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Learning of Dexterous Object Manipulation in a Virtual Reality Environment

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Abstract— **Humans have unrivalled abilities to perform dexterous object manipulation. This requires the sensorimotor system to quickly adapt to environmental changes and predictively counter act the external disturbances. Many studies have focused on the anticipatory control of digits with real-world experiments. However, examining manipulation using virtual reality with haptic devices expands the possibilities of investigation. In this work, participants grasped and lifted an inverted T-shaped object in a virtual reality setup. The graspable surface of the object was either constrained to a small area or unconstrained. The position of the object's center of mass changed between blocks, and the participants were asked to minimize the rotation of the object during the lift. Our results show that, consistent with the results of real-world experiments, participants gradually learn to adjust the digit positions and forces to predictively compensate for the torque due to the shifted center of mass prior to liftoff. The only major difference found was that the length of trials needed during the adaptation phase to each condition increased from 3 in real-world to 5 in virtual environment.**

I. INTRODUCTION

Dexterous object manipulation is a complex action. To achieve this, humans need to prepare for the manipulation prior to the physical contact, based on both the current visual information [1] and the representation of the object dynamics generated from previous sensorimotor interactions with the object [2], [3], [4]. When lifting a visually symmetric inverted T-shaped object, which has a concealed asymmetric center of mass (CoM), digit force and position need to be modulated in an anticipatory way in order to generate a compensatory torque that counteracts the torque generated by the CoM [5], [6], [8], [9]. Previous studies have shown that it takes only three trials to successfully minimize object roll while lifting the object [8].

Virtual Reality (VR) is a promising tool that offers more possibilities for experimenting with human sensorimotor control. Despite the widespread attention and rapid development of VR technology, it is still far from being able to accurately reproduce object interaction in the real world. Here, we develop a VR-based experimental environment to study dexterous object manipulation. The VR environment was simulated in 3D but shown on a 2D monitor. Subjects receive force feedback generated by haptic devices, but without tactile feedback. In [7] we showed that participants adapted their grip forces to the object mass. In this study, participants grasped and lifted a virtual inverted T-shaped object with and without constraints on digit placement. We expected the participants to adjust both digit placement and forces for the unconstrained object, while mainly adjust digit forces for the constrained object. By comparing with the real-world experiments [8], we can verify if the subjects' performance and learning process in the virtual environment is consistent with real-world object manipulation. Our results show that participants were able to learn to modulate the digit positions and forces in a similar manner as in the real world, but that the trial-by-trial adaptation takes longer. We propose that this may be due to the reduced sensorimotor feedback.

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II. MATERIALS AND METHODS

A. Subjects

Eight neurologically healthy, right-handed [10] human participants (23-32 years of age, 5 women) participated in both of two experiments. All participants were naive to the purpose of this study and provided written informed consent before participation. The study was approved by the institutional ethics committee at the Technical University of Munich.

B. Experimental apparatus

Participants were asked to reach towards, grasp and lift an inverted T-shaped object in VR. Two haptic devices (Phantom Touch; 3D SYSTEMS) were used in this experiment to create haptic feedback. The tips of the participants' thumb and index finger were attached to the haptic devices via a custom designed thimble (Fig. 1A) and secured with tape. The devices were calibrated such that the cursors in VR matched the position of the fingertips. The VR environment was rendered by Chai3D [11] and Open Dynamics Engine libraries [12]. Data in the VR environment, such as position of the cursors and the object and interaction forces, were sampled at 500 Hz. The visual feedback was projected via a monitor oriented at 45 degrees and reflected by a horizontal mirror such that direct visual feedback of the hand was prevented.

Participants needed to grasp the object on the left and right surface. There were two inverted T-shaped objects and the only difference was the dimension of the graspable surfaces. Specifically, the height of the graspable surface was 70 mm on the unconstrained object (Fig. 1B) and 20 mm on the

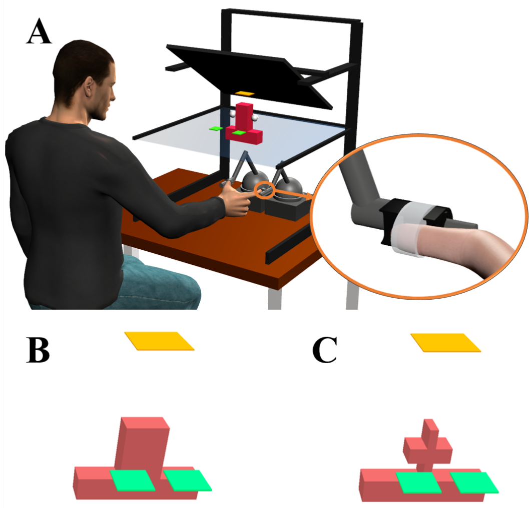

Fig. 1. Experimental setup. A, The experimental setup with two haptic devices connected to the thumb and index finger of the subject's right hand. Visual feedback is provided via a monitor oriented at 45 degrees and reflected by a horizontal mirror to the participant such that it appears in the hand workspace. B, The VR environment with the unconstrained inverted T-shaped object colored in red. Participants start each trial by placing the cursors on the start position colored in green and then grasp and lift the object to the height of the reference plane colored in orange. C, The constrained inverted T-shaped object.

constrained object (Fig. 1C). The depth of this graspable area was 30 mm and the horizontal distance between the two graspable surfaces was 50 mm for both objects. Participants were free to choose where to place the cursors on the graspable surfaces.

The object was represented as a rigid object with uniform mass distribution of 50 g. An external gravity of 1.5 N was applied on the object at the left, middle left, center, middle right or right along the bar at the bottom of the object. This caused a change in the CoM and an external torque of 75, 37.5, 0, -37.5 and -75 N·mm, respectively.

C. Experimental paradigm

At the beginning of each trial, the cursors were required to be placed on the two start positions, which were placed 8 cm in front of the object. After a beep, participants were then required to reach towards and grasp the object and then lift it up by 10 cm to the height of the reference plane and hold for 1 s. After a second beep, participants should release the object and return to the start position. The object was then automatically replaced at the original location. Participants were instructed to move at a natural speed and to keep the vertical axis of the object upright, i.e. to minimize object roll. Participants were asked to grasp using only their thumb and index finger while preventing contact between the other three fingers and the haptic devices.

All participants participated in two experiments: one with the unconstrained and one with the constrained object. The experiment order was counterbalanced across all participants. Each experiment consisted of 5 blocks of 20 trials. Each block had a different CoM and the order was pseudo-randomized and counterbalanced across all participants. Participants could not anticipate the CoM before the first trial of each block, but they were aware that the CoM would remain the same for the entire block. There was a 5 minute break between the two experiments.

There were 60 practice trials before the first experiment and 3 before the second experiment. The practice trials used the same object as the experiments and the external gravity was always added at the center of the object. The practice trials allowed participants to get familiar with the VR environment and the task.

D. Data Analysis

After data collection, the force and kinematic data were low-pass filtered with a tenth-order, zero-phase-lag Butterworth filter with 20 Hz cutoff frequency. The following values were computed: (1) grip force was defined as the normal component of the digit force with respect to the graspable surfaces; (2) load force was defined as the digit force component in line with the orientation of the object; (3) object roll was defined as the angle between the gravity vector and the vertical axis of the object within the frontal plane of the object. Positive and negative values denote counterclockwise and clockwise rolls; (4) compensatory torque was defined as the normal component of the torque caused by the subject with respect to the frontal plane of the object. It was calculated relative to the midpoint of the two fingertips. (5) object lift onset was defined as the time at which the vertical position of the object crossed 0.5 mm and remained for at least 400 ms. The participants could not yet perceive the external torque at this time, so the control at lift onset could only be anticipated. (6) the difference in vertical position between of the thumb and index finger (d_z). (7) the difference in load force between the thumb and index finger (d_{LF})

III. RESULTS

Participants learned to control the maximum roll of the objects within 5 trials (Fig. 2). After these initial trials with each object, the maximum roll varied within a similar range for different objects and CoM conditions. However, the left and right conditions of the constrained object showed slightly larger maximum roll than all other conditions suggesting that participants may have found these conditions most difficult to control.

In order to minimize object roll, participants needed to learn to generate a compensatory torque of the same magnitude and the opposite direction as the external torque caused by the external gravity. After several initial trials, participants should be able to build the representation of the object dynamics, anticipate the external torque and modulate digit positions and forces before the physical contact. Fig. 3 shows the compensatory torque generated at lift onset averaged across all participants as a function of trial for the unconstrained and constrained objects.

Since the external torque was unknown before each block, participants only exerted little torque on the first

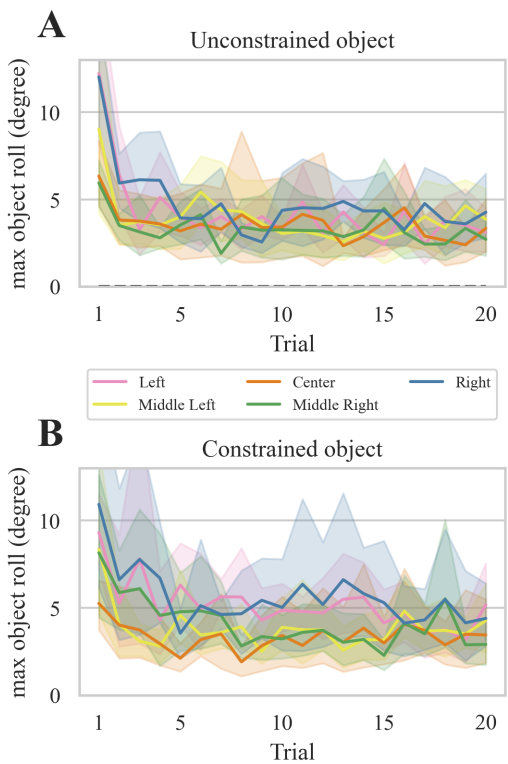

Fig. 2. The max object roll for the unconstrained (A) and constrained (B) objects averaged across all participants. The shaded region shows the 95% confidence interval of each condition.

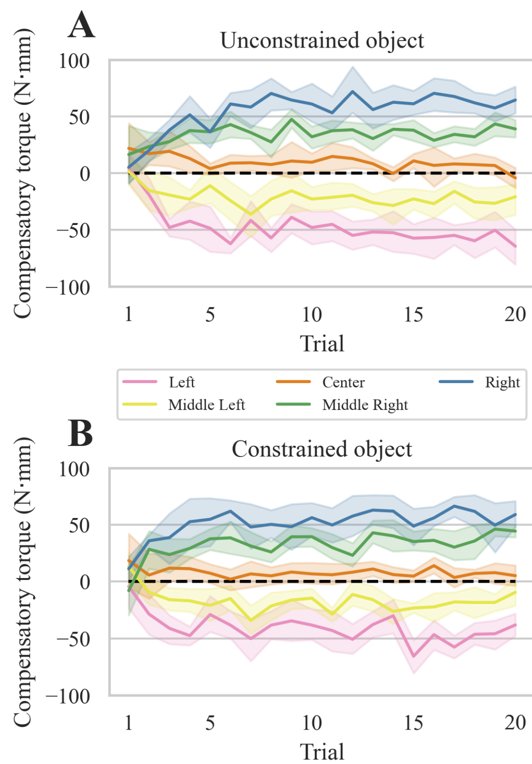

Fig. 3. Learning of the anticipatory compensatory torque for the unconstrained (A) and constrained (B) objects. Each line represents the mean across all participants and the shaded region shows the 95% confidence interval.

trial. However, over the subsequent trials the compensatory torque approached the level of the external torque. The mean compensatory torque of each object and CoM were fit by an exponential curve. The mean time constant across participants and conditions was 1.31±0.44 (mean±std) trials and was similar for both objects. In contrast to the 3 trials reported in the real-world experiment, participants needed about 5 trials to learn to adjust the compensatory torque in VR when the CoM is not in the center. After these initial trials, the compensatory torque remained stable.

Although the rate of adaptation to changes in the CoM was similar for the two objects, the compensatory torque was generated in different ways. Fig. 4 shows the change of d_z across trials for different CoM conditions. For the unconstrained object, participants adjusted d_z in a wide range according to the external torque. For the constrained object, although d_z was restricted to the graspable plane (20 mm), participants still adjusted d_z within this range. Note that for both objects, the magnitude of d_z was smaller when CoM was middle left or middle right, compared with when CoM was left or right.

The final level performance was examined using the mean compensatory torque, digit placement and forces across trials 10-20 (Fig. 5). The compensatory torque remained stable at -52.9±22.1, -22.7±18.4, 36.6±13.3 and 62.6±21.0 N·mm (mean±std) for the unconstrained object and at -44.6±22.2, -18.6±15.5, 37.0±16.5 and 56.6±15.5 N·mm for the constrained object (left, middle left, middle right and right CoM, respectively) (Fig. 5A). The compensatory torque plateaued at about 78.0% and 70.8% of the external torque, for the unconstrained and constrained objects respectively. In the real-world experiment, the compensatory torque at lift onset was about 70% of the external torque [8]. Note that participants were better able to compensate for the external torque when CoM was on the right or middle right compared to when it was on the left or middle left.

Participants showed clearly different strategies in generating the compensatory torque for the two objects. For the unconstrained object, participants were free to adjust digit positions and forces. The results demonstrate that they relied primarily on changes in the digit placement such that d_{LF} only varied in a small range (See Fig. 5B and C). For the constrained object d_z changed with a similar trend but within a much smaller range, and the compensatory torque was generated mainly by changes in d_{LF}. In both cases, the amplitude of d_z was generally larger when CoM was to the left than when it was to the right.

Moreover, consistent with real-world experimental results, the average grip force was higher for the constrained object than the unconstrained object (Fig. 5D).

IV. DISCUSSION

Our work shows that participants were able to form representations of the object dynamics, and modulate the

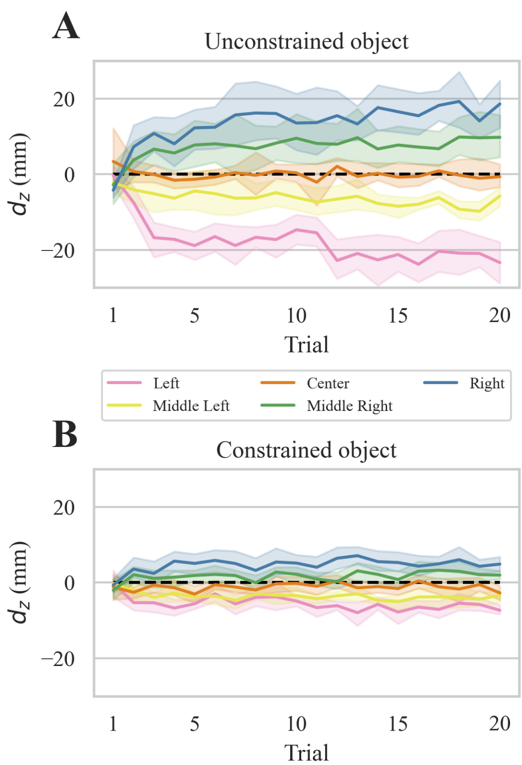

Fig. 4. Learning of anticipatory digit placement for the unconstrained (A) and constrained (B) objects. d_z varied proportionally to the external torque for both objects, but the range was smaller for the constrained object.

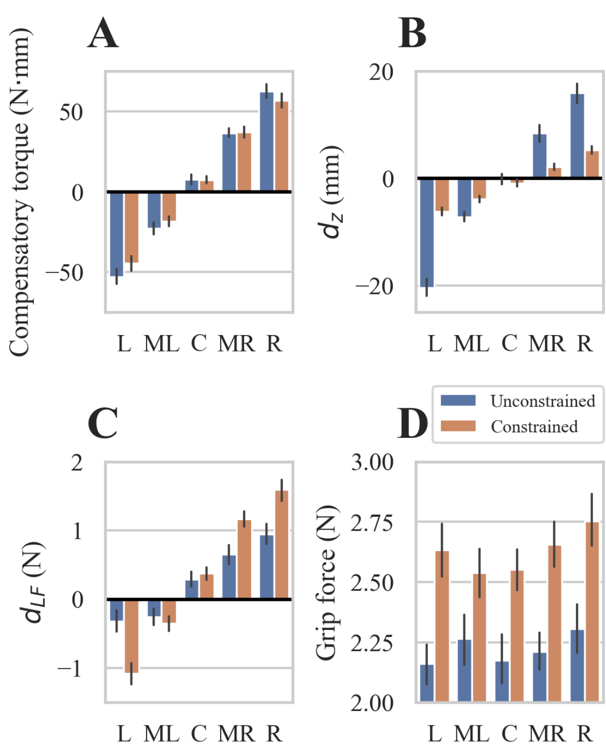

Fig. 5. Compensatory torque, digit placement and forces averaged across trials 10-20. Error bars represent 95% confidence intervals. L, ML, C, MR, R denote the left, middle left, center, middle right, right conditions, respectively.

digit positions and forces in VR in an anticipatory way. When the object was unconstrained, participants tended to generate compensatory torque by adjusting the digit positions and forces at the same time. However, when the object was constrained, participants still adjusted the digit positions within the small graspable surface, but primarily generated similar compensatory torque by modulating digit forces. Overall the performance in the virtual environment is very similar to that in the real-world [8], showing all of the same changes in grip forces and digit placement. Participants were able to predictively generate 70%-78% of the external torque which corresponds well to the 70% seen in real world inverted T-shaped objects [8]. The most obvious difference in VR experiments compared to real-world experiments is that participants needed more trials to adapt to each condition. This may be due to the reduced sensorimotor feedback in VR, particularly the lack of tactile information. In conclusion, participants have very similar performance in VR and real-world. This lays the foundation for us to conduct many experiments that are difficult to realize in real-life through VR in the future.

References

[1] I. Salimi, W. Frazier, R. Reilmann, and A. M. Gordon, "Selective use of visual information signaling objects' center of mass for anticipatory control of manipulative fingertip forces," Exp Brain Res, vol. 150, no. 1, pp. 9-18, May 2003, doi: 10.1007/s00221-003-1394-8.

[2] R. S. Johansson and G. Westling, "Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects," Experimental Brain Research, vol. 56, no. 3, pp. 550-564, 1984.

[3] R. S. Johansson and K. J. Cole, "Sensory-motor coordination during grasping and manipulative actions," Current opinion in Neurobiology, vol. 2, no. 6, pp. 815-823, 1992.

[4] R. S. Johansson and J. R. Flanagan, "Coding and use of tactile signals from the fingertips in object manipulation tasks," Nature Reviews Neuroscience, vol. 10, no. 5, pp. 345-359, 2009.

[5] J. Lukos, C. Ansuini, and M. Santello, "Choice of contact points during multidigit grasping: effect of predictability of object center of mass location," Journal of Neuroscience, vol. 27, no. 14, pp. 3894-3903, 2007.

[6] J. R. Lukos, C. Ansuini, and M. Santello, "Anticipatory control of grasping: independence of sensorimotor memories for kinematics and kinetics," Journal of Neuroscience, vol. 28, no. 48, pp. 12765-12774, 2008.

[7] C. Günter, Y. Liu, R. Leib and D. W. Franklin, "Force Control During the Precision Grip Translates to Virtual Reality," In: 2022 44th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Jul. 2022.

[8] Q. Fu, W. Zhang, and M. Santello, "Anticipatory Planning and Control of Grasp Positions and Forces for Dexterous Two-Digit Manipulation," J. Neurosci., vol. 30, no. 27, p. 9117, Jul. 2010, doi: 10.1523/JNEUROSCI.4159-09.2010.

[9] K. Mojtahedi, Q. Fu, and M. Santello, "Extraction of Time and Frequency Features From Grip Force Rates During Dexterous Manipulation," IEEE Transactions on Biomedical Engineering, vol. 62, no. 5, pp. 1363-1375, May 2015, doi: 10.1109/TBME.2015.2388592.

[10] R. C. Oldfield, "The assessment and analysis of handedness: the Edinburgh inventory," Neuropsychologia, vol. 9, no. 1, pp. 97-113, 1971.

[11] F. Conti, F. Barbagli, D. Morris, and C. Sewell, "Chai 3d: An open-source library for the rapid development of haptic scenes," IEEE World Haptics, vol. 38, no. 1, pp. 21-29, 2005.

[12] R. Smith, "Open dynamics engine," 2005.