WeightMorphy: A Dynamic Weight-Shifting Method to Enhance the Virtual Experience with Body Deformation

Naoki Okamoto
naoki.okamoto@star.rcast.u-tokyo.ac.jp
The University of Tokyo
Tokyo, Japan

Masaharu Hirose
hirose@star.rcast.u-tokyo.ac.jp
The University of Tokyo
Tokyo, Japan

Sohei Wakisaka
wakisaka@kmd.keio.ac.jp
Keio University
Kanagawa, Japan

Hiroto Saito
hiroto.saito@star.rcast.u-tokyo.ac.jp
The University of Tokyo
Tokyo, Japan

Atsushi Izumihara
izumihara@star.rcast.u-tokyo.ac.jp
The University of Tokyo
Tokyo, Japan

Masahiko Inami
drinami@star.rcast.u-tokyo.ac.jp
The University of Tokyo
Tokyo, Japan

Figure 1: WeightMorphy is a hand-mounted VR controller designed to provide passive haptic feedback by changing the moment of inertia. It allows for comfortable manipulation of virtual or tele-bodies with various hand shapes.

ABSTRACT

We propose WeightMorphy, a hand-mounted system designed to improve teleoperation manipulation's operability and immersive experience by changing the moment of inertia. This system reduces the discrepancy between the shape of the virtual hand and its corresponding moment of inertia, enabling instantaneous control by the user while maintaining accuracy. We have provided a detailed description of the design and concept of our system and conducted experiments to examine the effect of shifting the center of gravity on the operability of the deformable virtual hand using WeightMorphy.

CCS CONCEPTS

• **Computer systems organization** → *Robotics*; • **Human-centered computing** → **Interaction devices**.

KEYWORDS

Haptics, Robotics, Hardware, Telepresence, UI/Tools, VR/AR/MR

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1 INTRODUCTION

Teleoperation/tele-existence systems enable users to perform physical work remotely and share tasks with operating robots [9, 22]. Recent advancements include collaborative work between autonomous and manually controlled remote robots [20] and continuous manipulation switching between multiple remote robots by one operator [10]. Izumihara et al. proposed a teleoperation system where the user's body size changes to extend operability and optimize accuracy and control range for the robotic hand.

However, controlling a robotic hand becomes challenging when there are significant shape differences between the robotic hand and the user's hand or when the robotic hand's shape changes over time. This issue is encountered in teleoperation systems and virtual environments with changing user body shapes and tasks involving frequent tool changes [15, 17]. While various haptic feedback methods have been proposed to enhance operability, relying solely on haptic feedback has limited effectiveness [2, 12–14]. Achieving instant embodiment, where the user controls the robotic hand as if it were their own body, becomes crucial in teleoperation systems with complex situations requiring smooth and accurate manipulation.

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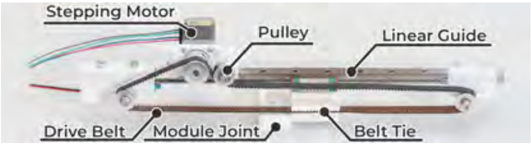

Figure 2: The structure of the slider part of our device.

We propose WeightMorphy, a system enabling teleoperated users to align the visual form of a robotic or virtual hand with the felt moment of inertia in the hand. By adjusting the weight (slider) based on the robotic hand shape, we control the Form and moment of Inertia Consistency (FIC). We hypothesize that improving FIC enables a virtual or robotic hand to be handled as if it were one's own body. We conducted experiments to validate the system's effectiveness in enhancing operability and present its details, experimental results, and potential for further development.

2 RELATED WORK

Research on methods for accurate object manipulation has been conducted in various fields. Sensory feedback is a popular technique for improving the accuracy [2, 12–14]. While studies on avatar manipulation in virtual environments have demonstrated collision reduction with obstacles through passive haptic feedback [8] and realistic representation of the user's avatar [18], there is currently no example of FIC to enhance operability, explicitly focusing on robotic hands. Weight-shifting for grasping objects and handheld tools has been explored in previous research. Fujinawa et al. demonstrated blind object recognition control through weight-shifting [4]. Zenner et al. focused on improving FIC of grasped virtual tools through weight-shifting to enhance reality and pleasure [24]. Studies have suggested increasing the dimension of weight shift [19, 21], exploring weight shift in other body locations [16], and presenting weight sensation through the air [23]. Hirose et al. proposed a flavor-changing system with FIC control [6, 7], highlighting the link between FIC and human perception. In this study, we apply FIC to enhance the operability of a remote manipulator. By adjusting FIC during manipulation, we can impact the perception of the center of gravity and immersion and the manipulator's operability. This direction opens up new possibilities for FIC research.

3 SYSTEM DESIGN

We present the WeightMorphy system, designed for use with a head-mounted display (HMD), which adjusts the perceived center of gravity based on virtual hand shape (Figure 1). The system includes a slider part, a hand-wear part, a multi-function button for basic operations, and a Vive tracker, allowing the center of gravity adjustments using stepping motors(Figure 2). WeightMorphy is attached to the back of fingers so that the hand itself does not grab anything. Note that our system's target is a hand deformation, not a deformation of tools grabbed by the hand. By utilizing an actuator and a slider instead of weights, the device achieves a moving weight: total weight ratio of 63% (76% without the Vive tracker), surpassing previous studies' ratios (Shifty: 29%, Transcalibur: 36%) while keeping the total weight largely unchanged. [21, 24].

The slider (weight) moves based on the deformation of the virtual hand in VR space or the robotic hand viewed in a remote camera to improve FIC (Figure 3). We believe that this could improve operability.

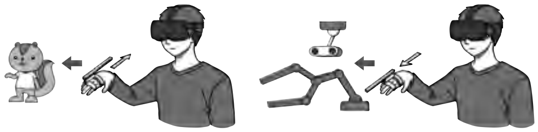

Figure 3: WeightMorphy Concept. The slider shifts backward (left) when controlling a small cartoon character-like virtual hand, and it shifts forward (right) when controlling a large robotic hand.

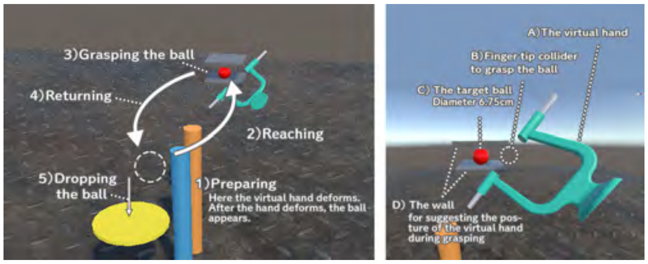

Figure 4: The screen captures of the experiment scene: Overhead view (left), participant's point of view (right)

4 EXPERIMENT

We experimented using a ball-picking task to evaluate the effect of weight-shifting on the operability of a deformable virtual hand. Participants' hands changed to a deformable U-shaped grasper (i.e., short or long). Figure 4 shows the details of the experiment. The task was to grasp a ball that appeared in virtual space at a predetermined location in front of them. We compared three weight-shifting conditions (Fake, Floating, Grounded) with different levels of FIC, described in the Condition section (Figure 5 top). By comparing task performance for each condition, we evaluated the effect of FIC. The experiment lasted approximately 70-80 minutes for each participant.

4.1 Participants and Conditions

Twelve volunteers (six female; aged between 21 and 40; one left-handed) participated in the experiment. All had normal or corrected-to-normal vision and previous experience with immersive VR.

We introduced two virtual hand-shape conditions and three weight-shifting conditions (2x3 factorial design), as shown in Figure 5 (top). The two types of virtual hand-shape conditions(U-shaped grasper length and target ball distance from the body) are as follows:

(1) *ShortHand*: Grasper length: 20 cm, ball distance: 40 cm.
(2) *LongHand*: Grasper length: 55 cm, ball distance: 75 cm.

Each session includes 12 randomized trials (6 ShortHand and 6 LongHand conditions). Ball locations were slightly changed for each trial in two predetermined areas for short hand and long hand. At the beginning of each trial, one of the three weight-shifting conditions described below was set. The experiment comprised 21 sessions (7 sessions for each condition) with randomized order (Figure 5 bottom).

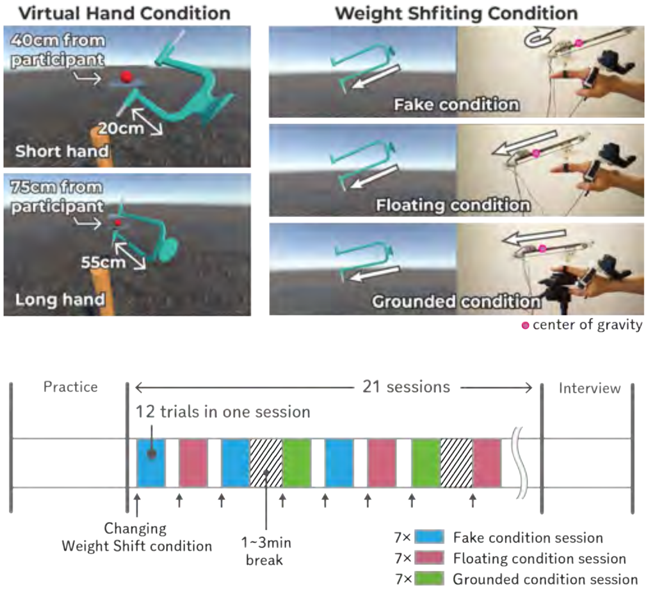

Figure 5: Two-way factors of the experiment (top). The procedure of the experiment (bottom).

1. *Fake*: Participants kept their hands still in the air during virtual hand deformation. The slider remained in its initial position, irrespective of the virtual hand's shape (e.g., Long-Hand condition lacked FIC).
2. *Floating*: The slider shifted with virtual hand deformation to improve FIC. The hand was floating, similar to the Fake condition. The figure shows the Long condition, but FIC is also maintained in the Short condition.
3. *Grounded*: This condition aimed to correspond to FIC by shifting the slider. Participants placed their hands on the wrist rest during hand deformation to prevent feeling weight-shifting. In the pilot study, we assumed the weight shift perception resulted from the wrist's somatosensory perception.

In the Fake condition, the slider was moved forth and back during the deformation of the virtual hand to prevent participants from noticing any difference in the hand change caused by the motor's vibration. Preliminary testing confirmed this. To investigate the effect of perceiving the movement of the center of gravity, we set the two conditions during the deformation (i.e., Grounded and Floating).

4.2 Procedure

Figure 5 (bottom) shows the experiment's procedure. During the practice session, participants were introduced to the experiment and familiarized with the HMD (Valve Index) and virtual environment. The movement of the slider between trials was mentioned, but the specifics were revealed during the interview session.

Participants were instructed to grasp the ball quickly and accurately by pressing the multi-function button and dropping it at a predetermined location (Figure 4 left). When the participant grabbed the ball, it snapped to the center of the fingertip collider (Figure 4 right). Non-collider walls were placed above and below the ball to suggest the posture of the virtual hand when participants grasped the ball.

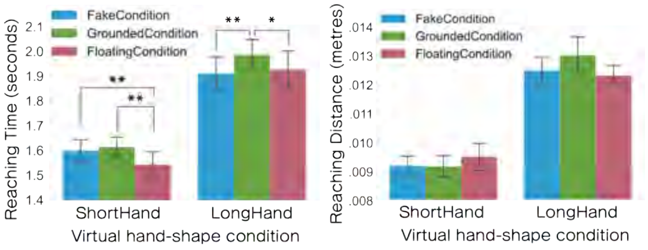

Figure 6: Reaching Time (left) and Reaching Distance (right). Error bars indicate the standard error. $^{*}p < .05, ^{**}p < .01$.

4.3 Analysis

For task performance evaluation, we measured the elapsed time between target appearance and grabbing except for the time of virtual hand deformation (Reaching Time) and the distance between the center of the fingertip collider and the ball at grab before snapping (Reaching Distance) in each session. We analyzed the means of Reaching Time and Reaching Distance using two-way repeated measures ANOVA. Post hoc pairwise comparisons were conducted using Shaffer's modified sequentially rejective Bonferroni procedure for weight-shifting conditions with significant interaction and simple main effects at the virtual hand-shape condition.

4.4 Results

Figure 6 shows the experiment results. First, we analyzed Reaching Time(Figure 6 left). We conducted a normality test using the Shapiro-Wilk method for a total of six conditions and confirmed that the normality was observed in all conditions ($p > .05$). Furthermore, we conducted a two-factor analysis of variance for the within-subjects design at a significance level of 5%. The result revealed a main effect of target ($F(1, 11) = 161.17, p < .001, \eta_G^2 = .4531$) and weight-shifting condition ($F(2, 22) = 6.52, p = .006, \eta_G^2 = .0195$) and an interaction ($F(2, 22) = 11.60, p = .0004, \eta_G^2 = .0064$). Since the simple main effect of weight-shifting was confirmed at both virtual hand conditions, pairwise comparisons of weight-shifting conditions at each virtual hand level were performed. For the ShortHand condition, a significant difference was determined between Fake and Floating conditions (Fake > Floating, $p = .0075$) and between Grounded and Floating conditions (Grounded > Floating, $p = .0094$). For the LondHand condition, there was a significant difference between Fake and Grounded conditions (Fake < Grounded, $p = .0081$) and between Grounded and Floating conditions(Grounded > Floating, $p = .0332$).

We analyzed Reaching Distance similarly (Figure 6 right). We conducted a test utilizing the Shapiro-Wilk method and identified normality in all conditions ($p > .05$). In the two-factor analysis of variance, only the main effect of the target ($F(1, 11) = 64.63$, $p < .001, \eta_G^2 = .5334$) could be identified, while the weight-shifting condition ($F(2, 22) = .62, p = .5475, \eta_G^2 = .0049$) and the interaction ($F(2, 22) = 2.61, p = .096, \eta_G^2 = .0188$) could not be identified. This result suggests that, in our experimental conditions, there was no significant difference in accuracy (Reaching Distance), while

Figure 7: Example application: Users can perform demolition tasks on a dynamic scale, freely switching between large and small bodies.

the speed of operation (Reaching Time) was faster when FIC was improved.

4.5 Discussion

We hypothesized that the Floating and Grounded conditions would result in shorter Reaching Times and distances than the Fake condition. The experimental results showed no significant difference in Reaching Distance among the three conditions, and only the ShortHand condition showed a significantly shorter Reaching Time. Post-experimental interviews indicated a potential for improved operability through dynamic and relative FIC, although a large load due on the hand may hinder operability in the Long condition. Additionally, some participants mentioned delayed response due to the hand being placed on the wrist rest in the grounded condition, suggesting the need for future experimental design revisions. Ten participants expressed comfort (or discomfort in the Fake & Long conditions) with the center of gravity shift, supporting previous findings. Six participants found the operation more manageable, and four reported an improved sense of ownership, suggesting FIC contributes to embodiment. Moreover, five subjects reported a sensation of finger extension or contraction accompanying the center of gravity during deformation, highlighting the importance of dynamic/relative FIC for embodiment and improved operability. However, ten participants reported fatigue and two experienced challenges with Long in the floating/grounded condition. These feedbacks align with the experimental results, which showed significant differences only in Reaching Time in the Short condition. Further research is needed to understand the conditions that induce cross-modal effects of visual deformation and weight shift for dynamic and relative FIC.

5 EXAMPLE APPLICATION

We developed a car demolition simulation application in which users perform relative shape changes of their hands (Figure 7). They disassemble a car using a single virtual robotic hand while freely expanding and contracting their body. This interaction allows the user to manipulate large objects over a wide area and to control small objects with a single robotic hand precisely. The weight shifts according to the relative size of the robotic hand, maintaining operability. While a detailed application evaluation is required, several users have voluntarily reported consistent embodiment across multiple bodies of varying sizes.

6 LIMITATION AND FUTURE WORK

This study has demonstrated that improving FIC is a factor in enhancing operability. However, the psychological impact of improved FIC on users and the development potential of the proposed device remains unexplored.

6.1 The Psychological impact of improving FIC

We propose two future directions to address this limitation. First, prior research has shown that the abstraction of the self-avatar's appearance and haptic feedback contributes to embodiment and collision avoidance with walls [5, 18]. Moreover, studies have demonstrated that motor learning in embodied VR is comparable to physical tasks [1]. By investigating the impact of our proposed system on these psychological effects, we can explore new feedback approaches. Secondly, we will focus on habituation. People can adapt to different tools and bodies of various sizes and shapes [3, 11, 15]. However, adapting to a robotic hand that deforms discontinuously may not be immediately feasible. Examining the relationship between shape changes of the robotic hand and embodiment over time can optimize the system's effectiveness in FIC mismatch and habituation.

6.2 Development potential of the proposed device.

We proposed a one-dimensional weight-shifting device for a single hand. However, its weight hinders the effectiveness of improving FIC in the experiments. Exploring alternative tracking systems like Leap Motion, Vicon, or OptiTrack and considering 3D printing a PLA rack could reduce weight and enhance operability. Future advancements include developing a multidimensional weight-shifting device[19, 21] and applying weight-shifting to different body parts like each finger, arm, leg, and back[16] for increased operability and a unique sensation of walking with a giant or tiny body.

7 CONCLUSIONS

This study reduced the deterioration of operability caused by deforming the virtual hand by improving the Form and moment of Inertia Consistency (FIC) using our proposed hand-mounted weight-shifting VR controller, WeightMorphy. The experiments showed that task performance improved under certain weight-shifting conditions. Furthermore, we outlined future research directions and proposed an application of WeightMorphy involving relative hand deformation.

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