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Get a Variable Grip: A Comparison of Three Gripping Techniques for Controller-Based Virtual Reality

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ABSTRACT

This work-in-progress paper details a user study comparing three techniques for grasping virtual objects that differ in terms of how the firmness of users' grip of the controller affects the behavior of the virtual object: *firm grip* uses a direct mapping between the movement of the controller and object, *firm+loose grip* allows gravity to affect the object when the grip is less firm, and *variable force grip* varies the extent to which the object responds to gravity depending on how forceful the user's grip is. The study did not reveal any differences between the conditions in terms of perceived task load and usability. However, our findings suggest that *variable force grip* may be perceived as the most realistic, and we found some indication that *variable force grip* may impair task completion time.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction (HCI)—Interaction devices—Haptic devices;

1 INTRODUCTION

Object selection and manipulation are among the most common forms of interaction in virtual environments (VEs), and grasping and manipulation with one's hands have been described as the most natural technique for performing such interactions [8]. A large body of work has explored hand-based selection techniques, including techniques that imbue users with supernatural abilities, such as extended reach [12] and the ability to control multiple hands [13]. Nevertheless, many virtual reality (VR) applications seek to mimic real-world interactions, and therefore, rely on *simple virtual hand* techniques involving a one-to-one mapping between the user's real and virtual hand movement [8].

To support hand-based object manipulation, the user's hand gestures can be tracked by different hardware (e.g., sensing gloves, wrist-worn electromyography, and cameras embedded in VR displays [2]), and touch feedback can be delivered in a variety of ways (e.g., physical props [11], vibrotactile gloves [10], mechanical exoskeltons [5], and actuated controllers [3, 4, 14, 15]). However, most virtual reality (VR) applications rely on consumer-grade VR controllers for detecting hand movements and gestures and for delivering haptic feedback.

When manipulating real-world objects, it is possible to change the orientation and position of the objects relative to the hand by gripping them more or less firmly. However, most commercial VR applications rely on more unnatural approaches to grasping. In particular, Bonfert et al. [1] describe that grasping is generally performed in one of two ways. Either the object is rigidly attached to the user's hand or controller (*firm grip)* or else the object follows the hand or controller while maintaining an upright orientation, as if hanging from the hand (*loose grip*). Firm grip prevents users from changing their grasp without releasing and regrasping the object, whereas loose grip limits their ability to control the orientation of the grasped object. To make manipulation more realistic, Bonfert et al. [1] proposed *variable grip*, which enables users to alternate between the two modes and either tighten or loosen their grip using different buttons on the *HTC Vive* controller. In addition, the authors present a user study that compared two types of variable grip to firm and loose grip, and found that variable grip was rated higher in terms of perceived usability, although it increased task completion time and the number of regrasps. Finally, Bonfert et al. [1] proposed that future work should explore variable grip in combination with the *Valve Index Controller* (also known as *Knuckles*), which can detect grip forces and is strapped to users' hands; thus, allowing users to release their grip without dropping the controllers.

In this work-in-progress paper, we present a user study comparing two versions of variable grip and firm grip developed for the Knuckles controllers. We found no significant differences in terms of self-reported task load and usability. However, the version of variable grip that mapped the physical grip force to virtual grip firmness was perceived as more realistic, and we found some indication that this condition increased task completion times.

2 METHODS AND MATERIALS

The study relied on within-subjects design and compared three gripping techniques: *firm grip* and two variations of variable grip, *firm+loose grip* and *variable force grip*.

2.1 Gripping techniques

The three gripping techniques were developed for the Knuckles controllers, and for all three, the position of grasped virtual objects was dictated by the controller's position. However, the techniques differed in terms of how grip forces affected the object's rotation with respect to gravity. The firmness of the user's grip was detected by the force sensors embedded in the controller's handle (Figure 1).

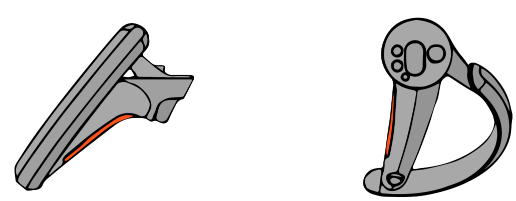

Figure 1: Side and top-down view of the Valve Index controllers with force sensors highlighted in red.

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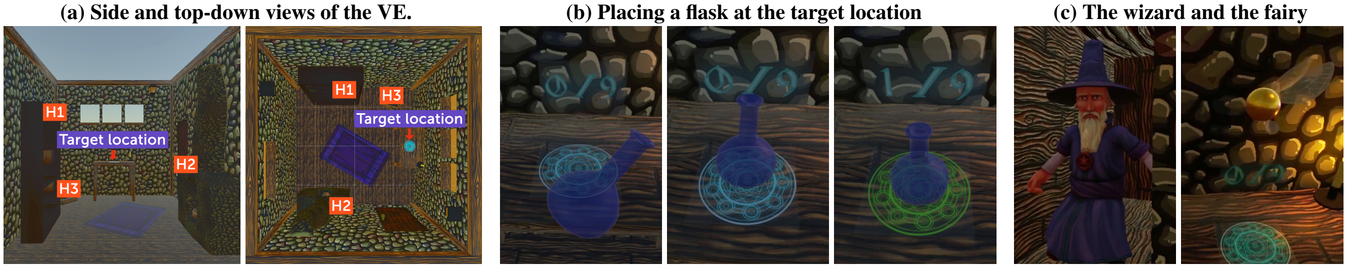

Figure 2: The virtual environment (a), a user placing a flask at the target location (b), and the two characters (c).

The three gripping techniques were implemented in Unity (version 2020.3.19f1) using the SteamVR API (version 2.7.3), which can translate the forces applied to the handle into a normalized value, denoted P.

Firm grip involves two states: released ($P = 0$) and firm grip ($P > 0$). During firm grip, the objects' rotation is locked to the movement of the controller on all 3 axes, regardless of how firmly the user grasps the controller.

Firm+loose grip involves three states: released ($P = 0$), firm grip ($P > 0.6$), and loose grip ($0 < P \leq 0.6$). During loose grip, the objects' rotation is affected by gravity, causing them to swing in response to hand movements, as if hanging from the controller.

Variable force grip involves a continuum of states ranging from released ($P = 0$) to firm grip ($P > 0.6$). That is, the objects are able to swing, but the angular velocity of the swinging is damped by the magnitude of the grip force. The damping was mapped linearly to P, so $P = 0$ would correspond to no damping and $P > 0.6$ would correspond to full damping (i.e., firm grip behavior).

For both *firm+loose grip* and *variable force grip*, the mapping became fixed when P exceeded a threshold 0.6, and the current angular offset between the controller and object was preserved when this threshold was exceeded. Both the threshold and the mapping were established during an informal user study involving six university students. Neither the controller nor the user's hand were visualized when grasping virtual objects, and all virtual objects were Florence flasks with predefined anchor points in their necks, which ensured that all flasks were grasped in the same way.

2.2 Participants

A total of 26 participants from the student body of Aalborg University Copenhagen were recruited. Their ages ranged from 19-28 years, all had normal or corrected-to-normal vision, were right-handed, and all gave written informed consent. In terms of prior VR experience, 6 participants (23%) had no experience, 10 (38%) had 1-10 hours of experience, 2 (8%) had 10-20 hours of experience, and 8 (31%) had more than 20 hours of experience.

2.3 Procedure and Task

Initially, the participants were informed about the broad aim of the study and introduced to the scenario and tasks, and then asked to give written informed consent and complete a questionnaire asking for demographic information. Subsequently, they were exposed to the three conditions, which all involved three steps: (1) First, the participants completed a training session asking them to move three objects using the current gripping technique. (2) Then they performed the study task, which was inspired by the original study by Bonfert et al. [1], and involved moving nine virtual objects to a target location. The nine objects were evenly distributed at three different locations at different heights; thus, requiring the participants to grab objects while reaching up, down, and forward. Figure 2a shows the location of the three objects (H1, H2, and H3) and the target. (3) Finally, the participants completed a questionnaire related to their experience of using each technique (see Subsection 2.5). The condition order was counterbalanced using a Latin square.

2.4 Scenario, Environment, and Equipment

The scenario and VE was designed with the aim of motivating the study task and explaining why the participants had to perform the task three times under varying conditions. Particularly, the participants assumed the role of a wizard's assistant who is tasked them with collecting Florence flasks that magically appear around the wizard's laboratory, and placing them at the target location on a table. A new flask appears whenever the previous one has been placed correctly (i.e., standing up) at the target location on the wizards magical table (Figure 2b). The scenario is introduced by the wizard, who explains that the participant has to perform the task three times because he is experimenting with different adjustments to the laws of physics. Before the actual task starts, the user is introduced to the new adjustments (i.e., the new gripping technique) by a fairy who guides the user while practicing. Figure 2c shows the wizard and the fairy, who provide narrative exposition and guidance throughout the experience. The 3D assets were modeled and textured using Blender (version 2.80), and the VE and scenario were produced using Unity (version 2020.3.19f1). To enable natural walking, the wizard's laboratory was made to fit within the tracking area of approximately 3×3 meters. The experience was run on a stationary PC with a NVIDIA GeForce RTX 2070 Super graphics card and was displayed using the *Valve Index*.

2.5 Measures

The three conditions were compared using self-reported measures of perceived realism, usability, and task load and two performance measures pertaining to the number of regrasps per object and task completion time. The self-reported measures comprised a questionnaire administered after exposure to each condition, and the performance data were logged during exposure.

Perceived realism and usability: To gauge *perceived realism* and *usability* we administered a questionnaire, which included six items inspired by the original work by Bonfert et al. [1]. The six items required the participants to rate the degree to which they agreed with presented statements on 5-point scales, where 1 indicated strong disagreement and 5 indicated strong agreement (Table 1). An item explicitly asked about how realistic the behavior of the grasped object was (Q1), and the remaining items related to intuitiveness, easiness, complexity, control, and comfort (Q2-Q5).

Table 1: Questions assessing perceived realism and usability.

Q1. Realism: The objects behaved realistically.
Q2. Intuitiveness: It felt intuitive to handle the objects.
Q3. Easiness: I thought this way of handling objects was easy.
Q4. Complexity: I found handling the objects unnecessarily complex.
Q5. Control: I was in full control of the objects.
Q6. Comfort: It was comfortable to handle the object.

Perceived task load: To evaluate participants' *perceived task load*, the NASA Raw Task Load Index (RTLX) [7] was administered after exposure to each condition. The RTLX is a variation of the NASA task load index (TLX) [6] comprising six items that require participants to rate the extent to which they experienced six dimensions of task load: mental demand, physical demand, temporal demand, performance, effort, and frustration. Each dimension was rated on 100-point scale with increments of 5 and the labels 'very low' and 'very high' at each extreme. As in the original work of Hart and Staveland [7], the scales did not include numerical values, but the values were assigned to each rating during data analysis.

Number of regrasps per object: *Firm grip* prevents users from changing their grasp, which may force them to release and regrasp objects to achieve a desired target orientation. *Firm+loose grip* should limit the need for regrasping, and *variable force grip* should offer users even greater ability to control the orientation of the grasped object. Thus, *firm+loose grip* and *variable force grip* should result in fewer regrasps. To determine whether this was the case, we logged the *number of regraps per object* (i.e., the number of regrasps performed from the object has been picked up until it is correctly placed at the target destination).

Task completion time: Finally, because *firm*, *firm+loose*, and *variable force grip* offer varying degrees of control, it seemed likely that they would differ in terms of efficiency. Therefore, to evaluate the efficiency of the three techniques, we logged task completion time during exposure to each condition (i.e., the total time from the beginning of each condition until all nine flasks were successfully relocated).

3 Results

Perceived realism and usability: The questionnaire items related to perceived realism and usability were individually analyzed using Friedman tests and pairwise comparisons were performed using Wilcoxon signed-rank tests with Bonferroni corrected alpha values ($\alpha = 0.017$). Figure 3a shows the corresponding results. Regarding *realism*, the Friedman test identified a statistically significant difference between scores, $\chi^2(2) = 7.378, p < 0.025$; and pairwise comparisons indicated that *variable force grip* (Mdn = 4) was significantly higher than *firm grip* (Mdn = 3), $p = 0.004$. No significant differences were found between *variable force grip* (Mdn = 4) and *firm+loose grip* (Mdn = 4), $p = 0.086$; and no significant difference was found between *firm+loose grip* (Mdn = 4) and *firm grip* (Mdn = 3), $p = 0.073$. The Friedman tests used to compare the remaining five items did not find any significant differences between scores: *intuitiveness* ($\chi^2(2) = 2.333, p = 0.311$), *easiness* ($\chi^2(2) = 1.143, p = 0.565$), *complexity* ($\chi^2(2) = 0.724, p = 0.696$), *control* ($\chi^2(2) = 1.481, p = 0.477$), and *comfort* ($\chi^2(2) = 1.853, p = 0.396$).

Perceived task load: To compare the perceived task load across the three conditions, we calculated the total RTLX score for each condition (i.e., the mean of the subscale ratings [6]). Figure 3b summarizes the results of the six subscales and the total scores (rightmost boxplots). The Shapiro-Wilk tests indicated that the assumption of normality was violated with respect to the total scores for *firm grip* ($p = 0.025$) and *variable force grip* ($p = 0.003$). Thus, the statistical comparison was performed using a Friedman test. The test did not identify a statistically significant difference between total scores, $\chi^2(2) = 5.780, p = .056$.

Task completion time: Figure 4a shows the results pertaining to *task completion time* for the three conditions across the three object heights. Shapiro-Wilk's tests indicated that normality could not be assumed with respect to *firm grip* at *height 1* ($p < .001$) and *height 2* ($p = .010$), *firm+loose grip* at *height 2* ($p < .001$), and *variable force grip* at *height 3* ($p = .019$). Thus, instead of analyzing all data using a two-way repeated measures ANOVA, we compared the three conditions at each height separately using Friedman tests and pairwise comparisons were performed using Wilcoxon signed-rank tests with Bonferroni corrected alphas ($\alpha = 0.017$).

With respect to *height 1*, the Friedman test indicated that task completion times differed significantly between conditions, $\chi^2(2) =$

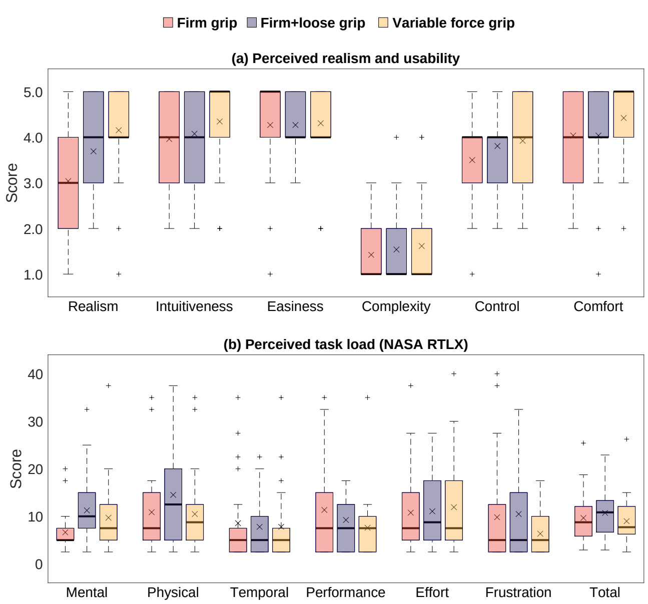

Figure 3: Boxplots visualizing results pertaining to (a) perceived realism and usability and (b) perceived task load in terms of medians (-), means (x), interquartile ranges, minimum and maximum ratings, and outliers (+).

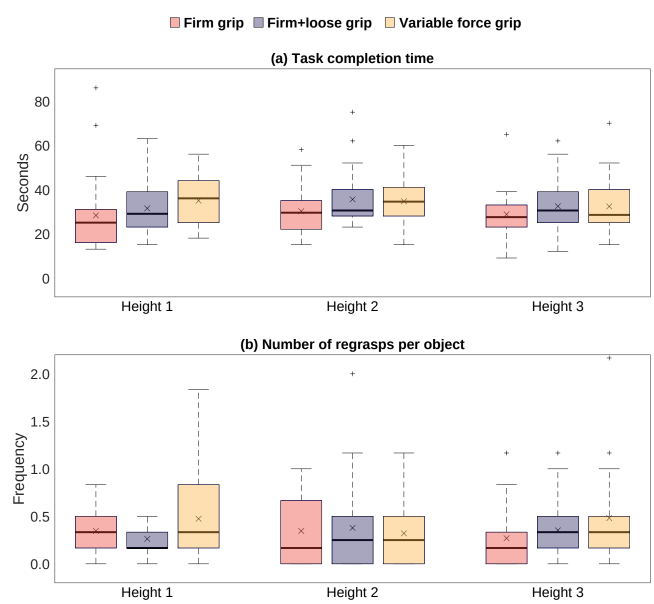

Figure 4: Boxplots visualizing results pertaining to (a) task completion time and (b) number of regraps per object, in terms of medians (-), means (x), interquartile ranges, minimum and maximum ratings, and outliers (+).

$7.901, p = 0.019$. However, pairwise comparisons did not find any significant differences. That is, *firm grip* (Mdn = 28 s.) and *firm+loose grip* (Mdn = 31 s.), $p = 0.276$; *firm grip* (Mdn = 28 s.) did not differ significantly from *variable force grip* (Mdn = 36 s.), $p = 0.028$; and *firm+loose grip* (Mdn = 31 s.) did not differ significantly from *variable force grip* (Mdn = 36 s.), $p = 0.230$.

With respect to *height 2*, the Friedman test found a significant difference between completion times $\chi^2(2) = 8.747, p = 0.013$. However, the pairwise comparisons found no significant differences between *firm grip* (Mdn = 30 s.) and *firm+loose grip* (Mdn = 31 s.) $p = 0.043$; between *firm grip* (Mdn = 30 s.) and *variable force grip* (Mdn = 35 s.), $p = 0.035$; or between *firm+loose grip* (Mdn = 31 s.) and *variable force grip* (Mdn = 35 s.), $p = 1.000$.

Finally, no significant difference between conditions was found for *height 3*, $\chi^2(2) = 1.196, p = 0.550$.

Number of regrasps per object: Figure 4b shows the results pertaining to *number of regrasps per object* for the three conditions across the three object heights. Shapiro-Wilk's tests indicated that the assumption of normality was violated with respect to all three conditions at all three heights. Thus, these data were also analyzed by applied Friedman tests separately for each height. However, the tests indicated that the three conditions did not differ significantly: *height 1* ($\chi^2(2) = 3.089, p = 0.213$), *height 2* ($\chi^2(2) = 0.270, p = 0.874$), and *height 3* ($\chi^2(2) = 1.826, p = 0.401$).

4 Discussion and Limitations

Judging by the distributions of scores (Figure 3a), *variable force grip* was considered the most realistic by a majority of participants, and these scores were significantly higher than *firm grip*. This indicates that the ability to interact by varying grip firmness can make the behavior of grasped objects seem more realistic. This finding is in line with the original work by Bonfert et al. [1] who found that techniques involving variable grip were perceived as more realistic.

The three gripping techniques were positively rated with respect to the five usability items, and no significant differences were found between conditions. That is, they were perceived as intuitive, easy, and comfortable to use; the interaction was not perceived as complex; and the participants felt that they were in full control when manipulating the virtual objects. The absence of statistically significant differences does not permit us to conclude that the three techniques are equivalent with respect to usability. Indeed, Bonfert et al. [1], found that techniques involving variable grip were generally rated the highest in terms of usability. It is possible to offer at least two explanations for this discrepancy.

First, in the current study participants had to move 9 objects per condition, while Bonfert et al. [1] required participants to move 60 objects per condition. In other words, it is possible that the difference can be attributed to varying levels of acclimatisation or fatigue between the two studies. We limited the number of objects per condition to reduce fatigue, but future studies involving more objects are needed to determine if this influenced experimental validity.

Second, it is worth noting the very high scores pertaining to easiness and and the high scores related to complexity. These may suggest that the task produced a ceiling effect with respect to the former and a floor effect with respect to the latter.

Taken together, this suggests that future studies involving different scenarios and tasks are needed to determine if the lack of difference in self-reported usability can be attributed to the use of the Knuckles controllers or methodological differences between the current study and the one performed by Bonfert et al. [1]. Moreover, future studies should involve measures of positioning accuracy to provide additional grounds for comparison with previous work. Notably, with respect to perceived task load, the current findings support the work of Bonfert et al. [1], as both studies did not identify any significant differences between conditions in terms of RTLX scores.

Regarding task completion time, we found significant differences between gripping techniques for two of the three object heights; namely, H1 requiring participants to reach upwards and H2, which did not require them to reach down or up (Figure 2a). The distribution of the data (Figure 4a) seemingly indicate that *variable force grip* yielded the slowest completion times for the two heights. However, pairwise comparisons did not reveal any significant differences between conditions. Notably, the original study by Bonfert et al. [1] yielded results that corroborate the current findings. That is, their results indicated that firm grip was significantly faster than the two conditions involving variable grip included in their study.

We found no significant difference between the conditions with respect to the number of regrasps per object across the three heights. Nevertheless, it is worth noting that the number of regrasps per object was low for all gripping techniques across all three heights (i.e., as apparent from Figure 4b, all medians are lower than 0.5). It seems possible that a larger number of regraps will be necessary when target locations are harder to reach, especially when using *firm grip*. Thus, future work should explore the need for regrasping during scenarios with target locations at varying heights and accessibility.

Moreover, it is relevant for future work to directly compare how variable grip is experienced when interacting using the Knuckles, as in the current study, and when interacting using the HTC Vive controller, which was used in the original work of Bonfert et al. [1]. Furthermore, it is relevant to explore variable grip in combination with controllers that provide haptic feedback related to the material properties of virtual objects. For example, recent work by Stellmacher et al. [15] showed that variable trigger resistance can affect weight perception, and it would be interesting to include such controllers in future studies. Finally, work by Li et al. [9] indicates that grip postures can affect task completion time, precision, and fatigue, when performing selection tasks using a pen-style controller. Considering that variable grip allows users to change their grip in a related manner, it is interesting for future studies to explore how different grips influence users' performance and experience on similar tasks.

5 Conclusion

Many VR applications rely on consumer-grade VR controllers to enable such hand-based interaction with virtual objects. The current work extended the controller-based technique variable grip [1] by allowing users to manipulate objects based on the grip forces detected by the Knuckles controller, and a user study provided preliminary evidence suggesting that the extra degree of interactivity may increase perceived realism, although possibly at the expense of efficiency. In addition to supporting some of the findings reported by Bonfert et al. [1], these results suggest that variable grip may also be useful when relying on VR controllers that can detect grip forces, such as the Knuckles. However, future studies are needed to determine whether the ability to control variable grip based on the firmness of users' grip provides more realistic experiences and better performance than interaction based on the triggers and buttons that are featured on most VR controllers.

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