Adding Haptic Feedback to Virtual Environments With a Cable-Driven Robot Improves Upper Limb Spatio-Temporal Parameters During a Manual Handling Task

Céline Faure, Alexis Fortin-Côté, *Member, IEEE*, Nicolas Robitaille, Philippe Cardou, *Member, IEEE*,
Clément Gosselin, *Member, IEEE*, Denis Laurendeau, *Member, IEEE*, Catherine Mercier,
Laurent Bouyer, and Bradford J. McFadyen

***Abstract*—Physical interactions within virtual environments are often limited to visual information within a restricted workspace. A new system exploiting a cable-driven parallel robot to combine visual and haptic information related to environmental physical constraints (e.g. shelving, object weight) was developed. The aim of this study was to evaluate the impact on user movement patterns of adding haptic feedback in a virtual environment with this robot. Twelve healthy participants executed a manual handling task under three conditions: 1) in a virtual environment with haptic feedback; 2) in a virtual environment without haptic feedback; 3) in a real physical environment. Temporal parameters (movement time, peak velocity, movement smoothness, time to maximum flexion, time to peak wrist velocity) and spatial parameters of movement (maximum trunk flexion, range of motion of the trunk, length of the trajectory, index of curvature and maximum clearance from the shelf) were analysed during the reaching, lowering and lifting phases. Our results suggest that adding haptic feedback improves spatial parameters of movement to better respect the environmental constraints. However, the visual information presented in the virtual environment through the head mounted display appears to have an impact on temporal parameters of movement leading to greater movement time. Taken together, our results suggest that a cable-driven robot can be a promising device to provide a more ecological context during complex tasks in virtual reality.**

***Index Terms*—Environmental constraints, handling, reaching, virtual reality.**

Manuscript received November 22, 2019; revised May 9, 2020 and August 4, 2020; accepted August 29, 2020. Date of publication September 2, 2020; date of current version October 8, 2020. This work was supported in part by the Fond de Recherche du Québec-Nature et Technologies (FRQ-NT; PC) and in part by the Natural Sciences and Engineering Research Council of Canada under Grant BJM: RGPIN/191782-2017 and Grant LB: RGPIN-2018-06184. The work of Catherine Mercier was supported by the Emeritus Research Scholar Award from the Fonds de recherche Québec-Santé (FRQS). *(Corresponding author: Bradford J. McFadyen.)*

Céline Faure, Nicolas Robitaille, Catherine Mercier, Laurent Bouyer, and Bradford J. McFadyen are with the Centre for Interdisciplinary Research in Rehabilitation and Social Integration, CIUSSS-CN, Quebec City, QC G1M 2S8, Canada (e-mail: brad.mcfadyen@fmed.ulaval.ca).

Alexis Fortin-Côté, Philippe Cardou, and Clément Gosselin are with the Department of Mechanical Engineering, Université Laval, Quebec City, QC G1V 0A6, Canada.

Denis Laurendeau is with the Department of Electrical and Computer Engineering, Université Laval, Quebec City, QC G1V 0A6, Canada.

Digital Object Identifier 10.1109/TNSRE.2020.3021200

I. INTRODUCTION

VIRTUAL Reality (VR) is a computer-based technology that provides a virtual environment (VE) in which a person can interact in real-time via multiple sensory channels [1]. Over the past several years, VR technology has become much more accessible and has emerged as a new tool for intervention in rehabilitation. The main strength of VR technology is its ability to harness neuroplastic mechanisms by providing meaningful, motivating, repetitive practice with salient and multimodal sensory feedback while also engaging cognitive processes, and promoting motor learning [2]. Studies have progressively demonstrated the potential of VR, and its use has even been recently recommended in a clinical practice guideline for adult stroke rehabilitation [3]. VR rehabilitation programs have the potential to increase movement practice and to supplement traditional therapy [3]–[5].

However, most VR systems in rehabilitation provide only visual feedback [6]. Haptic systems involving robots to provide tactile or interaction forces between the user and the predominantly visual VE has potential as a major development for VR-based rehabilitation [7]. The use of haptic devices in VE can provide an enriched sensory experience, add physical task constraints [8], potentially engage similar neural structures as when tasks are executed in physical environments [9] and may facilitate motor learning through enhanced sensory-motor integration [10]. Haptic systems also can result in more realistic movements performed within the VE as compared to the respective physical environment. For example, reaching movements were found to be straighter, more accurate, faster, and to involve greater ranges of shoulder and elbow joint excursions in a VE with haptic feedback [11]. Haptic feedback also appears critical for accurate and more realistic grasping movements [11], [12]. General performance within VEs involving the manipulation of objects with haptic feedback, have shown shorter times to complete tasks [14]. In addition, both spatial and temporal kinematics for reaching, grasping and transporting a ball in the presence of haptic feedback have been shown to be similar to those obtained in a physical environment [15]. Thus, haptic devices can improve the quality of sensory feedback within the VE and affect one's movement patterns for a given task.

Yet, as noted by [16], current haptic devices present different limitations such as being cumbersome (e.g., the CyberGrasp by CyberGlove Systems LLC) or constraining user movement with restricted workspaces or degrees-of-freedom (e.g., end-point robotic system like the MIT-MANUS by Interactive Motion Technologies or the Falcon by Novint Technologies). Cable-driven mechanisms have also seen some application for rehabilitation [16]–[18], but still have limited degrees of freedom or constrained workspace [20]. All of these limitations can restrict their use in more complex and ecological tasks, such as a manual handling from a standing posture, which is relevant to train daily activities, enhance transfer to real-world function and improve functional recovery [21].

Recently, a new prototype of a full body haptic interface was created to add haptic feedback to complex virtual tasks in a large workspace [22]. A cable-driven architecture composed of eight cables allowed the user to move an end-effector with six degrees of freedom within a workspace to provide haptic rendering of the weight of a virtual crate and any collisions with the VE constraints such as shelving. This prototype with combined visual and haptic feedback, has the potential to provide more natural, enriched environments for training manual handling tasks and is thus the focus of the present work. Knowing whether a cable-driven robot providing haptic feedback improves movement patterns during complex virtual tasks will be important for implementing the use of such devices in VR for skills training, rehabilitation and clinical assessment. Therefore, the objective of this study was to assess the impact on one's spatial and temporal movement patterns of using a cable-driven robot to add haptic feedback to a large space VE during a manual handling task. We hypothesized that the temporal and spatial parameters of grasping and free style object manipulation within a VE with such haptic feedback would be closer to that observed for the respective real physical environment than for the task within the same VE without haptic feedback.

II. Methods

A. Participants

Twelve healthy participants (7 female, mean age 28.1 ±4.7 years) were recruited. They had normal or corrected-to-normal vision, and did not report any neurological, orthopaedic or musculoskeletal disorders that could affect task performance. This study was approved by the local ethics committee of the "Centre Intégré Universitaire de Santé et de Services Sociaux de la Capitale-Nationale" (CER-2016-524) and all subjects provided written informed consent.

B. Handling Task Protocol

Participants were asked to perform a freestyle manual handling task to move a crate between two shelves set to 59 % and 36% of the participant's standing height. Participants stood with their arms resting along their sides at a distance from the shelf corresponding to the length from the glenohumeral joint to the middle of the palm. The initial position of the feet was indicated by a green virtual or real line on the floor. A virtual or real crate (30cm × 30cm × 28cm high) was positioned on a green target on the top shelf with a red target on the bottom shelf. At a verbal signal, participants were required to grasp the crate, lower it and place it on the bottom target, and then lift it back to the higher target after which they returned to the initial upright posture with their feet on the green line. These phases are shown in Fig. 1. Foot movement was not restricted, and participants could flex their lower limb joints along with the trunk. The task required more precision at the end of the lowering phase in order to pass the crate between the two shelves. Throughout the study, participants were instructed to perform the task at a comfortable pace and in a manner that felt most natural.

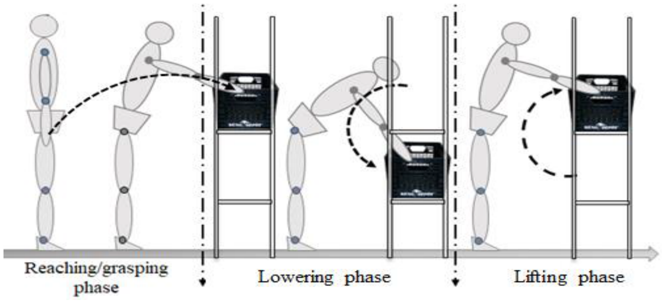

Fig. 1. Schema of the three analyzed phases of the handling task.

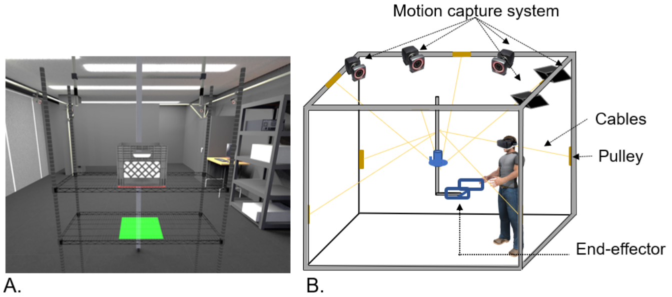

Fig. 2. A. Visual rendering of the virtual environment B. Simplified schema of the cable-driven robot used with the head mounted display.

Ten trials each were collected for 3 environments involving the real, physical environment (PE), a virtual environment presented in an HMD (Oculus Rift DK2, Oculus VR, USA) with haptic feedback (VE-Haptic) and without haptic feedback (VE-noHaptic). In the PE, the real crate had a mass of 2kg. For both the VE-Haptic and VE-NoHaptic conditions, the PE was computer simulated (Fig. 2.A.).

In the VE-Haptic condition, a six-degree-of-freedom cable-driven parallel mechanism (cable-driven robot; [22]) was used to create forces on an end-effector manipulated by the participant that simulated the crate mass of 2kg as well as the physical constraints of the shelves (mechanical stops in the vertical and horizontal directions) (Fig. 2.B.). To facilitate such simulation, the cable-driven robot was composed of 8 cables wound on fixed actuated pulleys at one end, six of which were attached to a rod connected to the 3D printed plastic end-effector simulating the crate handles. This set-up allowed motion around the longitudinal axis of the rod without encumbering the participants with the cables. The two other pullies were connected directly to the end-effector to control movement with respect to the rod. Within a workspace of approximately 1 m^3, the robot was able to apply net forces of ±5 N to the end-effector along the horizontal axes with vertical forces up to 15 N, and moments about all three axes of 0.1 Nm.

In the VE-NoHaptic condition, participants manipulated the virtual crate without haptic feedback. The virtual crate was attached to the participants' hands when the hands were within 5 cm of the middle of the virtual handles. The crate then followed hand movements while this distance was maintained. To become familiar with the VE, the robot and the task, participants first grasped and moved the crate (real or virtual) several times in different directions. They then practiced at least five reaching movements of each environment prior to its collection until they indicated they were comfortable with it. The order of presentation of the three environment blocks was pseudo-randomized between subjects. There were rest periods of approximately five minutes between blocks during which participants completed presence [23] and simulator-sickness questionnaires (SSQ) [24]. These questionnaires were used to monitor participants' presence in the VE as well as any negative effects induced by the VR system.

C. VE Rendering and Data Collection

Triads of three noncollinear reflective markers were placed on the back of the trunk (at the level of the fourth thoracic vertebra), on both feet and hands, on the real crate and the robot end-effector to be grasped, and on the head mounted display. Kinematic data were collected by a motion capture system composed of 12 infrared cameras (100 Hz; Vicon motion system Ltd. and Vicon Bonita, Oxford, UK). Part of these data were used for motion analysis as described below. These data were also sent to a visual interaction and rendering software (Vizard, WorldViz LLC, Santa Barbara, CA) which rendered, in real-time, the visual representation of the crate as well as the feet and hands of the participant. The first-person view of the VE was displayed in the HMD with a field of view of 110° and a refresh rate of 70Hz. The position of the center of the virtual crate was simultaneously recorded in Vizard (100 Hz).

D. Data Analysis

Before data collection, additional markers were temporarily placed on the glenohumeral joints, sternal notch, heels, midtoes and 5th metatarsals as anatomical references for a first calibration in an upright standing position with the trunk vertical. Raw marker coordinate data were filtered with a Butterworth, fourth-order, zero-lag filter with a cut-off frequency of 7Hz for the wrist and 8Hz for the trunk. Cut-off frequencies were chosen following a residual analysis [25] from two pilot participants by plotting the root mean square error of different filtered data as a function of the raw data and choosing the cut-off frequency at which this error curve broke linearity. Absolute trunk flexion was calculated as the angular movement from the calibrated up-right position in the sagittal plane that was aligned with the global reference system, and wrist velocity as the derivative of wrist position.

The manual handling task was broken down into three phases: 1) the reaching and grasping phase to take the crate; 2) the lowering phase; 3) the lifting phase. Onset of the initial reaching and grasping phase was defined as the time at which the linear velocity of the midpoint between the two wrists exceeded 0.5 cm/s along the antero-posterior axis (movement towards the shelf) and remained above this value for at least 0.3 seconds. The end of this phase was defined as the time the wrists were above the top shelf and the velocity fell below 0.5 cm/s and remained below this value for at least 0.5 s. The onset and offset times of the subsequent lowering and lifting phases were defined in the same way when the wrists were either just above the top or bottom shelves in accordance with the direction of movement. The timing criteria for onset and offset values were determined during pilot work to assure reliable detections of the onset and offset points across conditions. The main difference between the lowering and lifting phases was that the lower phase required more precision at the end of the movement to pass the crate between the shelves.

To describe temporal movement patterns, phase movement times (between onset and offset, in seconds), mean peak tangential velocity of both wrists together (in cm/sec), movement smoothness (number of times the wrist acceleration crossed zero), percentage of time to maximum trunk flexion (in %) and to peak wrist velocity (in %) were calculated for all phases. To describe the spatial patterns of movement, maximum trunk flexion (in degrees), range of motion (ROM) of trunk flexion/extension (in degrees), and the length of the wrist or crate trajectories (in cm) were calculated for all phases. For the lowering and the lifting phases, the crate trajectory curvature index (ratio of crate trajectory length to the linear distance between onset and offset positions), and the maximum clearance of the center of the crate from the shelf in the antero-posterior axis were also calculated.

E. Statistical Analysis

Statistical analyses were performed using R (version 3.6.3). Given the small sample size of the study, non-parametric analysis (NparLD, [26]) were used to compare differences between conditions. A separate NparLD analysis was performed for each phase of the movement (reaching and grasping/lowering/lifting) for all variables. Post-hoc analyses were performed using the Wilcoxon test to compare results across the three conditions. The presence and SSQ scores in VE-NoHaptic and VE-Haptic were compared with paired t-tests. Statistical significance was set at $P < 0.05$.

III. RESULTS

A. Effects of Haptic Feedback on Reaching and Grasping Phases

Average group data are presented in Table I.

1) Temporal Parameters: There was a main effect of condition on time to reach the crate ($P < 0.01$) and peak velocity ($P < 0.01$). However, there was no effect of condition on movement smoothness ($P = 0.84$), time to maximum trunk flexion ($P = 0.49$), or time to peak wrist velocity ($P = 0.93$).

Post-hoc analyses showed that, in comparison with PE, the participants took more time to reach the crate in VE-NoHaptic (+24.0%, $P < 0.01$) and VE-Haptic (+12.1%, $P = 0.01$), with lower peak velocity (−17.8%, $P < 0.01$; and −4.5%,

TABLE I

MEAN (SD) VALUES FOR THE REACHING AND GRASPING PHASE. ROM: RANGE OF MOTION, PE: PHYSICAL ENVIRONMENT, VE-NOHAPTIC: VIRTUAL ENVIRONMENT WITHOUT HAPTIC FEEDBACK, VE-HAPTIC: VIRTUAL ENVIRONMENT WITH THE CABLE-DRIVEN ROBOT. A,B,C $P < 0.05$ POST-HOC, BOLD VALUES ARE SIGNIFICANTLY DIFFERENT FROM THE PE CONDITION

	PE **(a)**		VE-noHaptic **(b)**			VE-Haptic **(c)**			P
Temporal parameters									
Movement time (sec)	1.22	(0.23)	**1.51**	**(0.20)**	**a,c**	**1.36**	**(0.21)**	**a,b**	**<0.01**
Peak velocity (cm/sec)	122.65	(13.69)	**100.81**	**(16.32)**	**a**	**104.88**	**(12.70)**	**a**	**<0.01**
Smoothness (number of zero-crossing)	2.48	(0.93)	2.51	(0.65)		2.64	(0.86)		0.839
Time to max. trunk flexion (% of movement time)	90.20	(20.41)	84.95	(29.21)		90.00	(21.11)		0.490
Time to peak wrist velocity (% of movement time)	37.75	(5.32)	38.81	(7.87)		37.15	(6.68)		0.935
Spatial parameters									
Maximum trunk flexion (°)	15.21	(8.48)	15.28	(9.87)		14.00	(9.76)		0.438
ROM trunk flexion (°)	14.78	(6.92)	15.70	(7.66)		13.27	(7.31)		0.137
Trajectory length (cm)	63.38	(6.09)	70.12	(6.30)	**c**	64.46	(6.47)	**b**	**<0.01**

TABLE II

MEAN (SD) VALUES FOR THE LOWERING PHASE. MAX.: MAXIMUM, ROM: RANGE OF MOTION, PE: PHYSICAL ENVIRONMENT, VE-NOHAPTIC: VIRTUAL ENVIRONMENT WITHOUT HAPTIC FEEDBACK, VE-HAPTIC: VIRTUAL ENVIRONMENT WITH THE CABLE-DRIVEN ROBOT A,B,C $P < 0.05$ POST-HOC, BOLD VALUES ARE SIGNIFICANTLY DIFFERENT FROM THE PE CONDITION

	PE **(a)**		VE-noHaptic **(b)**			VE-Haptic **(c)**			P
Temporal parameters									
Movement time (sec)	2.53	(0.30)	2.84	(0.45)	**c**	4.01	(0.66)	**a,b**	**<0.01**
Peak velocity (cm/sec)	91.37	(17.39)	**74.16**	**(14.78)**	**a,c**	**59.93**	**(10.62)**	**a,b**	**<0.01**
Smoothness (number of zero-crossing)	7.90	(1.55)	7.68	(1.80)	**c**	**16.25**	**(3.36)**	**a,b**	**<0.01**
Time to max. trunk flexion (% of movement time)	79.70	(21.96)	81.35	(17.45)		83.06	(18.23)		0.621
Time to peak wrist velocity (% of movement time)	27.21	(12.05)	45.82	(13.52)	**a,c**	32.56	(10.43)		**<0.01**
Spatial parameters									
Maximum trunk flexion (°)	70.49	(16.00)	71.14	(18.50)		65.57	(20.12)		0.090
ROM trunk flexion (°)	58.95	(14.85)	60.75	(19.22)		58.94	(18.72)		0.592
Trajectory length (cm)	135.44	(13.54)	122.38	(10.88)	**a,c**	139.43	(7.54)	**b**	**<0.01**
Index of curvature	3.47	(0.36)	**2.80**	**(0.21)**	**a,c**	3.50	(0.20)	**b**	**<0.01**
Clearance Max. from the shelf (cm)	33.92	(4.49)	30.11	(5.16)	**c**	36.05	(3.71)	**b**	**<0.01**

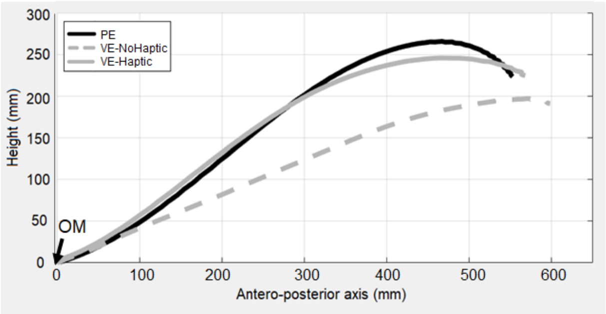

Fig. 3. Midpoint wrist trajectories of one participant for all conditions, for the reaching and grasping phase (sagittal view). The solid black line represents the physical environment condition (PE), the dashed grey line represents the virtual environment with the cable-driven robot condition (VE-Haptic), the grey solid line represents the Virtual Environment without Haptic Feedback condition (VE-noHaptic). OM: Onset of movement.

$P < 0.01$ respectively). The time to reach the crate was longer in VE-NoHaptic than VE-Haptic (+11.9%, $P = 0.04$), but the peak velocity was not different between VE-Haptic and VE-NoHaptic ($P = 0.08$).

2) Spatial Parameters: Fig. 3. illustrates the mean wrist trajectories for one participant for all conditions.

There was a main effect of condition on trajectory length ($P < 0.01$), but no effect on maximum trunk flexion ($P = 0.44$) or trunk ROM ($P = 0.14$). In comparison with PE, the wrist trajectory to reach the crate was longer in VE-NoHaptic (+10.6%, $P < 0.01$) and was not different from VE-Haptic ($P = 0.97$). The wrist trajectory to reach the crate was also longer in VE-NoHaptic than in VE-Haptic (+8.8%, $P = 0.01$).

B. Effect of Haptic Feedback on the Lower Phase

The average group data are presented in Table II.

1) Temporal Parameters: There were main effects of condition on time to lower the crate ($P < 0.01$), peak velocity ($P < 0.01$), movement smoothness ($P < 0.01$), and time to peak wrist velocity ($P < 0.01$). There was no effect of condition on time to maximum trunk flexion ($P = 0.62$). More precisely, post-hoc analyses showed that, when participants used the cable-driven robot (VE-Haptic), they took more time to lower the crate in comparison with PE (+58.5%) and VE-NoHaptic (+41.2%) ($P < 0.01$ for both), with lower peak velocity (PE; −34.4%, VE-NoHaptic; −19.2%, $P < 0.01$ for both), and less smooth movement (PE;+105.7%, VE-NoHaptic; +111.6%, $P < 0.01$ for both). There were no differences between PE and VE-NoHaptic in the time to lower the crate ($P = 0.06$), or for movement smoothness ($P = 0.840$), but the peak velocity was lower in VE-NoHaptic than PE (−18.8%, $P = 0.01$). The time to peak wrist velocity was earlier for PE (−18.61%, $P < 0.01$), and VE-Haptic (−13.26%, $P = 0.04$) in comparison with VE-NoHaptic, with no difference between VE-Haptic and PE ($P = 0.25$).

TABLE III

MEAN (SD) VALUES FOR THE LIFTING PHASE. MAX.: MAXIMUM, ROM: RANGE OF MOTION, PE: PHYSICAL ENVIRONMENT, VE-NOHAPTIC: VIRTUAL ENVIRONMENT WITHOUT HAPTIC FEEDBACK, VE-HAPTIC: VIRTUAL ENVIRONMENT WITH THE CABLE-DRIVEN ROBOT, VE+PE: VIRTUAL ENVIRONMENT WHILE MANIPULATING THE REAL CRATE IN THE PHYSICAL ENVIRONMENT, A,B,C $P < 0.05$ POST-HOC, VALUES HIGHLIGHTED IN GREY ARE SIGNIFICANTLY DIFFERENT FROM THE PE CONDITION

	PE **(a)**		VE-noHaptic **(b)**			VE-Haptic **(c)**			P
Temporal parameters									
Movement time (sec)	2.62	(0.33)	2.74	(0.37)	**c**	**3.51**	**(0.54)**	**a,b**	**<0.01**
Peak velocity (cm/sec)	86.29	(11.96)	81.16	(11.34)	**c**	**62.39**	**(7.91)**	**a,b**	**<0.01**
Smoothness (number of zero-crossing)	7.83	(1.77)	6.33	(1.58)	**a,c**	**14.55**	**(3.48)**	**a,b**	**<0.01**
Time to max. trunk flexion (% of movement time)	14.66	(15.92)	19.93	(28.53)		14.31	(16.29)		0.972
Time to peak wrist velocity (% of movement time)	49.13	(11.40)	42.71	(10.93)		44.55	(13.21)		0.199
Spatial parameters									
Maximum trunk flexion (°)	67.76	(18.89)	68.75	(19.51)		64.09	(20.01)		0.244
ROM trunk flexion (°)	59.62	(15.78)	52.42	(18.67)		52.37	(18.55)		0.087
Trajectory length (cm)	135.00	(12.95)	125.20	(13.56)	**c**	135.94	(9.67)	**b**	**<0.05**
Index of curvature	3.41	(0.34)	3.04	(0.38)	**a,c**	3.30	(0.24)	**b**	**<0.05**
Clearance Max. from the shelf (cm)	34.08	(3.76)	**28.16**	**(5.82)**	**a,c**	36.50	(3.67)	**b**	**<0.01**

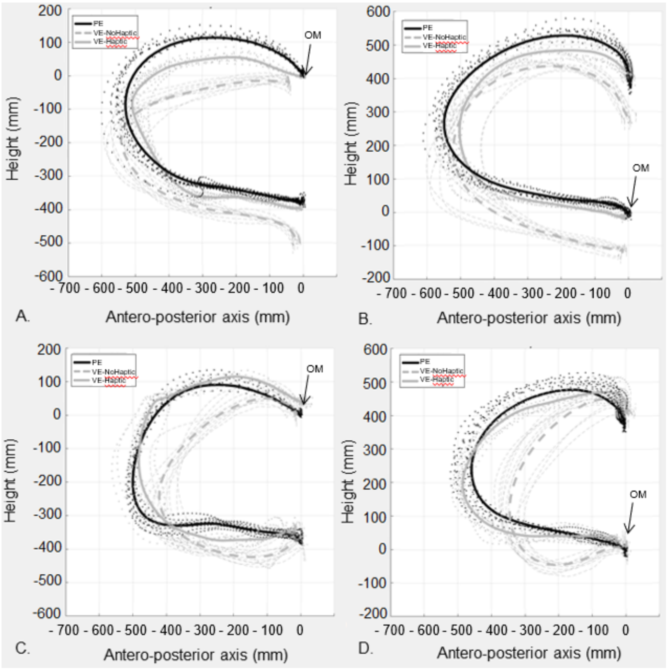

Fig. 4. Mean crate trajectory for two participants (sagittal view) during A.C. lower phase B.D. lifting phase. The black solid line represents mean trajectory for the Physical Environment condition (PE), the black dot lines represent each trials of the PE condition, the thick dashed grey line represent the Virtual Environment without Haptic Feedback condition (VE-noHaptic), the thin dashed grey lines represent each trials of the VE-noHaptic condition, the tick grey solid line represent the Virtual Environment with the cable-driven robot condition, the grey dot line represents each trials of the VE-Haptic condition. OM: Onset of movement.

2) Spatial Parameters: Fig. 4. A and C illustrate the mean crate trajectories for two representative participants for all conditions. It can be seen that while participants used different movements (P1 passed through the virtual shelving), qualitatively, trajectories for VE-Haptic were closer to PE than VE-NoHaptic. Only one participant showed a trajectory for VE-NoHaptic that was close to PE.

There was a main effect of condition on trajectory length ($P < 0.01$), crate trajectory curvature index ($P < 0.01$), and on maximum shelf clearance ($P < 0.01$). However, there was no effect of condition on maximum trunk flexion and trunk ROM ($P = 0.09$, $P = 0.59$, respectively).

More precisely, crate trajectory curvature index and trajectory length were smaller in VE-NoHaptic compared to VE-Haptic (−19.9%, $P < 0.01$ and −17.0cm, $P < 0.01$, respectively) and PE (−19.1%, $P < 0.01$ and −13.1cm, $P = 0.02$). Between PE and VE-Haptic, there were no differences in the curvature index ($P = 0.72$), or the trajectory length ($P = 0.41$). The maximum shelf clearance was shorter in VE-NoHaptic compared to VE-Haptic (−6.0cm, $P < 0.01$). There were no clearance differences between PE and VE-NoHaptic ($P = 0.08$) or PE and VE-Haptic ($P = 0.33$).

C. Effect of Haptic Feedback on the Lifting Phase

Average group data are presented in Table III.

1) Temporal Parameters: There was a main effect of condition on time to lower the crate ($P < 0.01$), peak velocity ($P < 0.01$) and movement smoothness ($P < 0.01$). There was no effect of condition on the time to maximum trunk flexion ($P = 0.97$), time to peak wrist velocity ($P = 0.20$), maximum trunk flexion ($P = 0.24$) or trunk ROM ($P = 0.09$).

More precisely, post-hoc analyses showed that, when participants used the cable-driven robot (VE-Haptic), in comparison with PE and VE-NoHaptic, more time was needed to lift the crate (PE; +34.0%, VE-NoHaptic; +28.1 % $P < 0.01$ for both), with lower peak velocity (PE; −27.7%, VE-NoHaptic; −23.1 %, $P < 0.001$ for both), and less movement smoothness (PE; +86.3%, VE-NoHaptic; +130.5%, $P < 0.01$ for both). The movement was smoother in VE-NoHaptic than PE (−19.26%, $P = 0.04$). There were no differences between PE and VE-NoHaptic in the time to lift the crate ($P = 0.33$), or for the peak velocity ($P = 0.11$).

2) Spatial Parameters: Fig. 4. B. and D. illustrate the mean crate trajectories for the same two participants for all conditions. There was a main effect of condition on the trajectory length ($P = 0.031$), on the curvature index ($P = 0.021$), and on the maximum shelf clearance ($P < 0.01$).

More precisely, in comparison with VE-NoHaptic, greater values were found for VE-Haptic and PE for maximum shelf clearance (+8.43cm, $P < 0.01$ and +5.92cm, $P = 0.01$ respectively), and the curvature index (+8.6%, $P = 0.02$ and 12.2%, $P = 0.03$ respectively). There were no differences between PE and VE-Haptic on the maximum shelf clearance ($P = 0.13$), or the curvature index ($P = 0.56$). Finally, the trajectory length was shorter in VE-NoHaptic compared to VE-Haptic (-10.74cm, $P < 0.01$), but there were no differences between PE and either VE-NoHaptic or VE-Haptic ($P = 0.08$, $P = 0.99$ respectively).

D. Presence and Cybersickness

The presence scores were not statistically different ($P = 0.52$) between VE-NoHaptic and VE- Haptic. Mean scores out of 147 (SD) were 112.8 (13.5) for VE-NoHaptic and 109.9 (10.8) for VE-Haptic. The mean weighted SSQ scores out of 235.62 (SD), were 7.2 (8.5) for VE-NoHaptic and 7.2 (6.4) for VE-Haptic, indicating negligible cybersickness symptoms for both conditions.

IV. DISCUSSION

Previous studies have compared movements between physical and virtual environments. The present study investigated a complex task involving manual handling during standing using a cable-driven robot to introduce haptic feedback related to the physical constraints of both the environment and the object to be manipulated. Knowing whether and how a cable-driven robot can enhance visual information during complex tasks in a VE will be important for optimizing the use of such devices in rehabilitation. The results suggest that adding haptic feedback to the VE improves spatial parameters of movement that better respect environmental constraints. However, temporal parameters such as movement time and velocity appear to be more related to visual feedback. These results show that adding haptic feedback to VEs is important to develop more complex tasks for VR in rehabilitation. These richer, multisensory VEs provide more ecological feedback influencing the planning and control for more realistic movement important to improving motor learning and transfer of skills to real life.

A. Effect of Haptic Feedback on the Reaching and Grasping Phase

As described in earlier studies, the wrist velocity profile during reaching to grasp is asymmetrically bell-shaped with a peak at 30-40% of total movement time [27]. Our results reproduced this profile (not shown) with a time to peak wrist velocity on average at 37.9% of total movement time across conditions. Thus, the temporal organisation of reaching in VE was close to PE whether haptic feedback was present or not. However, the movement appeared to be slowed down for both VE conditions, but even more so without haptic feedback. On-line control of hand movement in a VE may have been more difficult. As previously shown, the presence of information about physical contact with the environment has been shown to decrease movement time [28]. On-line control of the hand in VE may have been more difficult. Visual feedback of one's hands plays an important role to control pointing or grasping movements [29]–[31]. In addition, visual feedback of the target or any obstacle along the hand path is also important [29], [32]. Slower movements have been often reported during reaching and grasping movements in VEs [15], [33], [34]. Finally, it has also been shown that presence of information about physical contact within the environment also contributes to decrease movement time, in other words, to speed up movement [34]. The present results are aligned with these previous findings regarding VE and contact effects, with observed slower movements for both VE conditions compared to the PE condition and faster movements in both environments with physical contact compared (PE and VE-Haptic) to VE-NoHaptic.

With respect to spatial changes, the length of the movement trajectory to grasp the crate was increased (+5.6cm on average) with no haptic constraint at the end of movement (VE-NoHaptic). Adding haptic feedback appeared to improve the spatial organisation of movement, with participants reaching more realistically towards the crate (i.e., closer to PE). It is known that prior information about contact cues and local constraints is used to organize one's movements to grasp objects [28], [35]. The differences in movement trajectories for VE-NoHaptic may also have been due to a need to have a better viewing angle in order to see the hands and their path [36], or even by the difference in physical manipulation following the grasping of the crate [37]. Further work is required in order to better understand differences in spatial organisation of movements during the grasping phase.

B. Effect of Haptic Feedback on the Lowering and Lifting Phases

The main difference between the lowering and lifting phases was that participants had to pass the 28 cm high crate between shelves with a vertical spacing of about 38cm (± 1.5 cm) during the lowering phase. This required more movement precision than during the lifting phase in order to avoid contact with the real or haptic-simulated shelves. However, participants were instructed to perform the task in a manner that felt most natural, without any instruction about precision or collision avoidance.

With respect to spatial changes, in the absence of haptic feedback, the trajectory of the crate was different from that of other conditions throughout movement. From the participants' perspective, visual evaluation of the relative distance between the crate and the shelf could be difficult.

Indeed, the visual system is known to be limited in estimating depth distance (i.e. in the radial direction relative to the observer) on the basis of binocular cues alone [38] and the precision of visual information is higher in the azimuth side-to-side direction than in the orthogonal depth direction [39]. Adding haptic feedback within the VE improved the spatial performance of the crate trajectory during both lowering and lifting phases. It could be hypothesized that haptic feedback of the shelf allowed one to calibrate depth perception by providing an error signal when the crate hit the shelf. As described in previous studies, the lack of opportunity for the system to calibrate itself could change performance [40]–[43]. However, the different VE-NoHaptic trajectory of the crate could also be a strategy to minimize effort and maximize performance (less movement time compared to VE-Haptic) in the absence of any real risk of collision. Indeed, during manual obstacle avoidance, straighter paths reduce biomechanical costs, but increase the risk of collision [32].

As would be expected for the less precise lifting phase, the time to peak wrist velocity ranged from 42.7 to 49.1% of movement time across conditions with no significant differences. Yet, during lowering, we hypothesized that the presence of haptic feedback would have an effect, but it was not clear exactly how it would affect movement performance. When movement requires more precision, deceleration tends to begin sooner [44], [45]. This was found for the time to peak wrist velocity for PE (27% of movement time for lowering versus 49 % for lifting) as well as VE-Haptic (32.6% versus 44.6%) but not for VE-NoHaptic (45.8% versus 42.7%). It thus appears that in the absence of haptic feedback, lowering phase movement behavior was not influenced by task precision. The physical constraints associated with the visual environment, therefore, render such behavior in the VE more realistic. As suggested above, in the absence of haptic feedback and therefore of any risk of collision, biomechanical cost reduction may have had a higher contribution to movement planning than spatial error.

While the VE-Haptic condition appeared to render spatial parameters of movement closer to that seen for the PE condition, movement was still slower and less smooth during VE-Haptic even during the less precise lifting phase. A possible reason for this difference in VE-Haptic could be due to the constant minimal cable tension and friction in the winches during movement. This may have had an effect on the fidelity of the "virtual touch" of the environment and is known in robotics as the transparency issue [46]. In addition, a lack of experience with the cable-driven robot could also be a factor, and longer practice could improve the participant's performance. Further work to reduce cable noise and explore practice effects is required. However, this does not negate the general effects observed here and the potential of this device to improve the virtual experience.

Upper limb movement from a standing position involves whole-body control for balance and reaching, including coordination between the trunk and upper limbs [47]. It was found in the present study that trunk movement was not significantly changed across conditions and haptic feedback only affected upper limb spatial parameters. This may suggest that trunk movement is globally controlled for upper limb transport with refinements for grasping and object transport more related to the haptic interaction with the object. There is some support for this theory of autonomy between transport and grasping in the literature [47], [48]. Perhaps crate characteristics (e.g., weight, fragility) could have greater effects on trunk flexion to accommodate crate transport and postural support.

However, it must be pointed out that even though all participants began in the same upright posture and relative distance to the shelves, foot movement was allowed during the tasks. In ad-hoc analyses (using the NparLD statistics), we found that during the first Reaching/Grasping phase, participants on average placed a foot slightly closer to the shelves during PE (38.7 (10.3) cm) and VE-NoHaptic (34.9 (8.9) cm) conditions compared to the VE-Haptic condition (41.9 (8.4) cm). Foot proximities for PE and VE-NoHaptic were significantly different from VE-Haptic ($P = 0.03$ and $P = 0.002$ respectively) but not from each other. Yet, this slightly greater distance of the foot from the shelves during the VE-Haptic condition is counter intuitive with respect to the slightly, non-significant, decreased maximum trunk angle observed during the Reaching/Grasping phase for this condition. Further work is required to assess whole body control.

Adding haptic feedback with the cable-driven robot did not improve the presence scores compared with the VE-NoHaptic condition. This could be due, in part, to the transparency issue noted above. As suggested by [50], transparency issues could alter participant performance, and negatively impact presence in VE.

C. Limits

This study had a small sample size and further work should therefore confirm our results with larger cohorts and different populations. Surface friction was not simulated or accounted for in the study, and participants may have slid on the virtual surface. However, results presented in Fig. 4 suggest such post-contact movement was not significant. Virtual reality involves delays in rendering images to the HMD. Based on sampling frequencies and refresh rates, we estimate that worse case delays would have been no more than 40 ms. Participants did not report any issues in perceived timing when contacting and manipulating the virtual crates. In addition, feelings of cybersickness were negligible.

V. CONCLUSION

The aim of this study was to assess the impact on user movement of adding haptic feedback using a cable-driven robot during a manual handling task in a VE. The results showed that adding haptic feedback within the VE improves the spatial organisation of movement, resulting in more realistic end-effector trajectories and general motor behaviours. The precision demands of the task were particularly dependant on whether haptic information was involved or not. However, temporal parameters appear to be more influenced by visual feedback, and only when the task required precision.

These results are important to inform future ecological VEs designs for rehabilitation to improve motor learning and transfer training to real life. While technical limitations in the visual and haptic interfaces need further attention, the cable-driven robot has been shown to be a promising device to provide more ecological haptic feedback during complex tasks.

The development of technologies will continue to improve, making such systems more realistic. Finally, this cable-driven robot system has the advantage of being reconfigured to other mobility-based scenarios and complex tasks such as physical interaction with the environment during navigation, something that is currently further explored by this team.

ACKNOWLEDGMENT

The authors would like to thank Guy St. Vincent, Simon Foucault, Thierry Laliberté, Steve Forest, Félix Fiset, and Frédéric Dumont for their technical and general assistance throughout the project, and to Jean Leblond for statistical consulting.

REFERENCES

[1] P. L. Weiss, E. A. Keshner, and M. F. Levin, Eds., *Virtual Reality for Physical and Motor Rehabilitation*. New York, NY, USA: Springer, 2014.

[2] M. F. Levin, P. L. Weiss, and E. A. Keshner, "Emergence of virtual reality as a tool for upper limb rehabilitation: Incorporation of motor control and motor learning principles," *Phys. Therapy*, vol. 95, no. 3, pp. 415–425, Mar. 2015, doi: 10.2522/ptj.20130579.

[3] C. J. Winstein *et al.*, "Guidelines for adult stroke rehabilitation and recovery: A guideline for healthcare professionals from the American heart association/American stroke association," *Stroke*, vol. 47, no. 6, pp. e98–e169, Jun. 2016, doi: 10.1161/STR.0000000000000098.

[4] K. E. Laver, B. Lange, S. George, J. E. Deutsch, G. Saposnik, and M. Crotty, "Virtual reality for stroke rehabilitation," *Stroke*, vol. 49, no. 4, pp. e160–e161, Apr. 2018, doi: 10.1161/STROKEAHA.117.020275.

[5] M. C. Howard, "A meta-analysis and systematic literature review of virtual reality rehabilitation programs," *Comput. Hum. Behav.*, vol. 70, pp. 317–327, May 2017, doi: 10.1016/j.chb.2017.01.013.

[6] M. Maier, B. R. Ballester, A. Duff, E. D. Oller, and P. F. M. J. Verschure, "Effect of specific over nonspecific VR-based rehabilitation on poststroke motor recovery: A systematic meta-analysis," *Neurorehabilitation Neural Repair*, vol. 33, no. 2, pp. 112–129, Feb. 2019, doi: 10.1177/1545968318820169.

[7] M. S. Cameirão, S. B. I. Badia, E. Duarte, A. Frisoli, and P. F. M. J. Verschure, "The combined impact of virtual reality neurorehabilitation and its interfaces on upper extremity functional recovery in patients with chronic stroke," *Stroke*, vol. 43, no. 10, pp. 2720–2728, Oct. 2012, doi: 10.1161/STROKEAHA.112.653196.

[8] S. V. Adamovich, G. G. Fluet, E. Tunik, and A. S. Merians, "Sensorimotor training in virtual reality: A review," *NeuroRehabilitation*, vol. 25, no. 1, pp. 29–44, Aug. 2009, doi: 10.3233/NRE-2009-0497.

[9] M. Rakusa *et al.*, "Assessment of the haptic robot as a new tool for the study of the neural control of reaching," *Neurol. Sci.*, vol. 34, no. 10, pp. 1779–1790, Oct. 2013, doi: 10.1007/s10072-013-1337-5.

[10] S. Demain, C. D. Metcalf, G. V. Merrett, D. Zheng, and S. Cunningham, "A narrative review on haptic devices: Relating the physiology and psychophysical properties of the hand to devices for rehabilitation in central nervous system disorders," *Disab. Rehabil., Assistive Technol.*, vol. 8, no. 3, pp. 181–189, May 2013, doi: 10.3109/17483107.2012.697532.

[11] M. F. Levin, E. C. Magdalon, S. M. Michaelsen, and A. A. F. Quevedo, "Quality of grasping and the role of haptics in a 3-D immersive virtual reality environment in individuals with stroke," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 23, no. 6, pp. 1047–1055, Nov. 2015, doi: 10.1109/TNSRE.2014.2387412.

[12] G. P. Bingham, A. Bradley, M. Bailey, and R. Vinner, "Accommodation, occlusion, and disparity matching are used to guide reaching: A comparison of actual versus virtual environments," *J. Exp. Psychol., Hum. Perception Perform.*, vol. 27, no. 6, pp. 1314–1334, 2001, doi: 10.1037//0096-1523.27.6.1314.

[13] R. L. Whitwell, T. Ganel, C. M. Byrne, and M. A. Goodale, "Real-time vision, tactile cues, and visual form agnosia: Removing haptic feedback from a 'natural' grasping task induces pantomime-like grasps," *Frontiers Hum. Neurosci.*, vol. 9, p. 216, May 2015, doi: 10.3389/fnhum.2015.00216.

[14] E.-L. Sallnäs, K. Rassmus-Gröhn, and C. Sjöström, "Supporting presence in collaborative environments by haptic force feedback," *ACM Trans. Comput.-Hum. Interact.*, vol. 7, no. 4, pp. 461–476, Dec. 2000, doi: 10.1145/365058.365086.

[15] A. Viau, A. G. Feldman, B. J. McFadyen, and M. F. Levin, "Reaching in reality and virtual reality: A comparison of movement kinematics in healthy subjects and in adults with hemiparesis," *J. Neuroeng. Rehabil.*, vol. 1, no. 1, p. 7, 2004.

[16] L. Piggott, S. Wagner, and M. Ziat, "Haptic neurorehabilitation and virtual reality for upper limb paralysis: A review," *Crit. Rev. Biomed. Eng.*, vol. 44, nos. 1–2, pp. 1–32, 2016, doi: 10.1615/CritRevBiomedEng.2016016046.

[17] J. Kang, D. Martelli, V. Vashista, I. Martinez-Hernandez, H. Kim, and S. K. Agrawal, "Robot-driven downward pelvic pull to improve crouch gait in children with cerebral palsy," *Sci. Robot.*, vol. 2, no. 8, Jul. 2017, Art. no. eaan2634, doi: 10.1126/scirobotics.aan2634.

[18] L. Tappeiner, E. Ottaviano, and M. L. Husty, "A cable-driven robot for upper limb rehabilitation inspired by the mirror therapy," in *Computational Kinematics*. Cham, Switzerland: Springer, 2018, pp. 174–181.

[19] D. Surdilovic, R. Bernhardt, T. Schmidt, and J. Zhang, "STRING-MAN: A novel wire robot for gait rehabilitation," in *Advances in Rehabilitation Robotics*, vol. 306. Berlin, Germany: Springer, 2004, pp. 413–424.

[20] A. Fortin-Côté, "Développement d'un mécanisme parallèle entraîné par câbles utilisé comme interface à retour haptique visant la réadaptation physique en environnement immersif," Ph.D. dissertation, Univ. Laval, Québec, QC, Canada, 2017.

[21] A. S. Rizzo and G. J. Kim, "A SWOT analysis of the field of virtual reality rehabilitation and therapy," *Presence, Teleoperators Virtual Environ.*, vol. 14, no. 2, pp. 119–146, Apr. 2005, doi: 10.1162/1054746053967094.

[22] A. Fortin-Côté *et al.*, "On the design of a novel cable-driven parallel robot capable of large rotation about one axis," in *Cable-Driven Parallel Robots*, vol. 53, C. Gosselin, P. Cardou, T. Bruckmann, and A. Pott, Eds. Cham, Switzerland: Springer, 2018, pp. 390–401.

[23] B. G. Witmer and M. J. Singer, "Measuring presence in virtual environments: A presence questionnaire," *Presence*, vol. 7, no. 3, pp. 225–240, 1998, doi: 10.1162/105474698565686.

[24] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness," *Int. J. Aviation Psychol.*, vol. 3, no. 3, pp. 203–220, Jul. 1993, doi: 10.1207/s15327108ijap0303_3.

[25] D. A. Winter, *Biomechanics and Motor Control of Human Movement*. Hoboken, NJ, USA: Wiley, 2009.

[26] K. Noguchi, Y. R. Gel, E. Brunner, and F. Konietschke, "nparLD: AnRSoftware package for the nonparametric analysis of longitudinal data in factorial experiments," *J. Stat. Softw.*, vol. 50, no. 12, pp. 1–23, 2012, doi: 10.18637/jss.v050.i12.

[27] M. Jeannerod, "The timing of natural prehension movements," *J. Motor Behav.*, vol. 16, no. 3, pp. 235–254, Sep. 1984, doi: 10.1080/00222895.1984.10735319.

[28] M. A. Zahariev and C. L. MacKenzie, "Grasping at 'thin air': Multimodal contact cues for reaching and grasping," *Exp. Brain Res.*, vol. 180, no. 1, pp. 69–84, Jun. 2007, doi: 10.1007/s00221-006-0845-4.

[29] V. Gritsenko, S. Yakovenko, and J. F. Kalaska, "Integration of predictive feedforward and sensory feedback signals for online control of visually guided movement," *J. Neurophysiol.*, vol. 102, no. 2, pp. 914–930, Aug. 2009, doi: 10.1152/jn.91324.2008.

[30] L. Proteau and G. Isabelle, "On the role of visual afferent information for the control of aiming movements toward targets of different sizes," *J. Motor Behav.*, vol. 34, no. 4, pp. 367–384, Dec. 2002, doi: 10.1080/00222890209601954.

[31] M. Desmurget and S. Grafton, "Feedback control for fast reaching movements," *Trends Cognit. Sci.*, vol. 4, no. 11, p. 9, 2000.

[32] R. G. Cohen, J. C. Biddle, and D. A. Rosenbaum, "Manual obstacle avoidance takes into account visual uncertainty, motor noise, and biomechanical costs," *Exp. Brain Res.*, vol. 201, no. 3, pp. 587–592, Mar. 2010, doi: 10.1007/s00221-009-2042-8.

[33] E. C. Magdalon, S. M. Michaelsen, A. A. Quevedo, and M. F. Levin, "Comparison of grasping movements made by healthy subjects in a 3-dimensional immersive virtual versus physical environment," *Acta Psychol.*, vol. 138, no. 1, pp. 126–134, Sep. 2011, doi: 10.1016/j.actpsy.2011.05.015.

[34] L. A. Knaut, S. K. Subramanian, B. J. McFadyen, D. Bourbonnais, and M. F. Levin, "Kinematics of pointing movements made in a virtual versus a physical 3-dimensional environment in healthy and stroke subjects," *Arch. Phys. Med. Rehabil.*, vol. 90, no. 5, pp. 793–802, May 2009, doi: 10.1016/j.apmr.2008.10.030.

[35] R. Verheij, E. Brenner, and J. B. J. Smeets, "Why are the digits' paths curved vertically in human grasping movements?" *Exp. Brain Res.*, vol. 224, no. 1, pp. 59–68, Jan. 2013, doi: 10.1007/s00221-012-3288-0.

[36] K. I. Ustinova, J. Perkins, L. Szostakowski, L. S. Tamkei, and W. A. Leonard, "Effect of viewing angle on arm reaching while standing in a virtual environment: Potential for virtual rehabilitation," *Acta Psychologica*, vol. 133, no. 2, pp. 180–190, Feb. 2010, doi: 10.1016/j.actpsy.2009.11.006.

[37] C. Armbrüster and W. Spijkers, "Movement planning in prehension: Do intended actions influence the initial reach and grasp movement?" *Motor Control*, vol. 10, no. 4, pp. 311–329, Oct. 2006, doi: 10.1123/mcj.10.4.311.

[38] P. B. Hibbard and M. F. Bradshaw, "Reaching for virtual objects: Binocular disparity and the control of prehension," *Exp. Brain Res.*, vol. 148, no. 2, pp. 196–201, Jan. 2003, doi: 10.1007/s00221-002-1295-2.

[39] R. J. van Beers, D. M. Wolpert, and P. Haggard, “When feeling is more important than seeing in sensorimotor adaptation,” *Current Biol.*, vol. 12, no. 10, pp. 834–837, May 2002, doi: 10.1016/S0960-9822(02)00836-9.

[40] G. Bingham, R. Coats, and M. Mon-Williams, “Natural prehension in trials without haptic feedback but only when calibration is allowed,” *Neuropsychologia*, vol. 45, no. 2, pp. 288–294, 2007, doi: 10.1016/j.neuropsychologia.2006.07.011.

[41] G. P. Bingham and M. A. Mon-Williams, “The dynamics of sensorimotor calibration in reaching-to-grasp movements,” *J. Neurophysiol.*, vol. 110, no. 12, pp. 2857–2862, Dec. 2013, doi: 10.1152/jn.00112.2013.

[42] B. R. Fajen, “Perceiving possibilities for action: On the necessity of calibration and perceptual learning for the visual guidance of action,” *Perception*, vol. 34, no. 6, pp. 717–740, Jun. 2005, doi: 10.1068/p5405.

[43] B. R. Fajen, “Guiding locomotion in complex, dynamic environments,” *Frontiers Behav. Neurosci.*, vol. 7, p. 85, Jul. 2013, doi: 10.3389/fnbeh.2013.00085.

[44] C. L. MacKenzie, R. G. Marteniuk, C. Dugas, D. Liske, and B. Eickmeier, “Three-dimensional movement trajectories in fitts’ task: Implications for control,” *Quart. J. Exp. Psychol. A*, vol. 39, no. 4, pp. 629–647, Nov. 1987, doi: 10.1080/14640748708401806.

[45] R. G. Marteniuk, C. L. Mackenzie, M. Jeannerod, S. Athenes, and C. Dugas, “Constraints on human arm movement trajectories,” *Can. J. Psychol./Revue Canadienne de Psychologie*, vol. 41, no. 3, pp. 365–378, 1987, doi: 10.1037/h0084157.

[46] N. Gurari and G. Baud-Bovy, “Customization, control, and characterization of a commercial haptic device for high-fidelity rendering of weak forces,” *J. Neurosci. Methods*, vol. 235, pp. 169–180, Sep. 2014, doi: 10.1016/j.jneumeth.2014.07.001.

[47] Y. Tomita, A. G. Feldman, and M. F. Levin, “Referent control and motor equivalence of reaching from standing,” *J. Neurophysiol.*, vol. 117, no. 1, pp. 303–315, Jan. 2017, doi: 10.1152/jn.00292.2016.

[48] T. R. Kaminski, C. Bock, and A. M. Gentile, “The coordination between trunk and arm motion during pointing movements,” *Exp. Brain Res.*, vol. 106, no. 3, pp. 457–466, 1995, doi: 10.1007/BF00231068.

[49] J. Wang and G. E. Stelmach, “Coordination among the body segments during reach-to-grasp action involving the trunk,” *Exp. Brain Res.*, vol. 123, no. 3, pp. 346–350, Nov. 1998, doi: 10.1007/s002210050578.

[50] B. G. Witmer, C. J. Jerome, and M. J. Singer, “The factor structure of the presence questionnaire,” *Presence, Teleoperators Virtual Environ.*, vol. 14, no. 3, pp. 298–312, Jun. 2005, doi: 10.1162/105474605323384654.