Influence of visual information on bimanual haptic manipulation

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***Abstract*—The coordination of the upper limbs has been shown to be beneficial for post-stroke treatment. In virtual reality based rehabilitation, bimanual exercises can be performed by exploiting haptic rendering techniques that allow object manipulation with two haptic devices. Haptic interaction generally involves spherical end-effectors with invariant shapes. Furthermore, the position of the end-effectors can only be sensed haptically after object contact, which impacts the ability to determine the real position of the end effector and dynamically manipulate the object. The present study sought to examine whether additional visual information regarding the penetration of the wrists into the virtual object (i.e., the color and shape of the spheres changed according to the level of force exerted by the subject) leads to improved bimanual task performance in a virtual environment. To this end, six neurologically healthy participants performed an object manipulation task with haptic feedback (haptic condition) and with haptic feedback as well as additional visual cues (haptic+visual condition). Results demonstrated that interlimb coordination was enhanced during the haptic+visual condition. It is speculated that the presence of visual information provides a more natural way for individuals to exploit inter-limb coordination synergies, and may have useful implications for VR game development and post stroke rehabilitation protocols.**

I. Introduction

Virtual reality (VR) is a computer simulated environment in which the user can interact with virtual objects in real time by means of different sensory channels (typically vision, hearing and touch [1]). VR technology is used in several fields including healthcare, with promising applications in surgery simulation [2], phobia treatment [3], and rehabilitation [4]. VR based rehabilitation enhances patient motivation by mimicing standard rehabilitation protocols while having the added advantage of providing feedback about performance and allowing a large number of repetitive movements to be performed [5]. Most of the proposed VR games methods that address motor impairment focus on the rehabilitation of a single limb, despite the fact that activities of daily living often rely on the use of both hands and that activities in which the upper limbs are coupled have been shown to aid the post-stroke recovery process [6] [7].

The field of haptics has seen tremendous advances in the last decade. New devices provide the user with the opportunity to perform specific actions that require the use of both hands in virtual environments. While the manipulation of objects in real life involves a contact area between the fingers and the object itself, the interaction between the user's proxy (whose position is measured by the haptic device) and a virtual object in VR's uses single- or multi-point contacts [8]. Multi-point haptic devices require the use of multiple end effectors to perform stable grasping movements. In contrast, single-point devices require the user to interact with the virtual environment by means of one point that represents the position of the user's proxy [9]. In particular, with two single-point devices the user controls two rigid bodies (commonly spherical) whose position and/or orientation are updated according to the actual position and/or orientation of the haptic devices. After contact with a virtual object, the involved spheres are located where the haptic interface points (HIPs) would stay if the object could not be penetrated. The distance between this point and the HIP is used for the force estimation: this simplifies both the device and algorithm development while reducing the complexity associated with interaction force computation [10]. The real position of the HIP is therefore sensed only by the haptic feedback, as the user does not see any change in the appearance of the avatar.

Humans synergically exploit both visual and haptic information when performing manipulation tasks. The mechanisms behind visuo-haptic integration has been a topic of great debate for more than a century [11]. Early studies on sensory influence stated that vision was the dominant sense [12]. However, it is now commonly accepted that the two sensory channels are weighted based on their reliability and appropriateness [13]. When spatial interaction tasks are concerned, visuo-haptic coupling is characterized by strong visual dominance; the sense of touch is favoured in tasks that require the perception of texture and material properties [14]. Accordingly, it is argued that visual cues afford more efficient bimanual handling in VR.

The aim of this study is to investigate whether bimanual task performance in a virtual environment is enhanced if participants were provided with additional visual information regarding the penetration of the wrists into the virtual ob-

978-1-4799-1808-9/15/$31.00

ject(i.e., the color and shape of the spheres changed according to the level of force exerted by the subject). Results of this study has implications for VR game development and motor and proprioceptive rehabilitation.

II. Methods

A. Participants

A group of six male subjects were recruited at Nanyang Technological University. Their age ranged from 24 to 30. All subjects were right handed according to the Edinburgh Handedness Inventory and were naïve to the purpose of the experiment. All participants gave their informed consent and were randomly assigned to two groups which performed the same experiment with opposite order of feedback presentation. The first group, H 1st, initially performed the task with the presence of the haptic feedback and, at a later stage, with both the haptic feedback and the additional visual cues. The other group, H+V 1st, performed the same task with the opposite order of presentation of feedbacks.

B. Apparatus

For the experiment we used two fully backdrivable 3-DoF robotic devices (Wrist robots, Fig. 1a) developed for motor and sensory rehabilitation [15]. The range of motion (ROM) of the three DOFs almost matches the ROM of the human wrist (human: 65°/70°flexion/extension (FE), 15°/30°adduction/abduction (AA), 90°/90°pronation/supination (PS); Wrist robot: ±72°FE, 45°/27°AA , ±80°PS).

The robots are driven by 4 brushless motors: two motors for AA which can provide sufficient force to stabilize a human wrist against gravity and one motor for each of the two remaining DoFs; the maximum torque values are: 1.53 Nm (FE); 1.63 Nm (AA); 2.77 Nm (PS). Angular rotations on the three axes were measured by means of digital encoders with a resolution of 4098 bit/turn. The system is integrated with a virtual environment in order to provide a visual feedback to the user. The PC was equipped with an Analog and Digital I/O PCI card (Quanser QUARC® QPIDe), in which the following channels were used: a) Eight Analog channels to command the reference values of the motor currents and b) Eight Encoders to read and receive the repetition signals from the digital encoders. Rotations of each Wrist robot were read through a QUARC block in Simulink® and translate to linear movements in the virtual environment.

The virtual environment, shown in Fig. 1b, was simulated using Matlab® and a Simulink® model employing the QUARC Visualization Toolkits. It consists of a three dimensional representation of rectangular parallelepiped shapes, one resting on the floor representing the object to be manipulated and the other, semitransparent, representing the target position to be reached; two spheres representing the subject's end-effector positions which are evaluated by the wrists joint angles. The countdown displayed on the object shows the remaining time for the task completion; the maximum time allowed is set to 15 seconds. The position of the spheres (end-effectors) is controlled with FE and AA of the user's

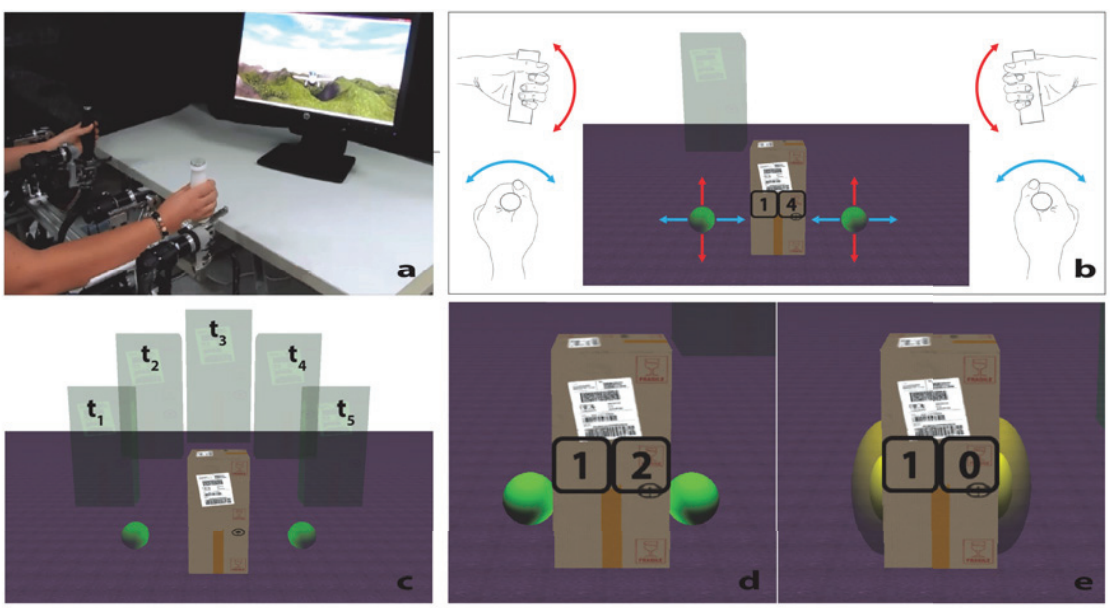

Fig. 1. (a) Wrist robots used in the study; (b) Mapping between virtual environment (VR) and wrist movements. The virtual environment consisted of two spheres, a cardboard carton representing the object to be manipulated (with a superimposed countdown timer), and a semitransparent carton representing the to-be-reached target. The horizontal displacement of the sphere is controlled by wrist flexion/extension (FE), while the vertical displacement is controlled by wrist adduction/abduction (AA); (c) Target positions shown during the experiment. Each position was randomly presented, for a total of 10 repetitions per condition; (d,e) Visual feedback used for the two conditions: (d) when haptic cues were provided the shape of the spheres did not change if a collision occurred, (e)while in the haptic+visual condition the shape and colour of the spheres deformed according to the haptic interface point (HIP) into the virtual object.

wrist in order to grasp the object and to transport it to match the target position. The PS joint is blocked to restrict the movements on the two dimensions of the screen, while the motion in FE and AA is unrestricted. The virtual object is simulated in such a way that only two of the three degrees of freedom are allowed (XY axes) while rotation of the object is blocked.

C. Procedure

Subjects sat comfortably on a chair in front of a computer monitor displaying the virtual environment with their hand holding the robot handle; their forearms firmly constrained to a rigid cast and secured by Velcro® strips to the robot devices.

Participants then performed a familiarization task in which the virtual object (i.e., cardboard carton) was lifted and transported to one of three targets located 4.5 cm from the initial starting point (-45°, 0°, and +45°). During this task, no additional visual cues were provided. After the virtual object was placed on the target a message was displayed that indicated that the object should be returned to the start position. Instructions also stated that the participant should complete each trial in less than 15 seconds, to maintain a stable grasp to prevent the object from falling, and that too much force would cause damage to the cardboard carton. If the movement exceeded the time limit, or the carton fell or was damaged from excessive force the carton changed texture. The participant was then instructed to relax their grip on the end-effectors, and wait one second for the next trial to begin. After the familiarization phase, the participant took a five minute rest break, after which the experiment started.

In the experimental phase, there were a total of 100 trials, comprised of the factors condition (haptic, haptic+visual) and target (t_1 = -60°, t_2 = -30°, t_3 = 0°, t_4 = 30°, t_5 = 60°). Targets are shown in Fig. 1c. During the haptic condition the two spheres did not change shape if a collision between the end-effectors and virtual object occurred (Fig. 1d). However, the participant was able to sense the force feedback due to the interaction between the haptic device and surface of the virtual object. In contrast, in the haptic+visual condition the color and shape of the spheres changed according to the level of force exerted by the subject. When the level of force reached 50% of maximum (1/4 penetration of the total object width) the spheres turned yellow (Fig. 1e). When the level of force reached the maximum (1/2 penetration of the total object width) the spheres turned red, indicating that the object was broken.

The experimental trials were divided into two blocks (i.e., haptic condition, haptic+visual condition) of 50 trials (10 trials for each target), separated by a five minute rest period. All trials were fully randomized. The entire experiment lasted approximately 40 minutes.

The virtual grasping was modeled using the God object algorithm including friction simulation [16]. The representation of the position of each device, the so-called god object, represented as a sphere, was placed where the HIP would stay if the virtual object could not be penetrated. The movement of the virtual object was the result of the application of the gravity force and of forces generated during the contact, modeled using the linear spring equation (Hooke's law) $F = -kx$ where k is the spring constant and x is the distance between the each HIP and their virtual representation. Forces were then summed and by using Newton's second law $F = ma$ the object's acceleration was computed. This was then integrated in order to update the velocity of the target object that was, in turn, integrated to update the position of the object. A damping coefficient d was introduced to simulate drag and the resting contact was achieved via impulse resolution.

D. Data analysis

Before data analysis, we excluded trials performed in a non-instructed manner (exceeding the required force limit resulting in a broken carton, application of force that caused the carton to slip from the spheres, task completion times that exceeded 15 s). Error trials comprised less than 13.2% of the data, and were approximately equally distributed across condition and participants. Given the low error rate, mean substitution was used to replace missing values.

Following data collection, movement trajectories of the two end-effectors was reconstructed and smoothed using a 6th order Savitzky-Golay filter (11 Hz cut-off frequency). Each trial was then divided into the reaching phase and the return phase. The reaching phase was defined as time period between when both spheres contacted the lateral surface of the carton to the time period the carton was placed on the target. The return phase was determined as the time of the sample between when the carton left the target to the time the carton was placed back to the start position.

The RMS trajectory difference of the two HIP trajectories was calculated to investigate the strength of the interlimb coupling throughout the reach and return movement segments.

Statistical analysis was performed using the Chi-square test to compare percentages of failed trials between Groups (H 1st, H+V 1st). Furthermore, statistical quantification of the differences in kinematic characteristics was conducted on the following dependent variables: reach time, return time, RMS difference of the reach phase, and RMS difference of the return phase. For all dependent variables, the average of each condition was submitted to a Repeated Measures Analysis of Variance with the factors Group (H 1st, H+V 1st), Condition (haptic, haptic+visual), and Target (t_1, t_2, t_3, t_4, t_5). Preliminary analyses were conducted to check for normality, sphericity (Mauchly test), univariate and multivariate outliers, with no serious violations noted. Results with p-values <0.05 were considered significant. Significant main effects and interactions were compared using Bonferroni corrected post-hoc analysis.

III. Results

A. Trials with Broken Objects

The total number of trials in which the applied force resulted in a broken carton was similar regardless of feedback

Condition (mean: haptic = 18.5%, haptic+visual = 21.0%) and Group (H 1st: 18.0% , H+V 1st = 21.5%). This non-significant result was confirmed via Chi-Square analysis, χ^2 $t_{(2)}$ = 0.152, p = 0.697.

B. Reach Phase

Analysis revealed a significant main effect of Condition on reach time, with significantly shorter reach times for the haptic (3.505 s, SE = 0.200) compared to the haptic+visual condition (4.031 s, SE = 0.293), $F_{(1,4)}$ = 9.931, p = 0.034. A significant main effect of Target was also observed, $F_{(1,4)}$ = 6.1763, p = 0.003, with Bonferroni corrected post-hoc analysis revealing significant shorter average reach times for t_3 (3.191 s) compared to all other targets (mean = 3.912 s), all p's $<$ 0.05 (Fig. 2). The interaction between Group and Condition was also significant, $F_{(1,4)}$ = 14.203, p = 0.020. For the H+V 1st group movements performed with the presence of haptic and visual feedback (4.692 s) yielded longer object transport times than movements performed with only haptic feedback (3.537 s). In contrast, reach time values for the H 1st group were similar for the two feedback conditions (haptic = 3.473 s, haptic+visual = 3.370 s) as reported in Fig. 3.

Analysis of the RMS difference during the reach phase revealed that the HIP trajectories were more similar for the haptic+visual feedback condition (4.681°, SE = 0.706) compared to the haptic feedback condition (5.654°, SE = 0.924), $F_{(1,4)}$ =7.257, p = 0.050. The main effect of Target was also significant, $F_{(1,4)}$ = 4.915, p = 0.009. Bonferroni corrected post-hoc analysis revealed significant differences between t_3 (4.559°) and all other targets (5.319°), all p's $<$ 0.05. In addition, the leftmost targets (t_1 = 5.105, t_2 = 4.926) differed significantly from the rightmost targets (t_4 = 5.429°, t_5 = 5.819° respectively), all p's $<$ 0.05.

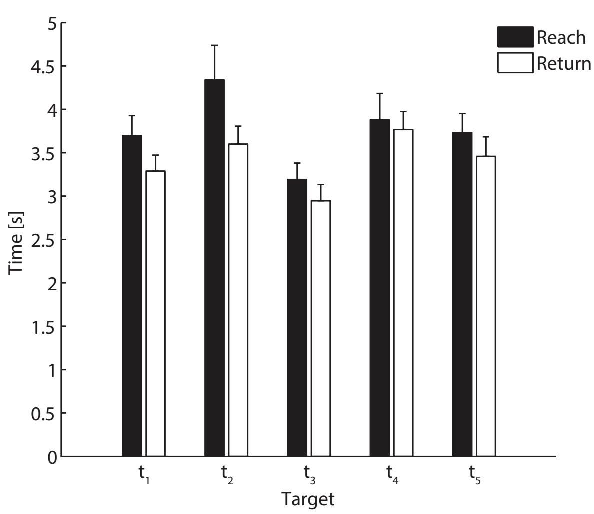

Fig. 2. Reach and return times for targets. Reach and return times where shorter for t_3 compared to all other targets.

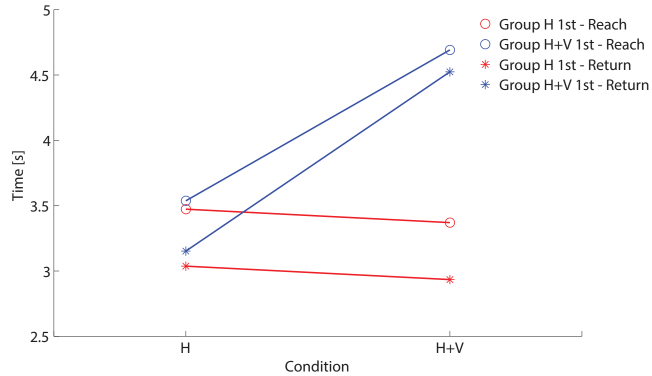

Fig. 3. Interaction between Condition (haptic: H, haptic+visual: H+V) and Group (haptic first: H 1st, haptic+visual first: H+V 1st). Object transport times were similar for group H 1st in the two conditions in reach and return task; group H+V 1st performed longer movements with haptic+visual feedback.

Last, there was a significant Target x Condition interaction, $F_{(4,16)}$ = 3.240, p = 0.040. Post-hoc analysis indicated that RMS difference values were similar for the two feedback conditions for targets t_1, t_2, and t_3 (condition difference: t_1 = 0.552°, t_2 = 0.554°, t_3 = 0.728°), all p's $<$ 0.05. In contrast, that RMS difference values were significantly higher for the haptic than the haptic+visual condition for targets 4 and 5 (condition difference: t_4 = 1.805°, t_5 = 1.225°) as shown in Fig. 4.

C. Return Phase

Analysis indicated that return times were significantly shorter for the haptic condition (3.094 s, SE = 0.192) compared to the haptic+visual condition (3.729 s, SE = 0.164), $F_{(1,4)}$ = 23.235, p = 0.009. Average return time values were influenced by target, $F_{(1,4)}$ = 5.957, p = 0.004. Bonferroni corrected post-hoc analysis revealed significant shorter average reach times for t_3 (2.946 s) compared to all other targets (mean = 3.528 s), all p's $<$ 0.05 (Fig. 2). In addition, a

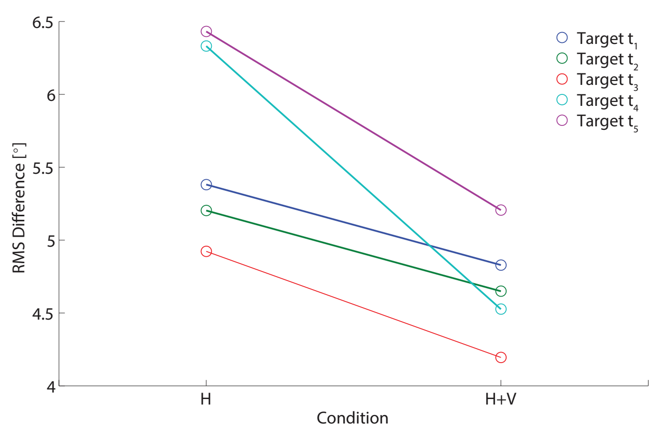

Fig. 4. Interaction between target position and condition. RMS difference values were similar for the two feedback conditions for targets t_1, t_2, and t_3. RMS difference values were significantly higher for the haptic than the haptic+visual condition for targets t_4 and t_5.

significant Group x Condition interaction was observed (Fig. 3), $F_{(1,4)}$ = 31.396, p = 0.005. Although average return time was similar for the two feedback conditions for the H 1st group (haptic = 3.037 s, haptic+visual = 2.934 s), return time values were significantly larger for haptic+visual condition for the H+V 1st group (haptic = 3.152 s, haptic+visual = 4.524 s), p = 0.001.

The RMS difference during the return phase was significantly higher for the haptic (4.277°, SE = 0.771) than the haptic+visual condition (2.923°, SE = 0.459), $F_{(1,4)}$ = 6.854, p = 0.050. No other effects reached significance.

IV. Discussion

The aim of this study was to examine whether bimanual task performance in a virtual environment is enhanced by the addition of visual information regarding the penetration of the wrists into the virtual object. Results indicated that while the number of broken objects was similar regardless of feedback condition, both reach and return times were significantly shorter for the haptic compared to the haptic+visual condition. A possible explanation for this finding is that when deformable end effectors are present (i.e., haptic+visual condition) the overall difficulty of the task increases and require participants to use a movement strategy in which deformation minimization and motion in space is decomposed ([17], [18]). Furthermore, we found that while average reach and return times were considerably longer for haptic+visual condition for H+V 1st group, they were shorter than times for haptic condition when the subjects trained with haptic first (H 1st group). This shows how training could lead to the same performances obtained with only haptic feedback in terms of task completion time. As expected, reach and return times were significantly shorter for movements towards the middle target, which involved a single degree of freedom (AA).

Interestingly, HIP trajectories for the reach phase were more similar for the haptic+visual feedback condition compared to the haptic feedback condition, even if the path drawn by the virtual object was not different for the two feedback conditions. We also found a difference in trajectory similarity related to the final target position: in absence of visual information on the penetration depth, movements towards the rightmost targets, in which the preferred arm stabilizes the movement, were less similar than movements towards the leftmost targets. This may be related to the asymmetry in feedback processing for movements of the right and left upper limb. Specifically, in neurologically healthy adults the preferred arm is generally faster and more accurate than the non-preferred arm [19], is specialized for limb trajectory control, and is more reliant on visual feedback. In contrast, the non-preferred arm relies on proprioceptive feedback to perform tasks such as object stabilization [20]. In the presence of ambiguous visual feedback the dominant hand performs the slower movement while the non-dominant hand (which relies more on haptic information) is less affected by the representation of its position.

Rehabilitation strategies that include bimanual movements seek to enhance movement control of the impaired limb and promote neural plasticity [21]. For hemiparetic patients (i.e., those without the residual ability to move the affected limb) the impaired limb can be rigidly coupled with the unimpaired limb, thereby using the unimpaired limb to direct the movements of the impaired limb (i.e., in mirror movements). The affected arm experiences better coordinated movement patterns which facilitates cortical reorganization [22]. Studies on bimanual practice employing both mirror and parallel movements showed hemispheric activation also during voluntary movements of the impaired arm [23]. Parallel movements, which are more similar to activities of daily living (e.g., transferring an object with two hands), have being recently evaluated as a bimanual training mode [24], [25]. While its superiority with respect to symmetrical movement recovery has not yet been established, it can be extended to a variety of robot-assisted bimanual exercises. The present study suggests that for parallel movements, the addition of visual feedback on the depth penetration does not affect task completion, which is often the primary objective of the subject [26]. It does however increase the coordination of both wrists during the exercise, which is essential for the performance of activities of daily living. Whether these results generalize for stroke survivors, and translate effectively to VR based rehabilitation is a topic of future work.

V. Conclusions

In bimanual virtual reality manipulation tasks the position of the end-effectors can only be sensed haptically after object contact. In this study we showed that the enhanced visual feedback is beneficial in tasks that require the hands to act in a cooperative fashion to achieve the end-goal. While this study was conducted on neurologically healthy individuals, future work will examine whether bimanual training can help stroke patients exploit the coupling between the upper limbs, thereby improving functional post-stroke outcomes.

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