Exploring The Neuromechanics of Object Manipulation in Physical and Virtual Environments

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Abstract:

Virtual reality (VR) technologies are continuously being adopted as training systems across many domains. Each domain often requires users to interact with virtual objects within the simulated environment. Recent studies have suggested that understanding user-object interaction fidelity can provide essential information about the feasibility of VR as a tool to enhance user performance. Since an implicit goal of all VR systems is to provide users with an experience that is perceived as realistic to improve performance, there is a clear need for metrics that can quantify essential attributes of the user's interaction with the virtual environment (VE). To address this need, this work proposes an objective, user-centric metric approach that considers the neuromechanics underlying the user's behavior that would allow for a quantitative analysis between object manipulations conducted in the real world and a haptic-free VE. It is hypothesized that the movement pattern of object manipulation in a haptic-free VE and the real world are largely consistent. In this pilot study, the examination of specific features of hand kinematics and electromyography during the pre-and-post-contact phases of a pick-and-place task revealed significant differences between the real world and the haptic free-VE. In the future, this paradigm will be applied as a framework to evaluate haptic displays and analyze the technology's effects on the neuromechanics of user-object interaction toward making VR more realistic.

1. Introduction

Virtual reality (VR) is an emerging technology that allows users to become immersed in a computer-generated virtual environment (VE)[1]. While VR was initially developed as a tool to enhance video games and entertainment, it has become prevalent in many growing fields, such as education[2,3], medical training[4,5], and rehabilitation[6,7]. Each application often requires users to interact with virtual objects within the VE[8]. Thus, understanding user-object interaction fidelity, or the exactness with which VR interactions resemble the real world (RW), can provide essential information about the feasibility of VR as a tool to enhance user performance[9].

Since an implicit goal of all VR systems is to provide users with an experience that is perceived as realistic, there is a clear need for metrics that can quantify essential attributes of the user's interaction with the VE. To address this need, I am proposing an objective, user-centric metric that considers the neuromechanics underlying the user's behavior that would allow for a quantitative analysis between object manipulations conducted in the RW and a haptic-free VE (Hf-VE).

Object manipulation has been cited as one of the primary tasks in VR[10,11,12]. However, the absence of physical contact in a VE creates challenges for achieving a realistic experience. Visual cues generally provide the sole indication of contact between the hand and an object, which differs fundamentally from physical manipulation as the neurobiological processes underlying motor control of the hand rely heavily on haptic feedback during reach-to-grasp tasks[13].

Current object-driven interactions in a VE are classified as *direct* when user input is provided by tracking hand and finger gestures and movements (see Fig 1)[14]. Presently, a few studies have investigated the differences and similarities between reach-to-grasp and transport movement kinematics in the RW and a VE[8,15]. Their findings indicated largely consistent movement patterns between aperture and transport velocity profiles in the RW and VE, with a few kinematic factors reported as slightly different during specific task phases (reach, grasp, transport phase) due to the lack of a physical object.

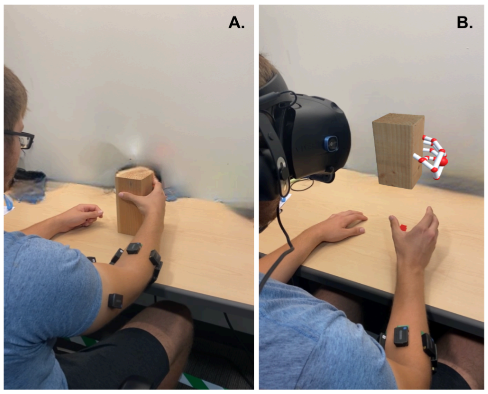

Fig 1. **Object-driven interactions in a VE compared to RW interaction**. **A.** RW hand object manipulation. **B.** *Direct manipulation* through the use of hand tracking controller

While these studies reveal how direct manipulation of virtual objects allows for hand kinematics to be preserved across environments, they fail to capture the neurophysiological and biomechanical attributes that are typical of physical manipulation. Neuromechanics are key determinants of user experience, especially during grasping and manipulation tasks, where contact forces are crucial for task performance. In RW object-driven manipulations, electromyography (EMG), which measures electrical activity from muscles, can provide a direct and continuous neurophysiological measure of motor output during a task[25],[17]. Therefore, this work proposes the use of EMG and marker-based tracking of hand kinematics to examine differences in object-driven manipulations in the RW and a Hf-VE.

The **central hypothesis** of this study asserts that both pre-and-post-contact phases of hand-grasp neuromechanics will differ significantly during an analogous task in a Hf-VE compared to the RW due to the lack of physical interaction in VR. In **Aim 1**, the effects of haptic-free manipulation on *maximum grip aperture, time to maximum grip aperture, percent overshoot, and grasp variability* during a pick-and-place task were quantified. Similarly, for **Aim 2**, the effects of haptic-free manipulation on muscle activation, through *EMG amplitude analysis*, were examined.

2. Methods

2.1 Study Design

2.1.1 Task Background

Direct object manipulation in a VE, through hand tracking devices, allows the user to apply intuitive and natural hand motions to the virtual interaction as they would in the RW[18]. Comparative work by Mangalam et al. (2021) and Furmanek et al. (2019), have shown no significant differences in hand trajectory across environments[19 8]. Nevertheless, as described by Gizzi et al. (2021), direct manipulation in VR alters the quality of sensory feedback due to the lack of contact events[20].

The task implemented in this study was adapted from Furmanek et al. (2019) whose study investigated whether the kinematics of the hand are preserved when performing reach-to-grasp movements under visual feedback alone (haptic-free) in a VE[8]. This experimental task builds off of the previous model of haptic-free interactions, to evaluate whether kinematic properties of the hand, such as maximum aperture, time to maximum aperture, percent overshoot of aperture, and grasp aperture variability, differ in both environments with the inclusion of EMG as an estimate of the neuromechanical output of limb mechanics in the two environments.

2.1.2 Participants

One neurologically intact, right-handed, participant (male; age: 25) was recruited to perform this pilot experiment. The participant completed a pre-experiment Likert-scale questionnaire of five questions to evaluate their familiarity with VR and VEs. The participant stated being moderately familiar with VR systems.

2.1.3 Experimental Task

The participant performed a pick-and-place task with three differently sized physical objects and matched 3D virtual renderings. The objects were wooden blocks with weights of 729 (large), 372 (medium), and 111 g (small), and graspable dimensions of 8.5, 7.3, and 3.6 cm, respectively. The participants viewed the virtual renderings of these objects in a custom 3D immersive VE design in Unity (ver. 2021.3.5f1, Unity Technologies) via a head-mounted display (HTC Vive, Corporation). The participant was prompted to rotate the block to an axis that would allow him to easily grasp without excessive wrist movement.

2.1.3 Experimental Procedure

A seven-camera motion tracking system (VICON; sampling rate: 200 Hz) recorded the 3D motion of *three 14 mm reflective markers* attached to the participant's *dorsum (nail) of the thumb and index fingers and the wrist at the center* of the line between the ulna and radial styloid process. Wireless bipolar EMG sensors (Avanti Trigno, Delsys Inc.; sampling rate: 1926 Hz) were used to record from two muscles: *Flexor Carpi Radialis* (FCR) and *Extensor Carpi Radialis* (ECR). The participant was instructed to place his right hand in the marked area on the table in a comfortable pinch position maintaining a starting distance between the thumb and index to prevent interference between the markers.

Data collection began with the participant performing two maximum voluntary contractions (MVCs) of his forearm (wrist flexed, wrist extended) for 3 s each. The MVCs were used to normalize the EMG. The participant was then allowed a training phase to become accustomed to the task, particularly in the VE, and to adjust the objects as preferred for comfort. The participant informed the researcher when he was ready to begin.

Each trial was cued by verbal prompts, which instructed the participant to rest, grab, lift, put the object down, release, and rest. The participant was advised to interact with the virtual and physical objects as naturally as possible. In the Hf-VE, the participant's hand position was rendered utilizing the UltraLeap Leap motion core system (Software Development Kit, Ultraleap). Contact with virtual objects was controlled with a collision detection algorithm which colored the virtual object yellow when the virtual fingertips reached the object. The experiment consisted of a total of 120 successive trials (20 trials x 2 conditions x 3 objects) followed by short breaks between conditions. Each trial lasted 10s. The participant conducted the physical task followed by the haptic-free task, and the order of object manipulation was randomized in each task.

2.2 Data Processing and Feature Extraction

Data was analyzed offline using custom python scripts. Each trial was split into pre- and post-contact phases. The pre-contact phase was characterized in terms of movement onset (start motion towards the object from rest) and offset (the moment of maximum distance between thumb and index), as specified by Furmanek et al. (2019)[8]. Similarly, the post-contact phase was characterized in terms of contact onset (the moment aperture distance between thumb and index became fixed in the RW and the moment the collision detection criterion was met in Hf-VE) and offsets (the moment prior to final maximum aperture distance after lifting the object down).

2.2.1 Kinematics

Following standards for marker-based research[21], the kinematic data were lowpass filtered at 6 Hz (2nd-order Butterworth). Based on the markers attached to the thumb and index, the following kinematics were calculated. Pre-contact phase: maximum grip aperture **(MGA)** (the largest distance reached between the thumb and index), and time to maximum grip aperture **(T-MGA)** (time MGA was reached). Post-contact phase: percent overshoot of grip aperture **(PO)** (difference between MGA and contact grip aperture)[22], and grasp variability (**GV**) (variability of fixed aperture).

2.2.2 EMG

Following standards for surface EMG[23,24], the EMG signals were bandpass filtered (20-500 Hz, 5th-order Butterworth). The filtered EMG signals for each muscle were normalized to the maximum value of the corresponding MVC. The EMG signals were aligned to movement/contact onsets and offsets from the kinematic data. As a measure of EMG amplitude, the root mean square **(RMS)** was calculated for both the pre-and post-contact phases[25].

2.3 Statistics

The experimental procedure followed a within-subjects design. MGA, TMGA, and PO fulfilled the conditions of normality, as evidenced by the Shapiro-Wilk test with a p-value greater than 0.05 for all levels of the within-subject factor. A two-way ANOVA was utilized to evaluate the effects of environment and object size for the normally distributed data. GV and EMG data did not fulfill normality. Assuming paired sampling, a Friedman test was utilized to evaluate the effects. A post-hoc Tukey's test and a Nemenyi post-hoc test for multiple comparisons were used to assess the statistical significance of each size factor (large, medium, small) and environment factor (RW, VE), accordingly. For all further statistics, p-values follow: *: $0.01 < p <= 0.05$, **: $0.001 < p <= 0.01$, ***: $0.0001 < p <= 0.001$, ****: $p <= 0.0001$.

3. Results and Discussion

3.1 Aim 1: Kinematics

3.1.1 Maximum Grip Aperture (MGA)

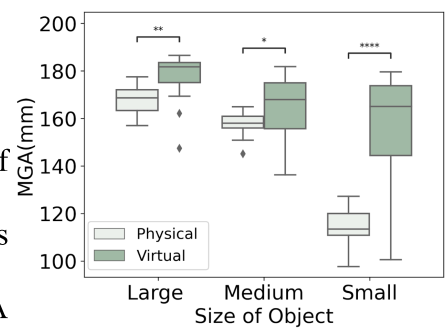

Fig 2. **Maximum Grip Aperture**

As expected, there was a significant main effect of MGA for size (p=9.6e-26), indicating that the aperture was scaled to object size[8,26,27]. A significant main effect of MGA was also observed for the environment (p=1.6e-14), and the interaction between environment and size (p =5.6e-09). Further examining the interaction effect, the posthoc Tukey test shows significant differences in MGA between the large (p=0.0022), medium (p =0.028), and small (p=5.4e-7) objects in the RW and VE (see fig. 2). Interestingly, **MGA for VE was higher than MGA for RW**, which agrees with findings by Keefe et al (2019)[28], that in the presence of varying visual and motor uncertainty, the probability of errors is managed by adjusting a margin for error by opening the hand wider with increased uncertainty.

3.1.2 Time To Maximum Grip Aperture (T-MGA)

Analysis of absolute T-MGA revealed a significant main effect of environment (p=0.002) and size (p=0.03). Interaction effects, for the medium (p =0.024) and small (p=0.049) objects,

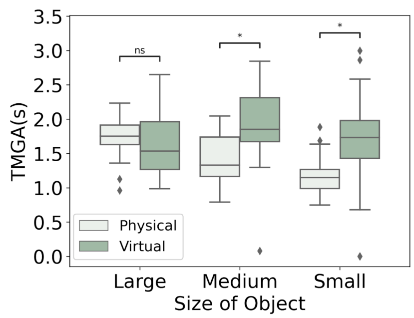

Fig 3. **Time to Maximum Grip Aperture**

revealed that **MGA occurred later in time in the VE compared to RW** (see fig. 3). T-MGA for the medium and small objects indicated that the participant did adopt an <u>alternative error-mitigation strategy</u> of moving more slowly in the VE, causing shorter T-MGA with increased visual and motor uncertainty[29].

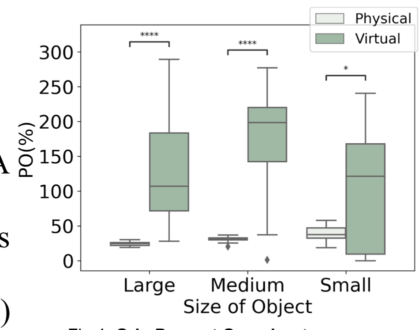

Fig 4. **Grip Percent Overshoot**

3.1.3 Percent Overshoot (PO)

PO was measured to examine the effect of MGA between environments regardless of object size. Analysis revealed significant main effects of the environment (p=3e-18) and size (p=9.3e-3), **indicating greater PO when grasping virtual objects** (see fig. 4). Interaction effects showed significant differences between all object sizes (large: p =7.7e-8, medium: p =2e-5, small: p=0.017), as described by Furmanek et al (2019)[8]. This result indicates that the <u>participant opened his hand proportionally wider than the object</u>.

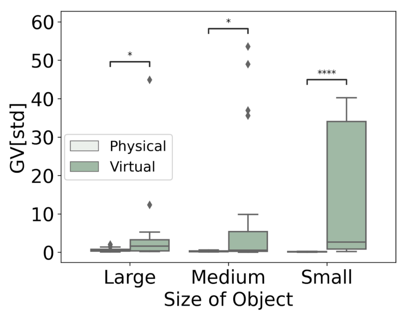

Fig 5. **Grip Aperture Variability**

3.1.3 Grasping Variability (GV)

The Friedman test revealed statistical significance (p=2.78e-11) between the factors of size and environment during the post-contact phase. Results revealed statistical significance across all sizes in VE and RW. This analysis indicates a **higher average amount of variability in aperture distance while attempting to hold objects in the VE compared to RW** (large: p =0.032, medium: p =0.012, small: p=5.7e-6) due to the lack of physical contact (see fig. 5).

3.2 Aim 2: EMG

For both muscles, the Friedman test revealed statistical significance between size and environment pre-contact (FCR: p=2.9e-11, ECR: p=3e-16) and post-contact (FCR: p=4.6e-14,

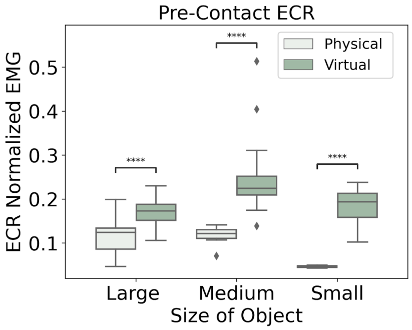

Fig 6. **Pre-Contact Extensor Carpi Radialis**

ECR: p=6.97e-15). RMS showed different muscle amplitude patterns for FCR and ECR during pre- and post-contact for each size within the VE and RW. During the pre-contact phase, as the participant reached MGA, **we noted higher ECR muscle amplitudes for all object sizes in the VE** (large:p =3e-5, medium: p =1.4e-5, small: p=6e-5) (see fig. 6). **The FCR muscles significantly co-contracted** to stabilize the wrist during the pre-contact phase for each object (large: p =0.002, medium: p =0.006, small: p=3e-5)[30] (see fig. 7). During the post-contact phase, the **FCR muscle amplitude for the large and medium objects was significantly higher in the RW compared to the VE** (large: p =4e-5, medium: p =0.008, small: p=0.07) (see fig. 8). This result indicated that there was a grasping force produced by the FCR muscle that resulted in a secure hold of the object and allowed for the objects to be lifted in the RW[31]. **The ECR muscle amplitude was significantly higher in the VE compared to the RW for all object**s (large: p =8e-5, medium: p =6e-6, small: p=5e-6)(see fig. 9). This analysis revealed that the participant's hand on the virtual object was most likely adjusted to use excessive wrist extension to prevent occlusion of the thumb and index finger.

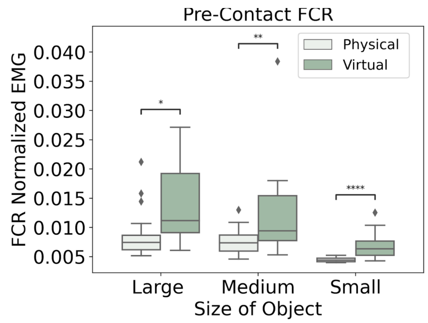

Fig 7. **Pre-Contact Flexor Carpi Radialis**

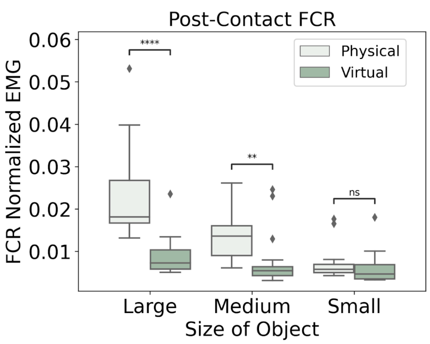

Fig 8. **Post-Contact Flexor Carpi Radialis**

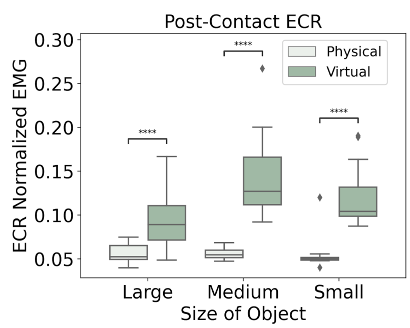

Fig 9. **Post-Contact Extensor Carpi Radialis**

3.3 Limitations and Future Work

In this pilot study, the sample size was limited. Secondly, the lack of a naturalistic grasp coupled with the UltraLeap inaccuracies likely led to grasp errors and measurement noise[32]. Finally, while Hf-VE is often criticized for its lack of terminal haptic feedback, it played a fundamental role in this study--establishing a baseline of the neuromechanical differences present in RW vs hf-VE.

In the future, we plan to address the topics of neuromechanics in object manipulation within VR and the RW through the use of haptic devices, to further understand whether haptic feedback reduces the differences in movement and muscle activity in VR interactions, as has been demonstrated in previous studies[33,34]. We seek to further develop this work as a framework for evaluating haptic displays and analyzing the technology's effects on the neuromechanics of user-object interaction toward making VR more realistic.

4. Conclusion

Through this pilot study, both pre-and-post-contact phases of hand-grasp neuromechanics differed significantly during an analogous task in a Hf-VE compared to the RW due to the lack of physical interaction in VR. Examining specific features of hand kinematics and EMG during the pre-and-post-contact phases of a pick-and-place task revealed differences between the RW and the Hf-VE. The characterization of these differences will be used as a framework to design better interactive devices to ultimately enhance user performance in a VE.

5. Statement of Contribution

The student performed the following roles in the research presented here: (1) task and experimental design, (2) hardware and software implementation, (3) data collection, and (4) data analysis. The PIs provided guidance and support throughout the project. Eni Halilaj and Justin Macey provided laboratory access for data collection. Omar El-Refy, Lauren Parola, Justin Yim, Owen Pearl, Mikayla Schneider, and Nikhil Verma offered training to the student using the motion capture and EMG recording system.

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