Optimizing Haptic Feedback in Virtual Reality: The Role of Vibration and Tangential Forces in Enhancing Grasp Response and Weight Perception

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Abstract. This study explored haptic feedback methods that do not rely on tangential forces, aiming to address the miniaturization challenges of haptic feedback devices in current virtual reality environments. We employed a six-degree-of-freedom haptic interface to construct a virtual grasping scene that simulates the stick-slip phenomenon. By comparing user grip response speed and force adjustment capability under different conditions: no haptic feedback, vibration feedback, and vibration with tangential force feedback, we collected data on users' grip responses under different haptic conditions. The results demonstrate that vibration feedback can significantly improve users' grip response speed without tangential forces. However, without tangential forces, users find it hard to differentiate responses based on the weight of objects. This indicates that while vibration feedback can simplify the design of haptic devices and enhance response speed, tangential forces are still essential for accurate weight perception. The theoretical and practical significance of this research lies in providing a new direction for haptic feedback devices in virtual reality.

Keywords: Haptics, · Virtual Reality · Grip Force Adjustment.

1 Introduction

In the realm of virtual reality (VR), haptic feedback technology plays a crucial role in enhancing user interaction by simulating touch sensations. This technology enables users to interact with and manipulate three-dimensional objects in virtual environments more realistically. Despite its potential, a significant challenge lies in the miniaturization of haptic devices, particularly those designed for hand-haptic feedback. Current solutions often rely on mechanical structures with movable parts, which can be bulky and limit the range of tactile sensations they can provide.

Research by Flanagan et al.[4] showed that the human body has reflexes that finely adjust grip force in response to changes in load force to prevent objects from slipping or being damaged. Wiertlewski et al.[14] explored how vibrations caused by sliding affect the grasping reflex, indicating that vibrational signals play a significant role in modulating grip force to compensate for unexpected object sliding. These studies highlight the importance of vibration in human tactile perception and suggest that using vibration instead of other types of force feedback could potentially reduce the size of devices. Konyo et al.[8] demonstrated that the sensation of friction can be conveyed through vibration without needing tangential forces at the fingertips. We aim to explore further haptic interfaces capable of generating tangential forces to investigate whether the coupling mechanism between grip force and load force remains after the removal of tangential forces, as well as the role of tangential forces in the dexterous manipulation of virtual objects. In our previous study [15], we investigated a tactile device for dexterous manipulation that relies on pressure and vibration, omitting tangential forces. This approach resulted in a reduction in the size of fingertip tactile devices. However, the effects of eliminating tangential forces on object grasping within our environment have not yet been investigated.

Our goal is to enable users to perform dexterous manipulations in virtual reality, especially to change the contact points of grasped objects through actions such as rolling and sliding [5], making the interaction more realistic. Therefore, identifying the minimal haptic elements that help dexterous manipulation is a worthwhile research topic. In other words, finding the types of haptic feedback that are less crucial during the object-grasping process is a valuable subject of study.

In this study, we utilized a 6-degree-of-freedom (DOF) haptic interface to construct a virtual object grasping scenario in a virtual environment that replicates the stick-slip phenomenon. Participants were asked to repeatedly perform "Re-grasping" actions on virtual objects in their hands, which involved brief sliding movements in a controlled environment. This task requires changing the current grasping posture and quickly transmit to another more advantageous posture. We compared three experimental conditions: no haptic feedback, vibration feedback, and vibration combined with tangential force feedback. We observed the characteristics of grip force changes during re-grasping, dividing the force changes into three stages and recording the users' reaction times based on these stages.

Our results indicate that the presence of both types of haptic conditions significantly improved users' grasping response speeds compared to visual feedback only, but there were no significant differences between having tangential force feedback and not. Regarding the grasping force after reflex, our findings suggest that most users could only distinguish the grasping force for objects of different weights when tangential force was present. Our results demonstrate that the coupling mechanism between grip force and load force remains intact with vibration alone, even with the removal of tangential force. However, our result also suggests that simply removing tangential force may not be sufficient for users to perceive the different weights, indicating the need for further investigation.

2 Related Work

Our research is based on the grip force applied by the fingers during object grasping, which can respond to sudden changes in load force. Coal et al.[3] indicated that the grip

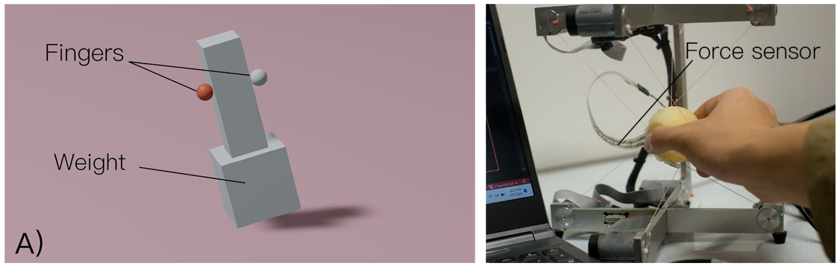

Fig. 1. Overview of the Experimental System: A) The user's view during the experiment. The mass of the virtual object is concentrated in the cube at the bottom, creating a "hammer"-like structure to keep it vertical, preventing undesired rotation slip. B) The device is a haptic interface equipped with a force sensor.

force began increasing in all subjects from 60 to 90 ms. Also, human can dynamically adjust their grip force based on the feedback of the load force[4]. Based on these basic adjustment principles, the tactile signals at the fingertips provide information on contact events, such as the contact timing, location, and direction of contact forces. This information is used to monitor task progress and achieve grasp stability, considered crucial for dexterous manipulation[6]. Moreover, distributed vibration stimuli on the fingers can unconsciously control human grip force[10].

Regarding the research on using limited tactile feedback as a substitute for traditional force feedback, some studies[12] utilized skin deformation feedback instead of traditional force feedback, showing that skin deformation could convey force information effectively. Konyo et al.[8] compared vibration friction against the friction generated by force feedback devices, indicating that tangential forces are not necessary to convey a sense of friction, simplifying the device and allowing for its combination with force feedback devices. We will further investigate whether tactile feedback replicating the friction sensation can evoke a grip response to sudden changes in load force.

Additionally, research by King et al.[7] has shown that, without tactile feedback, both new users and experts apply a grip force far greater than the minimum required to complete a task, indicating that continuous haptic feedback is necessary to maintain optimal grip strength. We will explore whether vibration alone can replicate this phenomenon.

Studies also suggest that vibration tactile feedback can help dexterously manipulate objects. A classic scenario of sudden load change is when an object unexpectedly falls out of grasp. Walker et al.[13] designed a scenario where the virtual floor suddenly drops, requiring users to prevent the object from moving. The results showed that when visual feedback was disabled, vibration feedback significantly positively impacted manipulation. Li et al.[9] designed a virtual task of grasping and holding fragile objects, proving that dual-modal feedback (sliding vibration and squeezing feedback) is significantly better than any single-modal feedback. However, their feedback signals were not applied to the hands, and we aim to verify if the results differ when stimulating mechanoreceptors on the hand.

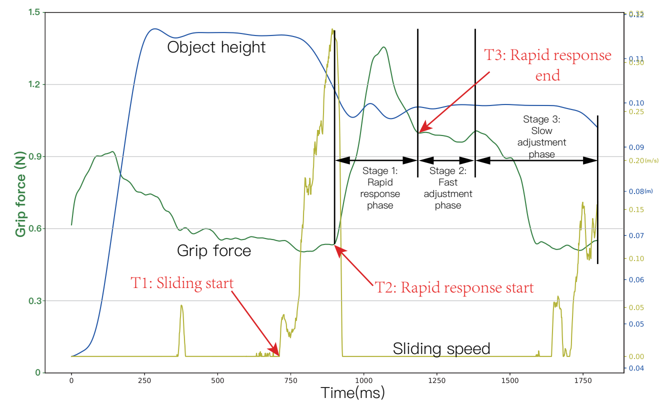

Fig. 2. The typical grip force adjustment process: Stage 1: Due to the sudden change in grip force caused by sliding, users begin to adjust their grip force to deal with unexpected sliding. Stage 2: To grip the object more comfortably, users will adjust their grip strength quickly, seeking the optimal grip. Stage 3: Users might release or continue manipulating the object once the grip is stable. T1 moment: To adapt to sliding, users gradually reduce their grip force, at which point the object begins to slide. T2 moment: Users perceive the sliding of the object and quickly increase their grip force in response, attempting to stop the sliding. T3 moment: Once the sliding is controlled, the grip force will stop increasing and tend to reduce. This figure also shows three stages of grip force adjustment:

Wiertlewski et al.[14] demonstrated that vibration characteristics were used by the central nervous system to regulate the grasping reflex and suggested that larger tangential forces and vibration power improve response speed. However, in their system, tangential forces were always present, and the scenario of vibration only has not been explored. Okamoto et al.[11] added vibration cues before sliding can enhance the speed of humans' grip adjustment response. However, in the real world, vibration cues synchronous with stick-slip occurrences, occurring simultaneously as sliding. We need further validation for physics-based manipulation.

3 Experiment

Participants were invited to take part in the experiment involving the grasping and sliding of objects in a virtual scene. This included a series of tasks requiring them to achieve controlled sliding of objects in their hands under different haptic conditions, collecting data on their reaction time and grip force.

3.1 Participants

Eight participants (six male and two female) joined the experiment after providing informed consent. The participants ranged in age from 24 to 33, with one being left-hand dominant. The experimental procedure received approval from the Tokyo Institute of Technology Review Board.

3.2 System Set-Up

For the hardware, we utilized a 6-DoF haptic interface equipped with pressure sensors, following the hardware configuration described in the work by Balandra et al.[1]. This setup allowed users to manipulate a virtual coupling in the virtual environment, controlling its position and rotation. Two spherical haptic pointers are linked to two device positions in the virtual environment. These pointers move in accordance with the device's grip position and rotation while the distance between the two pointers decreases proportionally to the applied pressure, enabling them to exert pressure on virtual objects to achieve grasping and releasing. The force feedback to the grip begins to appear when the user starts to touch virtual objects. The system could provide users with tangential forces in any direction and vibration feedback. When users grasp a virtual object or when the virtual object slips within their hands due to gravity acting on the object, a vertically downward tangential force is applied to the surface of the users' fingertips. Our haptic interface drives motors to pull the strings, providing users with a tangential force on their fingers in the corresponding direction. Users typically utilize this information to directly perceive the object's weight. When the object slides or when users shake the object while holding it, they will also experience greater tangential forces. The system setup is shown in Fig. 1.

For software, we employed the Springhead[4] physics engine, which calculates the forces experienced by the virtual coupling and outputs them directly on the haptic interface. During the manipulation of virtual objects, the physics engine detected the moment when static friction transitioned to dynamic friction between the coupling and the objects. At this moment, a 120Hz damped sinusoidal wave proportional to the contact force was output to create stick-slip tactile sensations. Similarly, during dynamic friction, a continuous damped sinusoidal wave proportional to the sliding velocity and contact force was output to create sliding vibratory sensations. The example of vibration signal is shown in Fig. 3 B. The system's update rate was 1000Hz.

3.3 Experimental Procedure

Our experiment focused on three haptic conditions: 0: no haptic feedback, 1: tangential force and vibration, 2: vibration only, and two mass conditions of virtual object: mass = 150, mass = 100. We avoided a significant difference in mass to prevent participants from subjectively perceiving the difference. Participants could always see the virtual scene on the screen, meaning visual was always available.

Before the experiment began, participants were given free play time under different conditions until they could successfully control the sliding of virtual objects to minimize the learning effect on the results. Each individual's free play time varies because this task is relatively challenging even in the real world, and different users have different operating habits. However, we strictly require users to complete the task with "haptic on" skillfully. When "haptic off", they must demonstrate the corresponding grasping reflex before ending the free play time, even if they cannot successfully complete the task. This requirement aims to minimize learning effects in subsequent experiments.

[4] https://springhead.info/

The specific experiment consisted of six trials, combining the three haptic conditions with the two mass conditions, and the order is condition 1 mass 100g, condition 1 mass 150g, condition 2 mass 100g, condition 2 mass 150g, condition 0 mass 100g, condition 0 mass 150g. We later arranged the condition 0 (no haptic feedback) trials to avoid the practice's effects. Because the 'Re-Grasp' task is an innate ability in real life that does not require extensive practice to accomplish, we provided participants with sufficient practice time before the experiment to familiarize themselves with the system. To streamline the experimental process, we fixed the order of the conditions, gradually increasing the difficulty level from the presence of haptic feedback to its absence.

During the experiment, participants were instructed to induce slippage by gradually and intentionally reducing their grip force, but making the object completely leave the fingers was prohibited. Furthermore, we allowed participants to attempt to minimize the slip by using a small release duration, but such attempts were not considered successful sliding. In the experiments under each condition, the trial concludes when the user successfully 're-grasps' the object 5 times. However, in the 'no haptic' condition, many users struggle to complete the experiment. Therefore, if the object is observed slipping and the user exhibits a reflexive tightening of the fingertips, it is considered a successful completion even if they fail to grasp the object.

Participants were not informed of the experimental conditions and were instructed to follow the specified order. An experimental trial was considered complete when at least three effective slides (the object should not leave the virtual finger or drop on the ground) were observed. The system recorded data throughout, including output from the force sensors, the vertical position of the virtual object, the relative speed between the virtual coupling and the object, and the output of the haptic interface.

4 Results

The typical sliding process under condition 1 is shown as Fig. 3.

4.1 Grip force response latency

The initial analysis included ANOVA, which revealed significant differences between the conditions. The ANOVA results indicated that the effect of condition on grip response time was statistically significant ($F(2, 234) = 84.83$, $p < 2.10e-28$). This result suggests that at least one group's mean differs significantly from the others. Then, we employ the Tukey HSD multiple comparison test and independent sample t-tests to find the impact of tangential force and vibration on response time. We analyzed the grip response time following sliding under different haptic conditions to see the significance of applying tangential forces and vibratory haptic feedback on fingers. We will collect the time of T2 - T1 shown in Fig. 2. The overall and individual result is shown in Fig. 4 and Fig. 5

In this research, we compared latency differences between three conditions (labeled 0, 1, 2), In our experiments, we required participants to perform 're-grasp' five times under each condition, which should have yielded 240 data. During subsequent processing, 3 data were eliminated from the analysis because the speed of finger opening was too fast, resulting in a lack of sliding friction. This resulted in the analysis of 237 valid

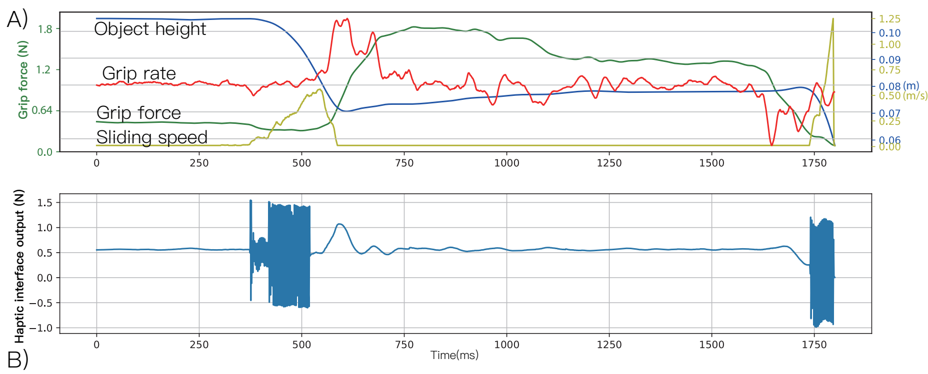

Fig. 3. In the typical sliding process under condition 1 (tangential force plus vibration) when grasping an object around 50g, the object height shown in the figure above(A) represents the object's vertical position. At around 500 milliseconds, the object begins to slide but does not touch the ground. During this process, to control the slide, the grip force suddenly increases; simultaneously, the sliding speed maintains a non-zero value throughout the sliding process. The grip rate—the derivative of grip force—helps us accurately locate the specific moment of the sudden force change. The figure below(B) shows the output of the haptic interface in the upward vertical direction, including the overlapped damped sinusoidal produced during the sliding process and the tangential force generated by the object's weight and the sliding.

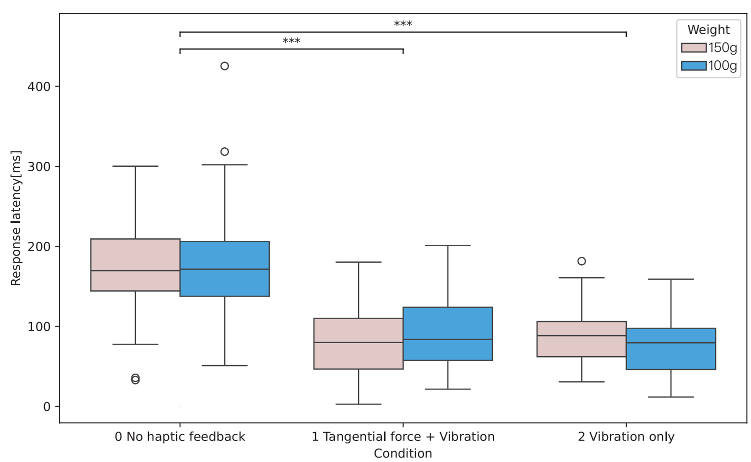

Fig. 4. The response latency after object sliding for all individuals under three conditions (0, 1, 2) shows significant differences between condition 0 and condition 1 and also between condition 0 and condition 2. However, the results between condition 1 and 2 are similar and do not show a significant difference. Additionally, the data range for condition 0 is wider. There is also no significant difference between weights 150 and 100.

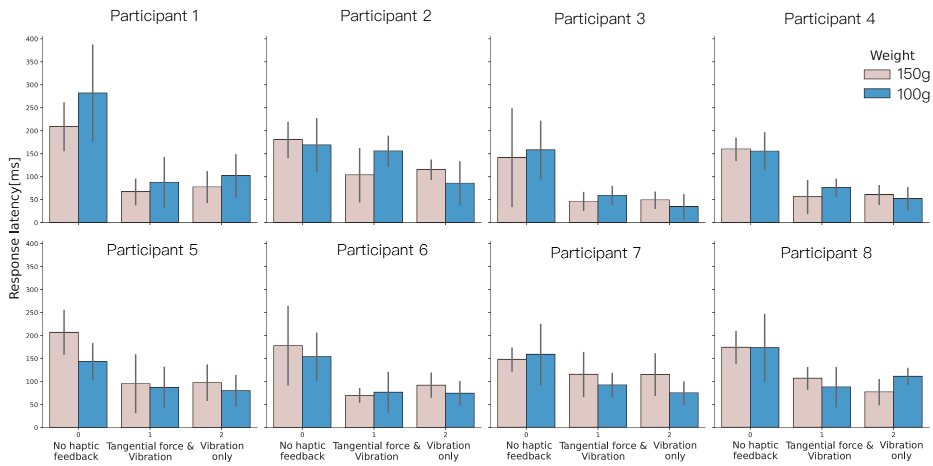

Fig. 5. The response latency after object sliding for each individual. Generally, the latency under condition 0 is greater than that under conditions 1 and 2.

samples across three haptic conditions and two weights. Our analysis aims to evaluate the impact of the presence or absence of vibration on grip force adjustment.

According to the results of the Tukey HSD multiple comparison test, we have found significant differences between group 0 and group 1, with a mean difference of -87.4211 ($p<0.001$, confidence interval: -106.0696 to -68.7726), and between group 0 and group 2, with a mean difference of -91.5215 ($p<0.001$, confidence interval: -110.2877 to -72.7554). This indicates that the grip force adjustment latency in group 0 is significantly lower than in groups 1 and 2. However, the mean difference between groups 1 and 2 was -4.1004 ($p=0.8623$, confidence interval: -22.7489 to 14.548), showing no significant difference between these two groups in grip force response time.

Further independent sample t-test results were consistent with the findings of the Tukey HSD test, revealing significant differences between group 0 and group 1 ($t=9.951$, $p<0.001$) and between group 0 and group 2 ($t=10.842$, $p<0.001$). In contrast, the comparison between groups 1 and 2 ($t=0.648$, $p=0.518$) did not reach statistical significance.

For condition 0, regardless of whether the mass was 150g (median response time: 169.53ms, SD = 58.37ms) or 100g (median response time: 171.49ms, SD = 72.00ms), the reaction times for participants were longer in the absence of vibration. In contrast, under conditions 1 and 2, where vibration was present, the median response times significantly decreased, regardless of the mass. In condition 1, the median response time was 79.82ms (SD = 43.74ms) for a mass of 150g and 83.69ms (SD = 43.80ms) for a mass of 100g. Similarly, in condition 2, the median response time was 88.3ms (SD = 35.00ms) for a mass of 150g and 79.50ms (SD = 36.30ms) for a mass of 100g. These results suggest that the presence of vibration alone can significantly reduce grip force response time, irrespective of the object's mass.

Moreover, we observed the variability in grip force adjustment response across conditions by comparing the minimum and maximum values. The maximum values in condition 0 reached 300.13ms and 425.31ms, much higher than in other conditions, indicating more significant variability in response time without vibration. The maximum values in conditions 1 and 2 were relatively lower, suggesting that users might tend to make predictions of sliding or respond slowly without tactile feedback.

Employing average-based analysis allows for comparing overall differences between various conditions. Subsequently, we attempt to conduct individual data-based analyses to uncover potential outliers and observe individual variations. Regarding individual user data, everyone demonstrated noticeably slower responses under the condition without haptic feedback than those with haptic feedback.

4.2 Grip force after sliding

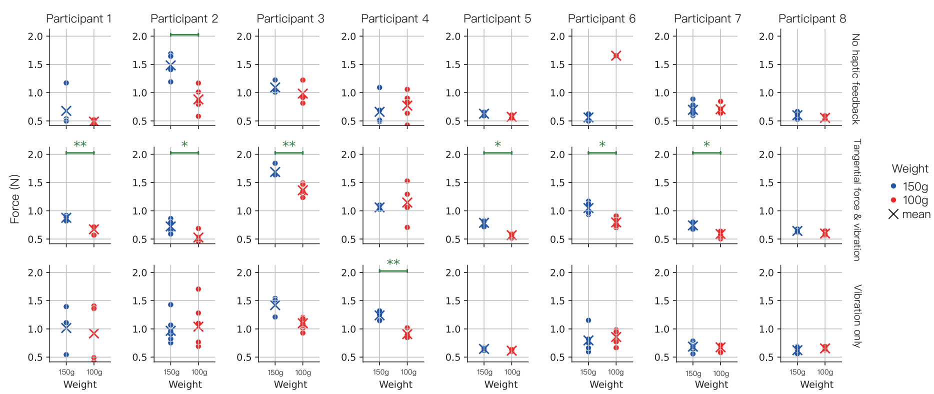

Fig. 6. During object sliding, the gripping force has a process of initial increase then decrease. We collected grip force data at the end of the rapid response phase under various weight conditions and presented them in scatter plots. In this chart, each column represents data from an individual participant, and in rows, with each row representing a condition (no haptic feedback, tangential force & vibration, vibration only).

To investigate whether users have different behaviors toward virtual objects of different weights under specific haptic conditions, we collected the gripping force of users after the object slid. Under each condition, there is no significant difference between weights of 150 and 100 ($P > 0.05$). Therefore, we will focus on analyzing each individual's performance and try to find if individual differences can be observed. The result of an individual is shown as Fig. 6. We conducted independent sample t-tests on the data of each user under a specific tactile condition. We will collect the grip force of T3 shown in Fig. 2. The results showed that under condition 1 (tangential force and vibration), 6 out of 8 users displayed significant differences ($P<0.05$) in their data, while two users did not show significant differences ($P>0.05$). In contrast, under condition 0 (no haptic feedback) and condition 2 (vibration only), only one user's data in each condition showed significant differences.

To explore the correlation between the force magnitudes under two weight conditions, we calculated the ratio of the mean grip force under two weights for each person under one tactile condition. For clarity in plotting, we subtracted one from the ratio, making the graph more understandable, shown as figure 7. The ideal ratio would be (150g / 100g) - 1 = 0.5. The results indicated that under condition 1, 6 people had ratios greater than 0.2, while under condition 0, 2 people did, and under condition 2, 2 people did. Additionally, condition 1 had one negative value, whereas conditions 0 and 2 had two and three negative values, respectively. These negative values indicate that some users almost responded opposite to the two weights. Overall, the ratios under condition 1 were closer to the ideal state than conditions 0 and 2, and condition 2 showed a relatively stable phenomenon compared to condition 0, without more significant variances.

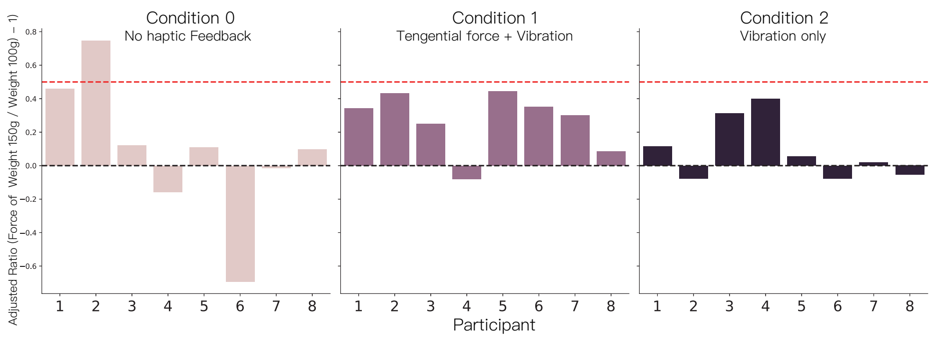

Fig. 7. The ratio of the average grasping force at the end of the rapid response phase for two different weights (150g and 100 g) under various haptic conditions. For each condition, we calculate the ratio of the average grasping force for weights of 150g and 100g, respectively. Then, we obtain the data presented in the chart by subtracting one from this ratio. Bars closer to the dashed line at the top indicate that the force ratio under is closer to the ideal value of 1.5. If the ratio is negative, it indicates that participants exert more force on the lighter object, demonstrating that they can't distinguish objects of different weights.

5 Discussion

5.1 Grip force response latency

From the results, it is clear that in the absence of haptic feedback (condition 0), latency is the longest, significantly higher than in conditions with haptic feedback (condition 1 and condition 2). However, there was no significant difference between condition 1 and condition 2. This indicates that haptic feedback can significantly enhance the response speed in the "Re-Grasp" task compared to relying solely on visual cues. More importantly, vibration feedback alone can improve users' grasping reflex speed, even when removing tangential forces. This is likely because vibration feedback is sufficient to trigger a rapid response that bypasses visual processing.

During this phase, the average response delay under conditions 0 and 1 is about 80 milliseconds. It is believed that a Long-Latency Reflex (LLR)[16] may occur, which is a reaction to the perception of sliding events, typically appearing 50 to 70 ms after the disturbance. Following is the delay from the electromyographic (EMG) signals to the muscle-generating response force, which spans approximately 30 to 100 ms[2]. This series of reactions constitutes the entire response process. A voluntary response may be required for condition 0, which is visual only and may cause a slow reaction. Furthermore, by comparing the minimum and maximum values, we can observe the variability in grip force adjustment response under different conditions. The condition without haptic feedback (condition 0) shows the most significant variance and numerous outliers. The presence of these outliers is not difficult to explain; sometimes, users might react slower due to not noticing the object slipping. However, many outliers show a faster response speed than in conditions with haptic feedback. These outliers might have originated from very slight slips. To improve success rates, some users remember the amount of force used during previous slips and then attempt to proactively predict the object's falling behavior, managing to "accidentally" succeed by quickly controlling the opening and closing of their fingers. The lack of haptic feedback makes this strategy more appealing in condition 0, as success rates are generally lower. Moreover, there is no significant difference between different weights, as the weight does not affect the speed of generating haptic signals.

Okamoto et al.[11] showed that grasping responses are significantly slower in conditions with only vibration feedback than those with tangential forces, which seems to conflict with our findings. However, the experimental conditions between the two studies are different. In their experiment, the vibration occurred before the object slipped, which helped identify the neural mechanisms related to tangential forces. In contrast, in our conditions, vibration occurred synchronously with the slip, serving as the primary source of information for users to detect object displacement.

5.2 Grip force after sliding

From the observations of Fig. 6, we note significant individual differences in the perception of force. Despite this, under condition 1, most individuals could still differentiate between two weights without being explicitly informed of the weight difference. However, the data from the two participants did not show significant differences. Specifically, participant 4, when dealing with the lighter weight, may have experienced finger fatigue due to too many attempts without adequate rest, affecting the accuracy of the data. Participant 8, perceiving the task as challenging, adopted a strategy that caused only a slight displacement of the object, resulting in low grip strength values and subtle variations. However, the overall data suggest that tangential force enables users to exhibit different grasping responses when handling objects of different weights. From Fig. 7, it is evident that under condition 1, the ratio of grip force more closely aligns with the ideal value. In contrast, under conditions 0 and 2, observing different responses from users towards objects of varying weights is challenging, implying that vibration feedback alone is ineffective in distinguishing between different weights.

Wiertlewski et al.[14] proposed a correlation between the power of vibration generated during sliding and the subsequent peak in gripping force. Our analysis suggests that haptic signals mainly originate from the stick-slip phenomenon in our experimental setup. Due to the effect of static friction, objects do not always slip after being successfully grasped, even if the grip force is reduced within a specific range. Zangrandi et al.[16] mentioned the slip process includes stick, partial slip, and complete slip phases. However, the partial slip is hard to display without tangential force under only vibration and no haptic feedback conditions. Without partial slip or sliding, it becomes difficult to perceive differences in weight. Moreover, our experimental setup allows for the complete elimination of tangential force in a vibration-only condition, differing from the conditions of previous experiments. This preliminarily indicates that in manipulation environments based on physics, we cannot conclusively state that tangential force is unnecessary for enabling users to distinguish weights through haptics.

5.3 Experimental Design Impact

The study had a relatively small number of participants. In the Grip Force Response Latency experiment, results showed no significant fluctuations or inconsistencies, suggesting that increasing participant numbers would unlikely change the conclusions. However, in the Grip Force After Sliding experiment, some differences were observed between the tangential force condition and the other two conditions. Increasing participant numbers might make these differences more statistically significant.

Although participants were given sufficient practice time and the experimental process was streamlined by fixing the condition order, order effects may not have been entirely eliminated. Counterbalancing the condition order across participants would have helped control for potential order effects.

6 Future work

We will focus on validating the correlation between different weights and vibration power to find if it will help to distinguish different weights without tangential force. Also, we aim to explore the potential of fingertip haptic devices lacking tangential force feedback, seeking the minimal tactile feedback necessary for achieving the most flexible and intuitive grasp.

7 Conclusion

In this study, we utilized a 6-DoF haptic interface to explore the effectiveness of vibration feedback in virtual object grasping, finding that vibration feedback significantly improves grasping response speed even without tangential forces, highlighting its importance in simplifying the design of haptic devices. However, tangential force is still essential for distinguishing object weight in virtual environments. Future research will delve into optimizing vibration cues and exploring the minimal haptic feedback required for physics-based manipulation.

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