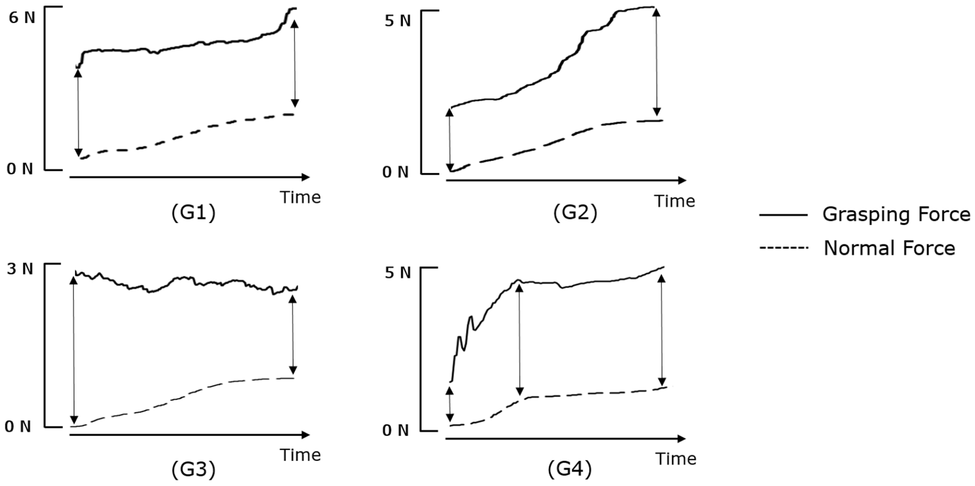


Fig. 9. Each case in the grasping force variation types during the tilt state.

grasping force before the beaker tilted, the looser the gripper because the user could not properly increase the grasping force.

G4, which showed a complicated change, occurred seven times but these cases were frequent when the grasping force before tilting was less than 2 N.

c) Force types to hold the tilted object: The maintain state was defined as when tilted angle changed less than 5°, and we analyzed 61 data items in which the angle was maintained for a sufficient time (mean=4.12 seconds).

Although the range of normal force was distinct to the beaker type, the grasping force to maintain the tilted angle was similar regardless of the type, 4.87±1.67 N ($p > 0.5$). In other words, the users tightened the gripper until the force feedback reached a certain value that they considered as suitable to maintain the grasped object. In two exceptional cases, a force over 8 N was used in the initial maintain state, but after a few seconds, the force decreased to within the average range. In addition, there were three cases where the gripper was tightened but the grasping force was not more than 1 N.

VI. CONCLUSION

We present a virtual grasping interface scheme applied to a gripper haptic device. To provide engaging visual feedback, we constructed a whole hand model with a skeleton as an avatar of the user's hand and proposed the hand rigging algorithm by defining the dependencies among the joints with the user's input controls on the thumb tip and index fingertip via the gripper. Depending on the shape of the object in contact, we developed heuristics of plausible finger resting so that the avatar reasonably holds the object by avoiding interpenetration as well as positioning all five fingers in a comfortable mode.

Based on the proposed whole hand model, in order to provide haptic feedback to the user holding the virtual object of some weights, we analyzed virtual force acting on the user's fingers when in contact as well as manipulating (i.e., moving and titling while holding) the object and formulated a pendulum-based force model that includes the main factors influencing grasping force. Different shapes of the object and the grip locations are considered for the experiment with a power grip.

In our analysis of the grasp type, defined based on the contact points and grasp location, we found that the number of fingers used for grasp was increased for the convex surface of an object. We also found that at certain contact points, the occurrence of contact has a significant relationship to the surface of the object. Although our experiment dealt with only cylindrical or spherical objects, we simulated that the object can be filled with liquid and can be emptied gradually by the user's tilting action so that the interaction derived the condition for voluntary adjustment on the haptic sensation. We also found that users responded to the immediate force feedback using a certain grasping force within a few hundred milliseconds. We also identified the types that react to changes in force feedback to properly control the gap between the fingers although the condition for grasp failure was not given, as well as the range of grasping force used to maintain grip conditions.

There is much room for exploration in the proposed scheme. We believe that the results from the proposed work can provide guidelines for further studies for developing a natural gripping force when configuring a virtual environment where the force feedback on the finger changes and further experiments can be conducted to determine the effect of grasping force changes on object manipulation and immersion.

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REFERENCES

1. H. Rijpkema and M. Girard, “Computer animation of knowledge-based human grasping,” *ACM SIGGRAPH Computer Graphics*, vol. 25, no. 4, pp. 339-348, 1991.
2. L. Hoyet, K. Ryall, R. McDonnell, and C. O’Sullivan, “Sleight of hand,” in *Proceedings of the ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games*, Costa Mesa, CA, 2012, pp. 79-86.
3. C. Qian, X. Sun, Y. Wei, X. Tang, and J. Sun, “Realtime and robust hand tracking from depth,” in *Proceedings of 2014 IEEE Conference on Computer Vision and Pattern Recognition*, Columbus, OH, 2014, pp. 1106-1113.
4. F. Mueller, F. Bernard, O. Sotnychenko, D. Mehta, S. Sridhar, D. Casas, and C. Theobalt, “GANerated hands for real-time 3D hand tracking from monocular RGB,” in *Proceedings of 2018 IEEE/CVF Conference on Computer Vision and Pattern Recognition*, Salt Lake City, UT, 2018, pp. 49-59.
5. N. S. Pollard and V. B. Zordan, “Physically based grasping control from example,” in *Proceedings of the 2005 ACM SIGGRAPH/Eurographics symposium on Computer Animation*, Los Angeles, CA, 2005, pp. 311-318.
6. W. Zhao, J. Zhang, J. Min, and J. Chai, “Robust realtime physics-based motion control for human grasping,” *ACM Transactions on Graphics*, vol. 32, no. 6, pp. 1-12, 2013.
7. F. Mueller, D. Mehta, O. Sotnychenko, S. Sridhar, D. Casas, and C. Theobalt, “Real-time hand tracking under occlusion from an egocentric RGB-D sensor,” in *Proceedings of 2017 IEEE International Conference on Computer Vision (ICCV)*, Venice, Italy, 2017, pp. 1284-1293.
8. S. Han, B. Liu, R. Wang, Y. Ye, C. D. Twigg, and K. Kin, “Online optical marker-based hand tracking with deep labels,” *ACM Transactions on Graphics*, vol. 37, no. 4, pp. 1-10, 2018.
9. O. Hilliges, D. Kim, S. Izadi, M. Weiss, and A. Wilson, “HoloDesk: direct 3D interactions with a situated see-through display,” in *Proceedings of the 2012 ACM Annual Conference on Human Factors in Computing Systems*, Austin, TX, 2012, pp. 2421-2430.
10. M. Prachyabrued and C. W. Borst, “Visual feedback for virtual grasping,” in *Proceedings of 2014 IEEE Symposium on 3D User Interfaces (3DUI)*, Minneapolis, MN, 2014, pp. 19-26.
11. D. Holz, S. Ullrich, M. Wolter, and T. Kuhlen, “Multi-contact grasp interaction for virtual environments,” *Journal of Virtual Reality and Broadcasting*, vol. 5, no. 7, pp. 1-11, 2008.
12. T. Ullmann and J. Sauer, “Intuitive virtual grasping for non haptic environments,” in *Proceedings the 8th Pacific Conference on Computer Graphics and Applications*, Hong Kong, China, 2000, pp. 373-457.
13. S. Mulatto, A. Formaglio, M. Malvezzi, and D. Prattichizzo, “Using postural synergies to animate a low-dimensional hand avatar in haptic simulation,” *IEEE Transactions on Haptics*, vol. 6, no. 1, pp. 106-116, 2013.
14. B. Humberston and D. K. Pai, “Hands on: interactive animation of precision manipulation and contact,” in *Proceedings of the 14th ACM SIGGRAPH/Eurographics Symposium on Computer Animation*, Los Angeles, CA, 2015, pp. 63-72.
15. J. Maycock, B. Bläsing, T. Bockemuhl, H. Ritter, and T. Schack, “Motor synergies and object representation in virtual and real grasping,” in *Proceedings of the 1st International Conference on Applied Bionics and Biomechanics (ICABB)*, Venice, Italy, 2010.
16. Y. Kim and J. Park, “Study on interaction-induced symptoms with respect to virtual grasping and manipulation,” *International Journal of Human-Computer Studies*, vol. 72, no. 2, pp. 141-153, 2014.
17. A. Buryanov and V. Kotiuk, “Proportions of hand segments,” *International Journal of Morphology*, vol. 28, no. 3, pp. 755-758, 2010.
18. D. C. Ruspini, K. Kolarov, and O. Khatib, “The haptic display of complex graphical environments,” in *Proceedings of the 24th Annual Conference on Computer Graphics and Interactive Techniques*, Los Angeles, CA, 1997, pp. 345-352.
19. K. J. Cole and J. H. Abbs, “Grip force adjustments evoked by load force perturbations of a grasped object,” *Journal of Neurophysiology*, vol. 60, no. 4, pp. 1513-1522, 1988.
20. A. W. Goodwin, P. Jenmalm, and R. S. Johansson, “Control of Grip force when tilting objects: effect of curvature of grasped surfaces and applied tangential torque,” *Journal of Neuroscience*, vol. 18, no. 24, pp. 10724-10734, 1998.
21. Q. Fu, W. Zhang, and M. Santello, “Anticipatory planning and control of grasp positions and forces for dexterous two-digit manipulation,” *Journal of Neuroscience*, vol. 30, no. 27, pp. 9117-9126, 2010.
22. M. Santello and J. F. Soechting, “Force synergies for multifingered grasping,” *Experimental Brain Research*, vol. 133, no. 4, pp. 457-467, 2000.
23. V. Zatsiorsky, F. Gao, and M. Latash, “Prehension synergies: effects of object geometry and prescribed torques,” *Experimental Brain Research*, vol. 148, no. 1, pp. 77-87, 2003.
24. N. J. Seo, T. J. Armstrong, J. A. Ashton-Miller, and D. B. Chaffin, “The effect of torque direction and cylindrical handle diameter on the coupling between the hand and a cylindrical handle,” *Journal of Biomechanics*, vol. 40, no. 14, pp. 3236-3243, 2007.

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