Validation of a Virtual Reality Environment to Study Anticipatory Modulation of Digit Forces and Position

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Abstract. *The aim of this paper is to validate a virtual reality (VR) environment for the analysis of the sensorimotor processes underlying learning of object grasping and manipulation. This study was inspired by recent grasping studies indicating that subjects learn skilled manipulation by concurrently modulating digit placement and forces as a function of the position of object center of mass (CM) in an anticipatory fashion, i.e. by modulating a compensatory moment before the onset of object manipulation (object lift onset). Data from real and virtual grasping showed a similar learning trend of digit placement and forces, resulting in successful object roll minimization. Therefore, the overall behavioral features associated with learning real object manipulation were successfully replicated by the present VR environment. The validation of our VR experimental approach is an important preliminary step towards studying more complex hand-object interactions.*

Key words: VR environment, object grasping, object manipulation, anticipatory grasp control.

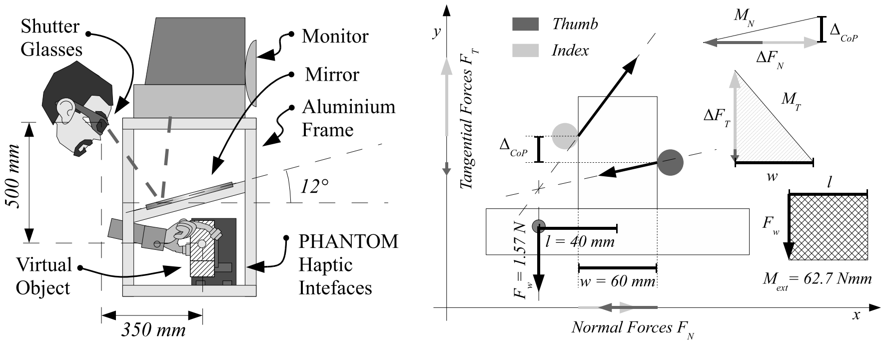
1 Introduction

The control of grasping and manipulation in humans has been extensively studied [1]. Two main modes of control are generally recognized: one based on sensorimotor memories, allowing for anticipatory grasp control, and another that relies on online sensing, leading to reactive control (for review see [1]). Anticipatory grasp control has traditionally been quantified by measuring digit forces between contact and the onset of object manipulation (e.g [5]). Examples of reactive grasp control are the force upgrades occurring shortly after the onset of object slip [7] or the detection of an unexpected texture shortly after contact [6]. It has been recently shown that anticipatory control of grasping is not limited to digit forces, but extends to digit placement [2, 8]. Specifically, when subjects are aware that object properties (object center of mass) do not change across consecutive trials, they modulate digit position before object lift-off in parallel with digit forces, both of these variables being instrumental for preventing object roll during the lift [2–4]. The functional role of the anticipatory modulation of digit placement appears to be the optimization of digit force distributions [3]. Furthermore, learning of digit placement and force modulation to object center of mass occurs within one or two trials [3, 4]. Such quick learning is likely to depend on the integration of several sensory modalities such as vision (digit placement and object roll), tactile input (forces at and during manipulation), and proprioception (hand shape, relative distance between the digits). However, due to the fact that object manipulation is learned very quickly, it is challenging to dissociate experimentally the role of each sensory modality when manipulating real objects. Virtual reality environments are particularly suited to pursue this question as they allow varying the weight of specific sensory modalities by introducing noise to the perceptual and/or motor processes [9, 10]. The present study focused on creating a VRE that could be used to quantify the effect(s) of individual sensory modalities on learning object manipulation. Here we describe human subjects' performance using our VRE in relation to previously published data on manipulation of real objects. We found that subjects in the VRE exhibited anticipatory control of digit forces and position. Furthermore, subjects learned object manipulation in a quantitatively similar fashion as reported by previous studies of manipulation of real objects [3, 4]. In these papers, we found that (a) subjects exert a compensatory moment in the direction opposite to that of the external moment generated by a mass added to the object; (b) this compensatory moment is learned within the first 2-3 object lifts; (c) subjects generate the external moment by modulating both digit placement and forces; (d) the digit on the side of the added mass is placed higher than the other digit. Therefore the VRE proposed in the present study offers promising avenues for research into the neural processes underlying the integration of multiple sensory modalities responsible for learning and control of object manipulation.

2 Materials and Methods

2.1 Subjects

Twelve healthy right-handed volunteers (6 females and 6 males, their age ranged from 23 to 33) with normal or corrected-to-normal vision participated in the study. Each subject gave informed consent to participate in the study according to the Declaration of Helsinki, and the experimental procedures were approved



(a) Virtual Reality Setup (b) Free Body Diagram

Fig. 1. Panel (a) shows the experimental setup. Two PHANTOM desktop devices were attached to the tip of the thumb and the index finger to generate haptic perception of a solid object. The tip of the two digits and the 3D image of the virtual object were visually rendered on a computer monitor and projected through a mirror. Panel (b) shows the free-body diagram of the virtual object and the variables of interest measured by the haptic interface. M_{ext} was produced by applying a suitable force F_w at a distance l from the midpoint of the object base. In condition of equilibrium: $M_{ext} = M_N + M_T$, where M_N and M_T were produced, respectively, by normal and tangential forces exerted by subjects.

by the Institutional Review Board at University of Pisa. All subjects were naive to the experimental purpose of the study.

2.2 Experimental Task

We asked subjects to reach, grasp, lift, and replace a virtual object with their right hand. The object consisted of a vertical block attached to a rectangular base (see Fig.1(b)) similar to the real object we used in previous studies [3, 4]. In the manipulation task of real objects, that was simulated in the present work, the behavioral consequences of anticipatory modulation of digit positions and forces are confined primarily to the frontal plane. This is because the added mass introduces an external torque in the frontal plane, whereas it negligibly affects the orientation of the object in the sagittal or horizontal plane during object lift. Therefore, manipulation in our VR was simulated to occur in the frontal plane only by preventing motion in the sagittal plane. Subjects were asked to perform the task using the fingertips of the thumb and the index finger. Note that no instructions were given about where to grasp the object along its vertical sides. Although the visual appearance of the object remained invariant throughout the experiment, an external moment (M_{ext}) of 62.72 Nmm was imposed in order to replicate the change in the center of mass (CM) in the experiment conducted in [2]. In [2], the CM of an inverted T-shaped object, consisting of a cylinder attached to a horizontal base, was changed by adding a mass in one of three slots at the base of the object. According to the position of the slot situated from the midpoint of the object base, the CM locations were indicated as left (thumb side) LCM, center CCM, and right (finger side) RCM, respectively. The same naming was used in this work, considering now the sign of the external moment; LCM for a negative M_{ext}, RCM for a positive M_{ext} and CCM for a M_{ext} equal to 0 (see Fig.1(b)). The only task requirement was to minimize object roll caused by M_{ext} while lifting the object vertically (5–10 cm above the virtual horizontal plane). During the task, subjects were comfortably seated and with the forearm resting on a table. Subjects were instructed to initiate the reach after a verbal signal from the experimenter and perform the task at a self-selected, natural speed. The experiment consisted of three blocks of six trials per CM. On each trial, subjects were provided with the visual-haptic object with a given pre-imposed CM. Each block corresponded to a position of CM. Before starting data collection, subjects were provided with three practice trials for the CCM condition, to allow them to familiarize with the virtual environment. These practice trials were not included in the data set used for analysis. At the beginning of each block, subjects were informed that the object CM was going to be changed, but they were not told the actual CM location. Subjects were also informed that the object CM location would be the same for the entire block of trials. Therefore, on the first object lift subjects were unable to anticipate the direction of M_{ext} before object lift-off. On following trials, however, we expected subjects to anticipate the CM location by generating a compensatory moment (M_{com}; see below) before lift-off. The order of CM presentation was randomized and counterbalanced across subjects. To prevent fatigue, we gave subjects rest periods of 10 seconds and 1 minute between trials and CM blocks, respectively.

2.3 Virtual Object

We presented the virtual object through stereoscopic visualization and haptic rendering. The image of the virtual object was visually rendered such that its visually and haptically perceived locations coincided, thus enabling the integration of these two sensory modalities. The visual feedback of the rendered scene was displayed on a monitor and reflected by a tilted mirror to allow co-allocation of visual and haptic stimuli, in front of the subjects, at a suitable reaching distance (see Fig.1(a)). Haptic rendering of the virtual object was obtained using two PHANTOM Desktop devices [11]. The algorithm for visuo-haptic rendering (and for both positioning of the object in the virtual scene and determination of the fingertips positions) is based on the standard ones contained in the PHANTOM Device software library. The two fingertips are modelled as two spheres with 9 mm radius, whose centers are located in correspondence of the endpoints of the two devices (where the centers of the two real fingertips are). The position resolution of the PHANTOM device is ~ 0.023 mm. The contact model is based on the standard linear visco-elastic contact point model used by the PHANTOM Device software library. The chosen friction coefficient is $\mu = 1.5$, the elastic constant of the surface is $K_e = 0.5$ N/mm. The mass of the simulated mass is equal to $M = 0.16$ Kg and the acceleration of gravity is the same as in the real world $g = 9.8$ m/s^2. Considering that the virtual object is constrained to move in the frontal plane (distance from the subject $\simeq$ 50% length of the subject's arm, as in the studies with real objects), both the angular momentum and the inertial tensor reduce to scalar quantities. The magnitude of the rotational inertial forces is much smaller than the magnitude of the other forces involved in the experiment. Rotational inertia of the simulated body is equal to 0.64 Kg$\cdot cm^2$.

2.4 Data Recording and Experimental Variables

The virtual environment was rendered at a frequency of about 75 Hz (non-noticeable jitter with a variance inferior to 1 μs). The haptic stimuli were rendered by an autonomous software thread running at a fixed frequency of 1 kHz. The time constant of the main rendering dominates both synchronization issues and sampling rate of position and force. The Phantom interface has a nominal position resolution of about 0.023 mm inside its workspace. This datum, and the stiffness of the virtual object ($K = 0.4$ N/mm), allows for a force resolution of about 9.2 mN. Recorded data consist of an array of five tuples of elements of the type

$$t_i = (Thb_i, Ind_i, Trj_i, Rll_i, t_i);$$

where, for each temporal instant i: Thb and Ind contain the three-dimensional coordinates of thumb and index finger, respectively (from these variables, the vertical distance between contact points, i.e. Δ_{CoP}, was computed); Trj_i and Rll_i contain the spatial coordinates of the cylinder and its roll angle and t_i records the temporal i-instant, from the beginning of the trial.

After recording, data were re-sampled at a fixed frequency of 50 Hz and smoothed using a 4^{th} order filter. Tangential forces exerted by each digit were used to compute the difference between tangential forces (ΔF_T). Anticipatory grasp control was quantified by measuring peak object roll during object lift. For details on the rationale and interpretation of these variables see [2, 4].

3 Results

Fig(2) shows representative data from the first, second and sixth trial performed by one subject (right object CM, RCM). Although on the first trial this subject exerted nearly zero compensatory moment (M_{TOT}, bottom trace) at object lift onset (first vertical dashed line), he was able to exert a compensatory moment that gradually approached the external moment (horizontal dash-dotted line) on subsequent trials at object lift-off. The compensatory moment was generated by exerting a larger digit tangential force (F_T) with the index finger than the thumb, while raising the index finger center of pressure (CoP) relative to the thumb CoP. As a result, this subject learned to reduce object roll during the lift.

3.1 Object roll minimization

The trial-to-trial changes in compensatory moment and peak object roll described in Fig.2 were common to all subjects Fig.3(b). Specifically, subjects learned to generate compensatory moments as a function of object CM and trial (main effect of both factors: $P < 0.01$). As expected, subjects generated little or no compensatory moment in the CCM condition (interaction CM x Trial, $P < 0.01$). The generation of a compensatory moment at object lift onset resulted in successful minimization of peak object roll during the lift (main effect of Trial, $P < 0.01$; Fig.3(a)), more so for the asymmetrical CMs than the CCM (interaction CM x Trial, $P < 0.05$). Note that these results are nearly identical to those reported by studies of the same task with real objects [3, 4].

3.2 Digit placement and digit forces

The compensatory moment is a function of CoP, F_N and F_T. To further examine how subjects learned anticipatory control of the compensatory moment, we performed separate analyses of its three components. Through consecutive lifts, subjects learned to separate the vertical distance between the thumb and index finger as a function of object CM ($P < 0.01$ and 0.05, respectively). Subjects adapt the CoP in trials of the LCM and RCM type (significant interaction CM x Trial, $P < 0.01$; Fig.3(c)) but not for CCM trials. Similarly, subjects use asymmetrical digit load forces that varied as a function of trial and object CM ($P <$ 0.01 and 0.05, respectively), the tangential force difference (ΔF_T) being smallest for the left than right and center CM (Fig.3(d)). Note that an opposite effect of CM was found for the difference of the CoP position for thumb and index (Δ_{CoP}). The Δ_{CoP} is larger for LCM than for RCM (Fig.3(c)). In contrast, the sum of digit normal forces did not change systematically with trials ($P > 0.05$). The trial-to-trial changes in digit CoP and forces as a function of object CM, as well as the inverse relation between Δ_{CoP} and ΔF_T, resemble the results reported by previous work with real objects [3, 4].

4 Discussion

The present study was designed to validate a VR environment for the study of object grasping and manipulation. The design of the task was inspired by recent grasping studies indicating that subjects learn to modulate digit placement and forces as a function of object CM [1, 3]. The focus of these studies was on anticipatory grasp control, i.e., on the modulation of the compensatory moment before object lift onset. Note that the above cited studies of two-digit [3, 4] and five-digit grasping [2] used objects that were significantly heavier (over 10-fold) than the object rendered by our haptic interface. Consequently, previous studies examined the effect of significantly larger external moments on anticipatory grasp control. This difference might account for some differences between present and previous results. Specifically, in previous work subjects used a larger digit CoP for right than left CM, whereas opposite results were found for the VR data. Nevertheless, data from real and virtual grasping showed a similar learning trend of digit placement and forces, resulting in successful object roll minimization.

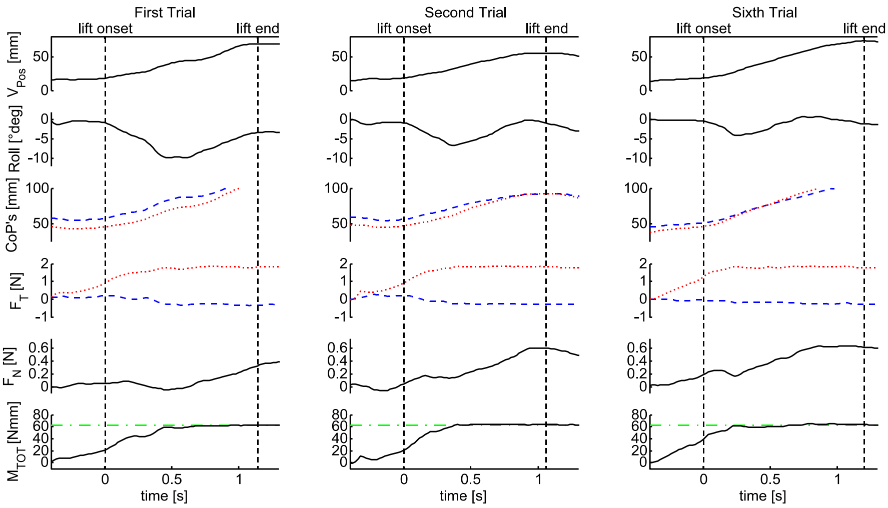


Fig. 2. Grasp performance (object roll) is shown for the first, second, and sixth trial together with object lift (V_{Pos}), digit centers of pressure (CoPs, blue dashed line for the thumb and red dotted line for the index finger, respectively), forces (tangential forces of each finger F_T and Average grip force F_N) net moment exerted by the digits (M_{TOT}) relative to the external moment (green dash-dot line).

Hence, the overall behavioral features associated with learning real object manipulation were replicated by the present VR environment. The validation of our experimental approach is an important preliminary step towards studying more complex hand-object interactions.

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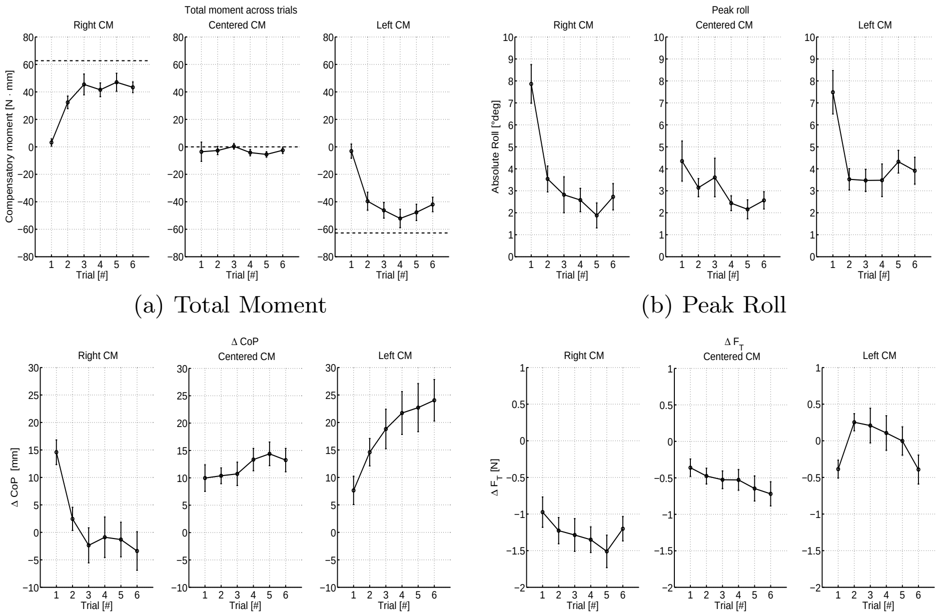

(a) Total Moment (b) Peak Roll

(c) Centers of Pressure Difference (d) Tangential force difference

Fig. 3. Panel (a) and (b) show the compensatory moment exerted at object lift onset and peak object roll, respectively, as a function of object center of mass and trial. Panel (c) and (d) show, respectively, The difference between thumb and index finger center of pressure (Δ_{CoP}) and tangential force difference (ΔF_T) as a function of object center of mass and trial. All data are averages of all subjects ($\pm S.E.$).

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