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ORIGINAL ARTICLE

Kinematics of aimed movements in ecological immersive virtual reality: a comparative study with real world

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Abstract
Virtual reality (VR) has recently emerged as a promising technology to rehabilitate upper limb functions after stroke. To promote the recovery of functions, retraining physiological movement patterns is essential. However, it is still unclear whether VR can elicit functional movements that are similar to those performed in the real world (RW). This study aimed to investigate the kinematics of reach-to-grasp and transport movements performed in the real world and immersive VR by examining whether kinematic differences between the two conditions exist and their extent. A within-subject repeated-measures study was conducted. A realistic setup resembling a supermarket shelf unit was built in RW and VR. The analysis compared reaching and transport gestures in VR and RW, also considering potential differences due to: (i) holding the controller needed to interact with virtual items, (ii) hand dominance, and (iii) target positions. Ten healthy young adults were enrolled in the study. Motion data analysis showed that reach-to-grasp and transport required more time in VR, and that holding the controller had no effects. No major differences occurred between the two hands. Joint angles, except for thorax rotation, and hand trajectory curvature were comparable across conditions, suggesting that VR has the potentialities to retrain physiological movement patterns. Results were satisfying, though they did not demonstrate the superiority of ecological environments in eliciting natural gestures. Further studies should determine the extent of kinematic similarity required to obtain functional gains in VR-based upper limb rehabilitation.

Keywords Immersive virtual reality · Kinematics · Movement analysis · Hand dominance

1 Introduction

Stroke is one of the major causes of chronic disability worldwide (Lindsay et al. 2019). Many stroke survivors present with motor functions' deficits in the affected upper limb, and these impairments persist in the chronic phase of the pathology (Norrving and Kissela 2013); this fact strongly limits the autonomy of stroke survivors in daily life, and negatively impacts their health-related quality of life (Mayo et al. 2002).

Following a stroke, improvements in motor functioning may result from the *recovery* of physiological patterns or from implementing *compensatory* strategies, i.e., by means of using alternate degrees of freedom or muscles to achieve the task (Levin et al. 2009). Standard rehabilitation aims at restoring the autonomy of the individual following either or both approaches, intending to promote maximal functional outcomes. However, recently it has been argued that while compensation produces quicker functional improvements, it may also hinder the recovery of physiological behaviors, especially in patients with mild issues (Jang 2013; Jones 2017). Moreover, it has been proved that the involvement of the paretic arm in the activities of daily living (ADLs) is strongly dependent on recovery; vice versa, in the case of improved functions due to compensation, arm use in ADLs remains limited (Lum et al. 2009a). This occurs possibly because compensatory strategies are more tiring, effortful

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and, if repeated in time, may become painful, and thus difficult to carry over (Lum et al. 2009b).

Among rehabilitation treatments dedicated to upper limb rehabilitation, virtual reality (VR) has been explored extensively in the last decades, with positive results (Lee et al. 2016; Yates et al. 2016). In 2014, a Cochrane review included VR-based rehabilitation among the most potentially effective interventions (Pollock et al. 2014). Indeed, it has many advantages. First, it offers the users the possibility to practice in an ecologically valid environment (Faria et al. 2016; Rizzo and Kim 2005). Second, it allows for a safe, controlled, and easily customizable training program (Rizzo and Kim 2005). Third, performance feedback could be easily implemented to increase patients' awareness (Mottura et al. 2015; Zahabi and Abdul Razak 2020). Finally, VR has been proven to elicit the so-called sense of presence. This feeling, which represents the sense of "being there" in a computer-generated scenario (Ijsselsteijn and Riva 2003), has been demonstrated to increase the patients' engagement, and thus the motivation to train (Grassini et al. 2020; Koenig, Krch, Lange, and Rizzo, 2019). Sense of presence generally increases as the degree of immersion provided by the VR device does (Cummings and Bailenson 2016). Among the most immersive VR devices there are the head-mounted displays (HMDs), which currently provide good quality visual experiences at relatively affordable prices. Therefore, the application of HMDs in the field of motor rehabilitation can be very fruitful.

Given these two premises, it comes clear the importance of developing VR applications that, by retraining functional movements, can foster patients' autonomy in ADLs by promoting the recovery of functions. To the authors' knowledge, there is currently no evidence regarding which paradigm (i.e., recovery or compensation) is applied in VR-based rehabilitation.

To make sure that VR can elicit functional movements that are consistently similar to movements performed in the physical world, specific studies are needed. In this work, we considered two of the most studied functional gestures in rehabilitation: reach-to-grasp and transport, and we argued that the elicitation of natural behaviors (i.e., of movements that are similar to RW's) could be favored by (i) an HMD with good visual quality (i.e., with wide field of view [FoV], high frame rate, reduced lag, improved graphical fidelity (Stanney et al. 2020); e.g., HTC Vive and HTC Vive Pro,[1] or Oculus Rift and Quest[2]), and (ii) an ecological environment. Indeed, the more the sensory experience is similar to RW, the more the behaviors shown in VR should be similar to those performed in the physical reality (Subramanian et al. 2008). In turn, a good sensory experience could be considered dependent on a large field of view (FoV); and on a familiar experience (Fahle & Henke-Fahle 1996), which can be obtained by reproducing a situation typically experienced in ADLs.

We thus designed a study whose goal was the investigation of kinematic differences of reach-to-grasp and transport movements performed in the real world (RW) vs. an immersive VR, using an HTC Vive HMD, and in an ecological environment resembling the features of a supermarket. We obtained promising results, finding that the hand trajectory curvature and the ranges of motion (RoMs) of the joints involved in reaching and transport movements were mainly not affected by immersive VR and by holding a controller for both the dominant and the non-dominant hands. However, as for previous works, we recorded differences in movement times (MTs) and peak velocities, especially for the reaching phase. Thus, the potential added value of ecologically valid environments remains still to be investigated.

The remaining of this paper is organized as follows: Sect. 2 describes some previous works dealing with the assessment of the kinematic differences between aimed movements in RW and VR; Sect. 3 details the aims of this work and the methods we used to achieve them; Sect. 4 presents the results of the conducted study, and Sect. 5 discusses them, by also presenting its limitations. Section 6 draws some conclusions and reports some general remarks for future studies involving VR for rehabilitation.

2 Related works

In the literature, few studies aimed at investing the kinematic similarities of functional movements can be found. Most of them were performed with the specific goal of investigating whether VR—either immersive or not—is able to elicit RW-alike gestures and thus whether it could be suitable for rehabilitation purposes by means of retraining physiological movement patterns.

Studies comparing the similarities between reach-and-grasp in a two-dimensional virtual environment and in RW (Liebermann et al. 2012; Viau et al. 2004) reported slower movements and more curved hand trajectory in VR. The lack of an appropriate perception of depth was considered the primary cause of these differences: In fact, difficulties in estimating the depth position of an object cause more cautious movements and the different involvement of arm joints.

In the attempt of improving the perception of depth, and thus the similarity of VR movements to RW (González-Alvarez et al. 2007), researchers designed studies on reach-to-grasp (Furmanek et al. 2019; Magdalon et al. 2011) or reaching only (Knaut et al. 2009; Liu et al. 2009; Stewart

[1] HTC devices description is available at: https://www.vive.com/eu/.

[2] Oculus devices description is available at: https://www.oculus.com/.

et al. 2013) that made use of stereoscopic environments, using either projected screens and active goggles (Stewart et al. 2013), or HMDs.

In stereoscopic environments, the perception of depth was expected to improve, as the slight mismatch between the images seen by the two eyes should recreate the illusion of a 3D space. Nonetheless, also these studies found differences when comparing real and virtual world movements. Hand velocity (Furmanek et al. 2019; Knaut et al. 2009; Magdalon et al. 2011), curvature (Furmanek et al. 2019; Knaut et al. 2009), reach precision (Knaut et al. 2009), and trunk displacement (Magdalon et al. 2011) were different, in the case of both healthy volunteers and post-stroke patients. In 2008, a study performed by Subramanian et al. evaluated the effect of the VR medium on the movement quality by comparing an HMD and a non-stereoscopic rear-projection system. They found no kinematic differences between the two conditions and thus argued that projection systems' use should be encouraged because it was more cost-effective; nowadays, on the contrary, good quality HMDs have become more affordable than most projection systems. To the best of our knowledge, there are no studies comparing HMDs and 3D projected screens' performances related to movements kinematics or rehabilitation.

Regarding the use of interaction devices, Magdalon et al. (2011) showed that wearing a cyber-glove influenced both the reaching and the grasping movements, with the first being slower and the second wider, also in RW. When using VR, reaching times were even longer.

Another relevant element to be considered for the kinematic analysis of movements occurring in VR appeared to be the FoV provided by the device; previous studies have shown that a limited FoV causes slower movements: This behavior was recorded both in RW (González-Alvarez et al. 2007) and in VR. From this point of view, the most performing devices currently available on the market reach 110° for both vertical and horizontal directions (Murphy et al. 2018). Though this constitutes a substantial improvement (e.g., the HMD employed by Knaut et al. (2009) and Magdalon et al. (2011) accounted for 50° of diagonal FoV; 30° vertical and 40° horizontal), it is still not comparable with the human eye, which reaches around 120° vertical, 200° horizontal.

The use of more up-to-date devices seemed indeed to have reduced the gap between VR and RW; e.g., Furmanek et al. (2019) (using the Oculus Rift) obtained prolonged movement times in VR but also observed that reach-to-grasp strategies were conserved. Given this, in this work, we decided to employ the HTC Vive HMD, whose FoV was the best available at the time of the study.

Furthermore, we noticed that all the virtual environments were ad hoc developed environments representing just simplified targets (e.g., points, spheres, etc.). This could be comprehended considering that the aim was to compare movement kinematics and not to engage the user. Additionally, the environment had to be the most controllable as possible to compare the real and the virtual conditions.

On the other hand, however, this reduced the potentialities offered by VR of deploying realistic environments (Minderer et al. 2016; Parsons 2015). Up to date, the potential of recreating ecologically valid environments has been discussed mostly in the field of cognitive and neuropsychological interventions (Pieri et al. 2021). In such a field, in fact, it is sometimes difficult to assess the patient's capabilities in ADLs by performing standard paper-and-pencil tests (Câmara et al. 2021). It has thus been suggested that VR could overcome this limit by presenting stimuli in a controlled way in order to provide researchers with: (i) a truthful control of laboratory measures and (ii) the verisimilitude of expressed behaviors, i.e., people behave as they were in of real life (Parsons 2015). Given this, we hypothesized that the same paradigm could be applied to the field of motor rehabilitation too. Having a more ecological setting, perhaps including realistic elements belonging to real life, could contribute to elicit more natural behaviors and thus more kinematically similar movements.

Finally, all the studies mentioned above considered just the movement of the participants' dominant hand. Nonetheless, rehabilitation may have to be performed on the non-dominant side, or it could include bi-manual tasks (Sampson et al. 2012). Previous studies not involving VR have shown that some differences may occur between movements performed with the dominant and the non-dominant arm. For instance, Assi et al. (Assi et al. 2016) identified different movement strategies and diverse RoMs between the two arms, especially at the elbow level, while performing anatomical movements with upper limbs. Differences were also found while throwing (Sachlikidis and Salter 2007) and elevating the shoulder (Matsuki et al. 2011; Yoshizaki et al. 2009). Bagesteiro and Sainburg hypothesized a different neural control of movements depending on the arm dominance, based on their findings on different curvature and torque patterns (Bagesteiro & Sainburg 2002). On the contrary, some research seems to support the idea that the superiority of the dominant hand is task-dependent (Gershon et al. 2015). Therefore, we also focused our attention on estimating the differences occurring between the dominant and non-dominant arm during both the reach-to-grasp and the transport phases in order to inform the future development of rehabilitative VR-supported applications, also from the point of view of handedness.

3 Materials and methods

3.1 Aims

Our experiment aimed at comparing the kinematic of reach-to-grasp and transport movements in virtual vs. real environments.

To try to overcome the limitations of previous studies, our virtual environment was designed to be controllable and reproducible in a real setup and to be as ecological as possible. In addition, as already mentioned, we employed an HMD that was among the most performing ones, having 110° of vertical and horizontal FoV (Murphy et al. 2018) and about 110° of diagonal FoV.[3] We expected all these elements to contribute to reduce the kinematic differences between reaching movements in VR and RW recorded by previous studies.

Concerning virtual objects' interaction, we decided to use a controller (instead of cyber-gloves) for several reasons. First, the study of Magdalon et al. (Magdalon et al. 2011) has already demonstrated the influence of wearing a glove during reach-to-grasp, showing that it caused slower movements also in RW. Second, the study of Olbrich et al. (Olbrich et al. 2018) has shown that users preferred the controller to interact with a virtual object during a maintenance task, highlighting the higher efficiency of controllers over cyber-gloves. Third, the interaction modality we designed for the Virtual Supermarket environment (i.e., the virtual environment that was simplified for the current study) revealed usable and intuitive, for both young and older adults with cognitive deficits with no familiarity with VR (Arlati et al. 2021; Mondellini et al. 2018).

Fourth, using controllers meant to study the "simplest" setup available for the HTC Vive to interact with virtual objects; controllers are included in the VR kit and do not require neither additional software nor calibration. Together with the higher cost-effectiveness, this fact may favor the actual employment of VR technology in clinical settings. Finally, it could be possible that stroke patients would have pathologies preventing from wearing a glove (e.g., hand spasticity or muscular hypertonicity).

Nonetheless, since Magdalon et al. (2011) reported slower movement times also in RW while using a haptic glove (weight: 0.45 kg + the haptic system[4]), we decided to design this study controlling for the effects of holding a controller (weight: 0.2 kg) while reaching-to-grasp and transferring. If differences would occur with and without the controller in RW, it would be plausible to hypothesize that the controller's weight influences the kinematics of the arm movements. This point would be particularly relevant to inform the development of an application for rehabilitation purposes, as patients may suffer from weakness in their upper limbs and thus may experience—even more—this issue. Given this, the study was conceived considering VR and RW, plus a condition "real world with controller" (RWC), whose aim was to investigate whether potential differences found in VR were dependent on the controller weight rather than on the fact that being immersed in a virtual environment.

Dealing with hand dominance, we hypothesized that the non-dominant hand would show no differences in terms of movement times and peak velocities with respect to the dominant one, as our tasks did not require high precision (i.e., the target items to grasp are not small) (Magdalon et al. 2011), and participants were left free to choose the velocity they preferred (Xiao et al. 2019). Since none of the target items required a high-precision grasping, we did not consider possible differences due to the different hand accommodations in RW (Magdalon et al. 2011). The only variable that appeared to be influenced by hand dominance during reaching in RW is trajectory curvature (Xiao et al. 2019); thus, this behavior may be recorded in VR too.

Finally, in our study, we also considered the possible influence of targets' position on the shelves across the different conditions of testing. There exist proven differences among contralateral and ipsilateral reaches. Contralateral reaches are more complicated, as they require to cross the body midline and have been measured slower and less efficient (Knaut et al. 2009; Xiao et al. 2019). The analysis of these differences was outside the scope of this work; however, we expected to observe the same pattern in both VR and RW.

The study was thus designed as a within-subject repeated-measures study, in which three different experimental conditions were considered (see further §3.4), i.e.:

- real world (RW), in which the participant had to reach and grab a physical item on the shelf and transport it on a table;
- virtual reality (VR), in which the reach-to-grab and the transport occurred entirely in VR, by means of the pulling the trigger button on the HTC Vive controller;
- real world while holding the HTC Vive controller (RWC), in which the user had to hold the controller without wearing the HMD and reach for a real object, pretending to grab it by pulling the trigger (as in VR), and then pretending to transport it on the table.

In all the conditions, the tasks to perform were the same (§3.4) and were repeated for the dominant and the

[3] HMD Geometry Database, available at: https://risa2000.github.io/hmdgdb/.

[4] Cybergrasp system v2.0 user-guide: https://www.upc.edu/sct/documents_equipament/d_184_id-485.pdf.

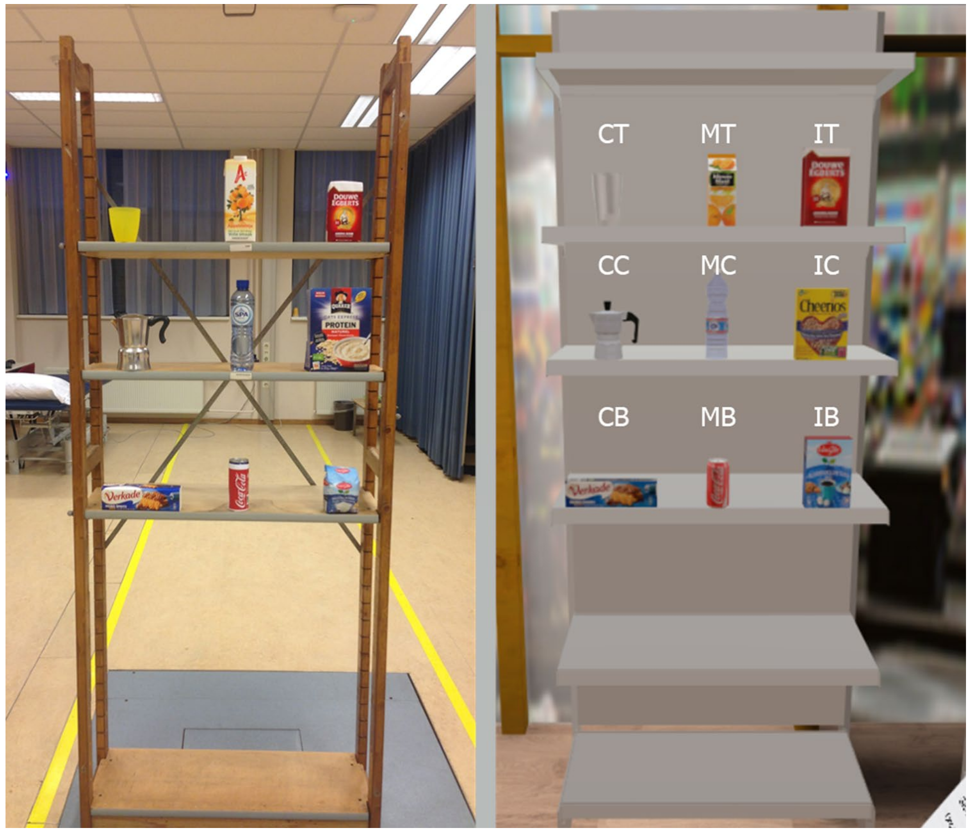

Fig. 1 Real and the virtual shelf units. On the virtual shelf, also target positions' encoding is reported: T stands for top, C for center, B for bottom; C for contralateral; M for medial; and I for ipsilateral. The latter classification is reported thinking of a right-handed person

non-dominant side. To control the order effects, participants' exposure to each condition was randomized.

The study was carried out at the Sint Maartenskliniek (Netherlands) and approved by the clinic's Medical Ethical Committee.

3.2 Participants

A group of healthy young adults (aged > 18 and < 40 years old) was recruited for the study. The only inclusion criterion was to be in good cognitive status (i.e., without a diagnosis of cognitive impairment). Exclusion criteria were: motor and balance disabilities, severe vision impairments, sensitivity to motion sickness, history of seizure, having strong familiarity with immersive VR technologies, and inability to provide informed written consent.

3.3 Equipment

In order to perform movements' comparison, a virtual and a real setup sharing the same characteristics were used. The immersive Virtual Supermarket environment described in Arlati et al. (2021) was simplified (i) to better control for the variability of participants' movements and (ii) to allow for a comparable reproduction of a real shelf. The virtual environment was deployed for HTC Vive using Unity[5] rendering engine and SteamVR[6] plug-in functionalities.

Nine different grocery items were placed on the shelves for both environments. They constituted the 9 targets to reach, grab, and transport to perform a trial; the 9 items were placed at the hip, trunk, and head level of the participant, in ipsi-, medial and contralateral position. The heights of the real shelves could be adjusted according to the person's anatomical characteristics by using shelf pins; virtual shelves' heights were then adjusted accordingly (see further). All the products on the shelves had to be reachable by the participant while standing and without stepping forward. Figure 1 shows the comparison between the real and the virtual shelves.

In the Virtual Supermarket, a cart was placed either on the right or the left side of the participant, depending on the arm performing the trial. Participants were instructed to "buy" items by placing them inside such a cart. To do this, the participant had to make the controller collide with the grocery item and then pull the back trigger. Only the controller was visible in the virtual scene; no other proprioceptive

[5] Unity Real-Time Development Platform, available at: https://unity.com.

[6] Steam VR, available at: https://store.steampowered.com/steamvr.

feedback was provided. A vibration was used to signal the collision with the grocery item. Keeping the trigger pressed allowed dragging the object around; once the object has been transported above the cart, releasing the trigger caused the object to drop.

The list of the items to pick (always all the 9 items on the shelf) was presented on the side of the cart. In RW and RWC, lists were printed and placed on a high table placed on the same spot of the cart. Such a table was also used to place the real items in the RW condition. The high table was preferred to an actual cart because we did not want people to bend to place the item in the (physical) cart, as this did not occur in VR; in fact, the vibration signaling that the product could be released was triggered when the superior edge of the cart was hit.

All the target items' positions had to be the same in all the 3 conditions of testing to compare the kinematics of reaching and transport movements. To ensure this, the functionalities of a VICON stereo-photogrammetric motion capture system were integrated in Unity programming environment. To do this:

1. the alignment of the two cameras systems' (i.e., VICON infrared cameras and HTC Vive base stations) was performed by exploiting the *VR Alignment Tool*[7] plug-in and implementing ad hoc algorithms—via Unity scripting—to adjust translations and rotations of tracked rigid bodies within the virtual scene.
2. VICON *DataStream* SDK[8] was exploited to stream 3D positions data from VICON Nexus[9] (i.e., the commercial software provided by VICON to capture and post-process data) to Unity programming environment using a client/server architecture.
3. Three reflecting markers were placed on the left side of the shelf unit, in correspondence with the three shelves (+ 1 marker on the right side); a rigid-body subject was built in Nexus using the dedicated procedure, and its 3D position and orientation were streamed to Unity.

The horizontal position of the targets did not vary depending on the study participants. Therefore, they were defined relative to the shelf width: In the VR environment, they were coded to be always the same, while in RW and RWC conditions, they were identified by notches. This expedient also prevented the occurrence of occlusion issues during the trials.

The motion capture system was also used to track the user's body movement during the trials using Plug-In Gait Full-Body.[10] The data sampling rate was 100 Hz.

3.4 Protocol

At the beginning of each day of trials, the two cameras' systems were calibrated according to respective manufacturers' instructions—using SteamVR for HTC Vive[11] and VICON Nexus for the stereo-photogrammetric system[12]—and aligned (as indicated in §3.4, item 1). This procedure allowed for the alignment of the heights of the virtual and real shelves and ensured the correct tracking of the participant' movements. The Nexus 3D models of a participant performing the task and of the shelf (in orange) are shown in Fig. 2c.

All participants wore tight-fitting sports clothes (i.e., shorts and bra for females) to limit the impact of markers' displacement due to clothes slips while moving Fig.2 (a and b). The experimenter attached reflective markers to the participant's body and checked their positions by analyzing joints' axes in VICON Nexus during the subject's calibration procedure.[13] Once all the 39 markers were placed as required from Plug-In Gait Full-Body model, each participant was asked to stand in front of the real shelf unit at a distance equal to their arm length; this ensured that each participant could reach all the target items without stepping forward. The feet position (and thus the distance from the shelf) determined in this phase was marked on the floor using tape: In this way, if the participant moved, he/she could restart from the same exact position.

Each trial consisted in picking the 9 items on the shelf following the order reported in the shopping lists. A total of 5 trials were completed by each participant with the two hands, for a total of 30 trials per person (5 repetitions × 3 conditions × 2 hands). If a participant stepped forward or made an error during a trial, the entire trial (i.e., picking of the 9 items) was interrupted and repeated.

[7] VICON VR Alignment Tool, available at: https://www.Vicon.com/Software/ Utilities-and-Sdk/vr-Alignment-Tool/.

[8] VICON Datastream SDK, available at: https://www.Vicon.Com/Software/ Datastream-Sdk/.

[9] VICON Nexus, Available at: https://www.Vicon.Com/Software/Nexus/.

[10] Full Body Modeling with Plug-in Gait, available at: https://docs.Vicon.com/Display/Nexus210/Plug-In+Gait+Reference+Guide.

[11] HTC Vive setting up room-scale play area, available at: https://www.vive.com/nz/support/vive-pro-hmd/category_howto/setting-up-room-scale-play-area.html

[12] Calibrate a VICON system, available at: https://docs.vicon.com/display/Nexus27/Calibrate+a+Vicon+system

[13] Create a new subject from a template, available at: https://docs.vicon.com/display/Nexus27/Create+a+new+subject+from+a+template

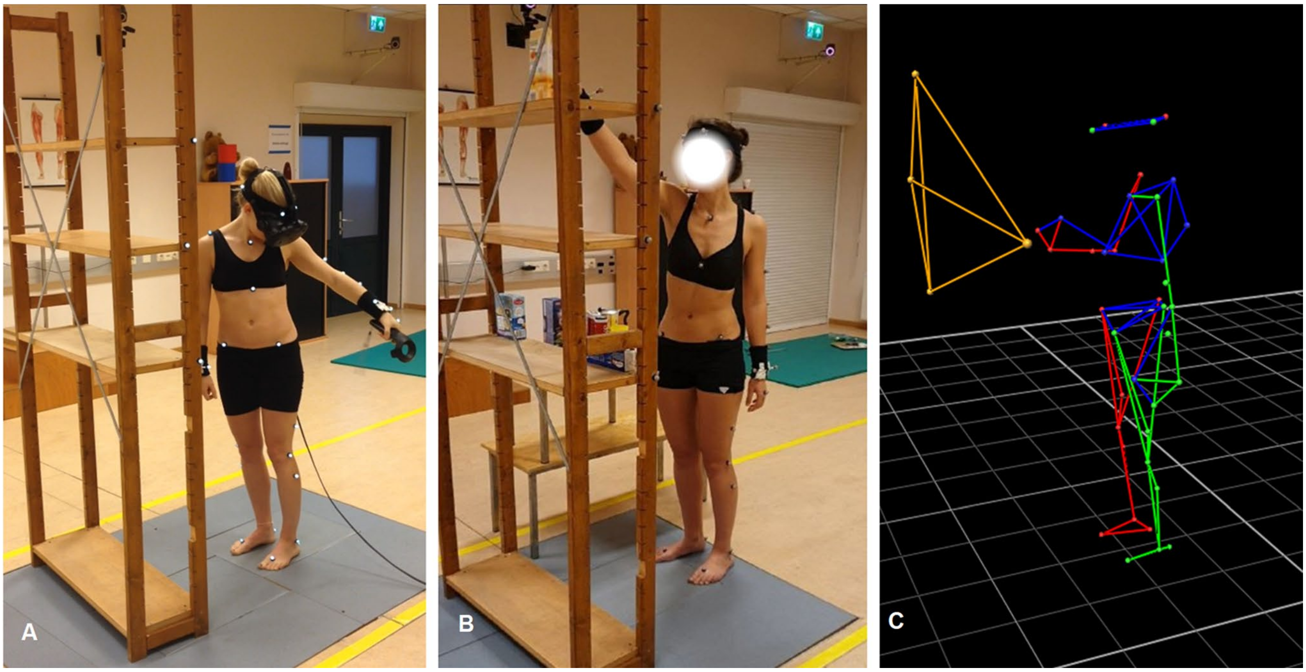

Fig. 2 Participants performing a trial in VR (**a**) and RW (**b**), plus a screenshot showing participant and shelf tracking during the exercise (**c**). Reflective markers are applied by means of bi-adhesive tape; a headband and two wristbands are used, respectively, to ease the stable placement of the markers on the hair, and to improve the quality of tracking (the wristband holds a bar that keeps the markers away from the skin, increasing the inter-marker distance)

Instructions for the completion of the shopping tasks in the 3 conditions were orally given by the experimenter before the beginning of each condition.

For the VR condition, the experimenter explained how the interactions occurred (i.e., grabbing by pressing the trigger) and that vibration would signal when the product could be picked or released into the cart. After the explanation, the experimenter helped the participant wear the HMD, adjust the interpupillary distance of the lenses, and fix it firmly on their head using straps. Each participant then performed a familiarization trial to learn how to deal with the controller (Mondellini et al. 2018). Within this phase, items on the shelf were different from the ones present in the actual trial and placed in 6 different positions. This trial also served to limit the "wow effect" possibly occurring when being immersed in a VR environment for the first time (Arlati et al. 2018).

For the RW condition, the experimenter asked the participants to reach for the item on the shelf as they would do in reality, adjusting the hand normally, and then to place it on the table.

Finally, for the RWC condition, the experimenter asked the participant to point toward the target item on the shelf, to press the trigger when being near it, and then to pretend to place it on the table.

In all cases, participants were told to perform all the tasks at their preferred velocity.

Between the conditions, participants were given a couple of minutes to rest. Resting within a condition was possible upon request, as each trial was recorded separately. The whole experience lasted around 60 min, of which about 30 were dedicated to markers' placement and subjects' calibration.

The positions of the items on the shelves were always the same. Instead, 20 different lists were coded and identified with a specific ID. Five of these 20 lists were selected randomly prior to the beginning of the experiment, but the same IDs and the same order of presentation were kept for all the conditions (e.g., IDs 1—2—3—4—5 for RW, RWC, and VR).

3.5 Measures

Study outcomes were the following:

- Movement time (MT) for both the reaching (MT_R) and the transport phases (MT_T); MTs were defined as the time elapsed from the movement onset till the movement offset. Movement onset was set when the velocity of the marker placed on the participant's hand (RFIN or LFIN, according to Plug-in Gait model) surpassed and remained above 0.2 m/s (Stewart et al. 2013). Movement offset

Table 1 Results of ANOVA; the considered factors were hand (dominant, non-dominant), condition (cond; RW, RWC, VR), and target position (pos). MT_R, MT_T: movement time during reaching and transport; V_R, V_T: peak velocity during reaching and transport phase; and Curv.: curvature

	Hand	Cond	Pos	Cond*hand	Hand*pos	Cond*pos
MT_R	$F_{1,9}=0.01$ n.s	$F_{2,18}=27.04$ $p<0.001$	$F_{8,72}=1.52$ n.s	$F_{2,18}=0.99$ n.s	$F_{8,72}=3.33$ $p=0.003$	$F_{16,144}=1.27$ n.s
MT_T	$F_{1,9}=0.13$ n.s	$F_{2,18}=9.45$ $p=0.002$	$F_{8,72}=3.17$ $p=0.004$	$F_{2,18}=0.82$ n.s	$F_{8,72}=0.53$ n.s	$F_{16,144}=1.34$ n.s
V_R	$F_{1,9}=4.24$ n.s	$F_{2,18}=107.1$ $p<0.001$	$F_{8,72}=2.91$ $p=0.007$	$F_{2,18}=2.78$ n.s	$F_{8,72}=1.32$ n.s	$F_{16,144}=1.62$ n.s
V_T	$F_{1,9}=0.003$ n.s	$F_{2,18}=19.30$ $p<0.001$	$F_{8,72}=8.12$ $p<0.001$	$F_{2,18}=0.51$ n.s	$F_{8,72}=4.24$ $p<0.001$	$F_{16,144}=1.72$ n.s
Curv	$F_{1,9}=0.055$ n.s	$F_{2,18}=2.53$ n.s	$F_{8,72}=0.61$ n.s	$F_{2,18}=1.12$ n.s	$F_{8,72}=1.21$ n.s	$F_{16,144}=0.50$ n.s

was set when velocity fell and remained below the same threshold.

- peak endpoint velocity, i.e., the maximum hand velocity during reaching (V_R) and transport phase (V_T).
- endpoint trajectory curvature, defined as the ratio between the length of the actual endpoint trajectory and the length of a straight line connecting the hand positions at movement onset and offset.
- relevant RoMs for the reaching and transport gestures (i.e., shoulder flexion/extension, shoulder abduction/adduction, elbow flexion/extension (Cirstea et al. 2003)); backward tilt and rotation of the trunk. All angles are defined according to Plug-in Gait human model.

3.6 Data analysis and statistics

Skeleton data were reconstructed using VICON Nexus 2.7 dedicated pipelines. Each trial was reviewed by the experimenter to verify its correctness and to fill data gaps. Nexus software was also used to extract joint angles and to calculate markers' position derivatives. Data were then streamed to MATLAB 2019a, thus allowing for their analysis using ad hoc developed scripts. All the statistical analyses were performed with MATLAB 2019 Statistics and Machine Learning Toolbox.

Only the data concerning the last 3 trials were considered for the analyses to exclude the possible effects of familiarization occurring during the first two trials. This choice was made as an additional countermeasure to account for potential differences arising in first trials, in all three conditions (VR, RW, RWC), and despite the execution of a preliminary familiarization phase in VR.

Data were checked for normality and sphericity using Shapiro–Wilk and Mauchly test, respectively.

To compare the 3 conditions of testing when using either the dominant or the non-dominant hand, 2 × 3 × 3 repeated-measures ANOVA was performed for each one of the variables of interest (§3.5); factors were: hand (dominant, non-dominant), condition (RW, RWC, VR), and target position (the combination of top, center, bottom, and ipsilateral, medial, and contralateral position, see Fig. 1). The significance level was set to $\alpha = 0.05$. Tukey–Kramer HSD post hoc comparisons were used to assess differences whenever significant interactions or main effects were observed.

4 Results

Ten healthy young adults (2 males, 8 females) aged 26.7 (SD = 5.46) were enrolled among the Master students and the graduate researchers of the Sint Maartenskliniek. One participant was left-handed, and all the others were right-handed. Eight of them had no previous experience with immersive VR, 2 had tried HMDs once. All participants concluded the experiment without signaling any adverse event and without requiring any breaks. Two trials in VR condition had to be repeated because (i) the dropping of a shopping item outside the cart and (ii) the participant making a step forward.

Descriptive statistics for all the collected variables are reported in Tables 3 and 4 for the dominant and the non-dominant hand, respectively (see Supplemental Material).

4.1 Kinematic outcomes

All the kinematic variables we considered—except curvature—were influenced by the test condition and target position. None was influenced by hand dominance alone. Results of ANOVA are reported in Table 1.

4.1.1 Effects of condition

MTs were longer in VR condition during both the reaching (+47% with respect to RW, $p < 0.001$; +41% w.r.t. RWC, $p < 0.001$) and the transport phases (+27%, p = 0.038 for RW, and +35%, $p = 0.005$ for RWC; Fig. 3, first row). No differences emerged for the two conditions occurring in the physical reality.

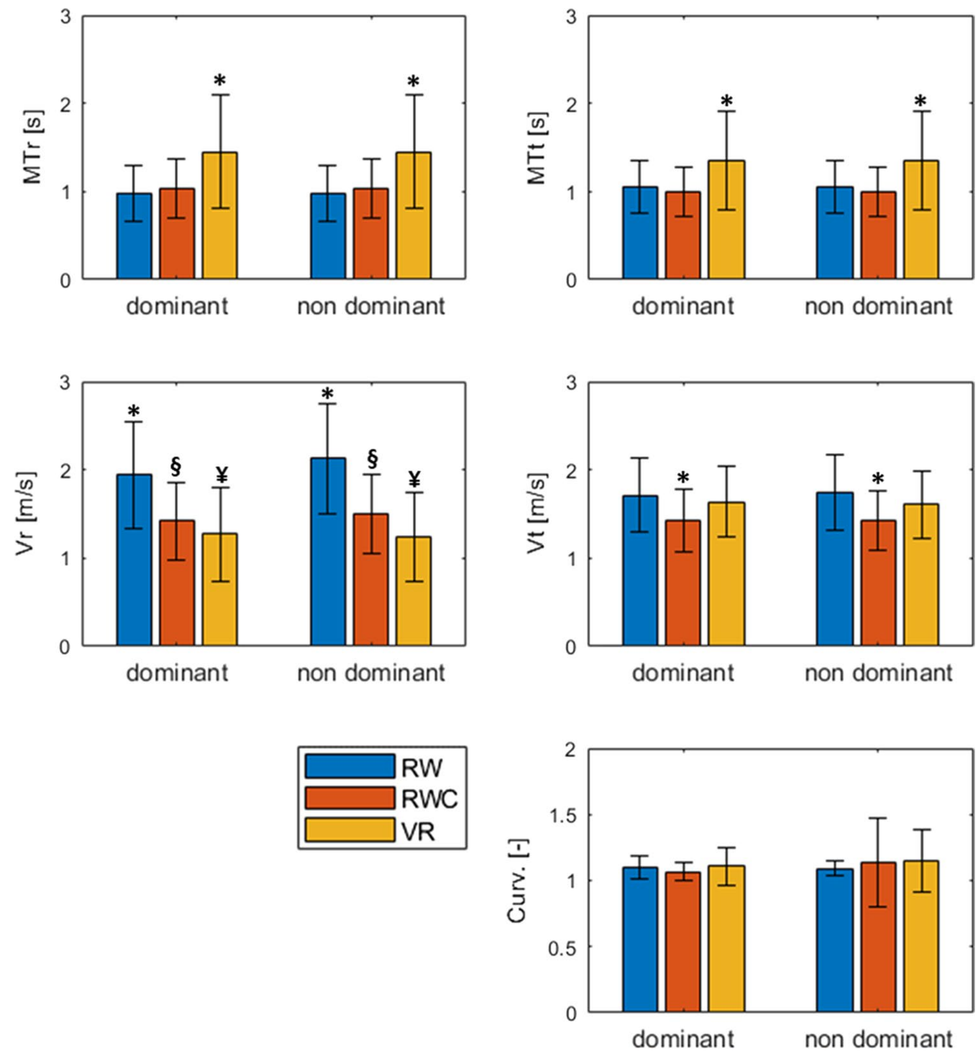

Fig. 3 Comparison of kinematic variables across conditions and hand dominance. Symbols indicate significant differences ($p<0.05$). MT_R and MT_T: movement times during reaching and transport; V_R and V_T: peak velocities during reaching and transport phase; and Curv.: curvature

Concerning peak velocities (Fig. 3, second row), the difference between VR and real-world conditions was more marked during the reaching phase. This was confirmed by the post hoc analysis that highlighted a significant difference in V_R between VR and RW (-38%; $p<0.001$), VR and RWC (-13%; $p=0.01$), and also between RWC and RW (-28%, $p<0.001$). During the transport phase, the lowest peak velocities were associated with RWC condition; indeed, differences reached significance only between RWC and VR (-12%; $p=0.003$) and RWC and RW (-17%; $p=0.002$).

No effects of condition were recorded for curvature (Fig. 3, last row).

4.1.2 Effects of hand dominance

No main effects of hand dominance emerged (Fig. 3) for any kinematic variables. Two interactions occurring between hand and target position were instead recorded for MT_R and V_T.

In both cases, CB target resulted different between the two hands (Fig. 4): MT_R was significantly shorter (-19%, $p=0.007$) and V_T lower (-14%, $p=0.02$) when using the dominant side. In the case of IC, V_T was significantly lower when using the non-dominant hand (-5%, $p=0.02$).

4.1.3 Effects of position

The post hoc analysis of position effects highlighted no clear patterns. For MT_R, no main effects were found. For what concerns MT_T, significant differences were found between targets placed in IC and MC ($+11\%$, $p=0.02$), and IC and CB ($+16\%$, $p=0.03$);

For V_R, post hoc analysis for target position revealed only a significant difference, i.e., between CT and CC, with the first target reach eliciting a higher peak velocity ($+12\%$, $p=0.037$).

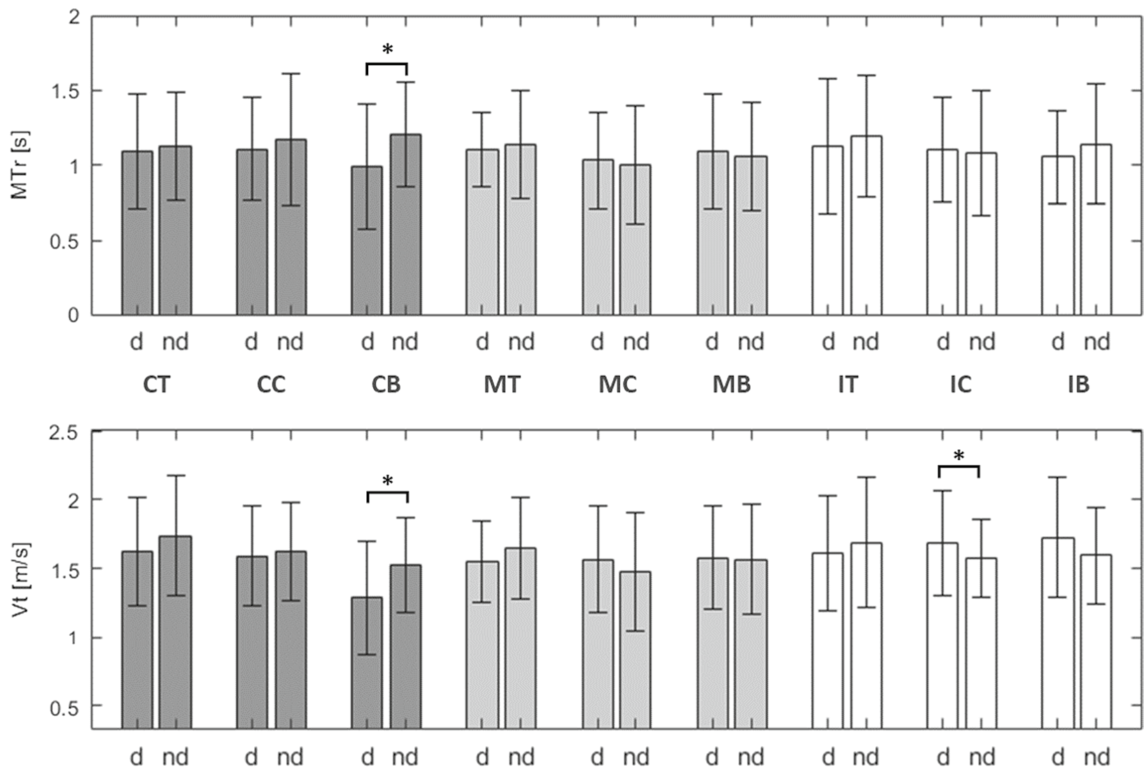

Fig. 4 Differences between dominant and non-dominant hand in movement times during reaching phase (MT_R), and transport peak velocity (V_T). Results are presented for each one of the targets according to the coding presented in Fig. 1. *: $p<0.05$

Table 2 Results of ANOVA; the considered factors were hand (dominant, non-dominant), condition (cond; RW, RWC, VR), and target position (pos)

	Hand	Cond	Pos	Cond*hand	Hand*pos	Cond*pos
Sh. Abd	$F_{1,9}=3.49$ n.s	$F_{2,18}=10.01$ $p=0.007$	$F_{8,72}=3.61$ $p=0.004$	$F_{2,18}=0.78$ n.s	$F_{8,72}=1.41$ n.s	$F_{16,144}=1.26$ n.s
Sh. Flex	$F_{1,9}=0.06$ n.s	$F_{2,18}=3.67$ n.s	$F_{8,72}=3.66$ $p=0.003$	$F_{2,18}=0.42$ n.s	$F_{8,72}=0.93$ n.s	$F_{16,144}=1.05$ n.s
Elb. Flex	$F_{1,9}=0.35$ n.s	$F_{2,18}=0.11$ n.s	$F_{8,72}=3.69$ $p=0.003$	$F_{2,18}=1.32$ n.s	$F_{8,72}=1.27$ n.s	$F_{16,144}=1.37$ n.s
Th. Tilt	$F_{1,9}=0.67$ n.s	$F_{2,18}=3.63$ n.s	$F_{8,72}=1.10$ n.s	$F_{2,18}=1.12$ n.s	$F_{8,72}=1.02$ n.s	$F_{16,144}=2.23$ $p=0.01$
Th. Rot	$F_{1,9}=1.59$ n.s	$F_{2,18}=87.17$ $p<0.001$	$F_{8,72}=1.96$ n.s	$F_{2,18}=4.45$ $p=0.042$	$F_{8,72}=1.07$ n.s	$F_{16,144}=4.50$ $p<0.001$

Sh: shoulder, Elb: elbow, Th: thorax, Abd: abduction, Flex: flexion, and Rot: rotation

4.2 Joint angles

Results of ANOVA on the joint-related variables we measured are reported in Table 2. In general, hand factor alone did not cause any differences for any of the considered joints. In contrast to what was found for kinematic variables, condition factor did not appear to play a critical role: Only trunk rotation and shoulder abduction showed a few significant differences.

4.2.1 Effects of condition

A main effect of condition was recorded for shoulder abduction and thorax rotation. In the case of shoulder abduction, a significant difference emerged between RW and RWC ($p=0.038$), with the latter requiring less RoM (−67%); differences with VR condition reached no significance for both RW (−23%, $p=0.12$) and RWC (+35%, $p=0.17$).

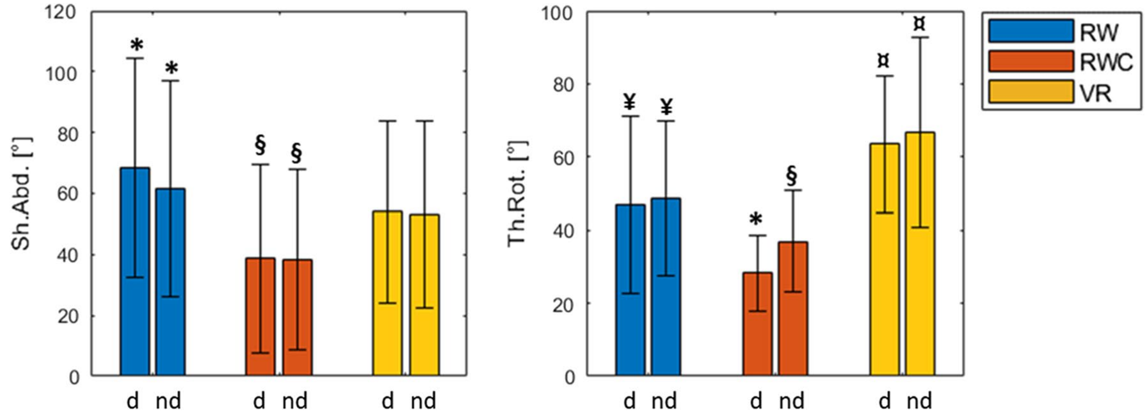

Fig. 5 Shoulder abduction and thorax rotation in the three conditions of testing. d: dominant hand, nd: non-dominant hand. Symbols indicate significant differences ($p < 0.05$)

In the case of thorax rotation, VR was significantly different from the other two conditions: + 90% ($p < 0.001$) for RWC and + 36% ($p = 0.002$) for RW. Also, RW and RWC resulted different (+ 46%, $p = 0.001$, Fig. 5).

4.2.2 Effects of hand dominance

No main effect of handedness was recorded for the considered values. The analysis of hand*condition interaction for thorax rotation resulted in a difference between dominant and non-dominant hand only for RWC (− 23% for the dominant hand, $p = 0.017$, Fig. 5). No differences occurred between the two sides for RW ($p = 0.82$) and VR ($p = 0.34$).

4.2.3 Effects of position

Overall, position CB appeared to require a different movement strategy, as multiple comparisons revealed higher shoulder abduction (statistical significance was reached only for the comparison with MT: + 59%, $p = 0.007$), reduced shoulder flexion (for IT: −20%, $p = 0.03$), and reduced elbow flexion (from + 15% to + 19% for CT, MT, IT, CC, IC, and MB; $p < 0.047$) with respect to all the other targets.

Post hoc analysis following the significant condition*position interaction highlighted that all target positions elicited a thorax rotation that was statistically different in the three conditions of testing, whereas CB required the same trunk ROM in both VR and RW ($p = 0.36$). Instead, thorax tilt resulted in no differences at post hoc tests.

5 Discussion

The main goal of this study was to determine whether the movements performed in immersive VR were comparable to those performed in the physical world in order to assess whether an ecological virtual environment seen through a good quality HMD could favor the elicitation of physiological movement patterns and thus promote recovery from the rehabilitation perspective.

We found that movement times were significantly longer and peak velocities significantly lower during the reach-to-grasp phase in the VR condition. These results confirmed what was already highlighted by previous studies on reach-to-grasp (Furmanek et al. 2019; Magdalon et al. 2011) and reaching only (Knaut et al. 2009; Liu et al. 2009; Stewart et al. 2013).

What emerged as a novelty in our study was that moving slower while in VR was not dependent on holding the controller (i.e., RW and RWC denoted no differences). This partially contrasted what was found by Magdalon et al. (2011), who reported that wearing a cyber-glove (i.e., having an additional load on the hand) influenced both reaching and grasping parameters.

However, it has also been demonstrated that the VR interaction requires less time and occurs more efficiently when performed with controllers than with cyber-glove (Olbrich et al. 2018). Therefore, we may hypothesize that cyber-gloves technology has not reached complete maturity yet, as their presence and weight (which is higher than controllers') still influence the accomplishment of tasks in both the physical and virtual world. Instead., controllers probably have.

Given these facts, plus the potential advantages of controllers listed in §3.1, we argue that controllers could represent a valuable tool to implement interactions in immersive VR environments dedicated to rehabilitation. Another solution may be represented by haptic-free technologies (e.g., the Leap Motion, or the Oculus Quest hand tracking), which may appear more natural as they implement isomorphic manipulation. However, lacking haptic feedback during grasp may be responsible for inducing the so-called violation of the expectations (Villa et al. 2018; Weech et al. 2019). This fact may severely affect sense of presence and thus the ecological validity of the whole experience in VR (Slater & Steed 2000).

Controllers surely force the use of an interaction metaphor, but their consistent, though different, paradigm allows avoiding disruptions in presence; device-free methodologies remain a more than valuable alternative for patients with grip deficits (Holmes et al. 2016). On the contrary, haptic technologies still have to be improved for efficient employment: Wearable devices are heavy and little realistic, fixed ones are precise but strongly limit the playing area (Furmanek et al. 2019).

The occurrence of slower movements in VR, as already mentioned, may be dependent also on the limited FoV (Knaut et al. 2009; Magdalon et al. 2011) provided by VR systems. This hypothesis appears plausible as also other studies investigating the effects of reduced FoV, irrespective from VR (González-Alvarez et al. 2007; Loftus et al. 2004), have reported the same behavior.

Lack of familiarity, and thus of the chance on relying on previous experiences, could have played a role too (Fahle & Henke-Fahle 1996). However, due to the ease of use of our system (discussed in (Mondellini et al. 2018) and (Arlati et al. 2021)), and having excluded the very first trials, we believe that it was plausible to exclude this element's contribution.

Finally, the wrong estimation of distances, which has been proven to occur in VR (Gerig et al. 2018; Jamiy & Marsh 2019), could have contributed to movement slowness also in our case. However, the analysis of joint angles (except for thorax rotation) revealed no differences in the 3 conditions of testing, indicating that probably no under-/over-estimation of distances occurred in our VR environment (Magdalon et al. 2011). Nonetheless, future studies may add elements to the virtual scene to try to improve the depth perception. We stuck to the most straightforward setup, but, for instance, having a human avatar animated according to the participants' movement and displaying a proper shadow over the environment could be of help in improving the whole scene visual perception (Connolly & Goodale 1999; Schettino et al. 2003).

Regarding the difference denoted for trunk rotation, they may be attributed to the lack of precise constraints for movement onset and offset. The seeking to create an ecological VR environment led us to prefer a very little constrained setup, thus potentially introducing some limitations in the study. However, the fact that there existed greater differences between VR and RWC rather than RW and VR was encouraging.

In previous studies, where more attention was paid to create a controllable setup rather than on creating ecological environments [e.g., participants were sitting (Knaut et al. 2009) or they had to reach targets on a horizontal surface (Magdalon et al. 2011)], trunk movements were indeed more limited, and no differences were recorded between RW and VR conditions.

The same consideration is also valid for the in-depth study of the transport phase. Despite longer MT_T, no differences were found in peak velocities (V_T) between VR and RW. Assuming that movements in VR always occur slower, a possible hypothesis could be related to the need to physically place the real object on the desk and thus to the search for free space occurring concurrently with the movement. However, this hypothesis would not explain the behavior recorded in RWC condition. Therefore, further studies should try to shed some light on this aspect too.

In terms of trajectory curvature, we found results that are in contrast to previous ones. Knaut et al. (2009), for instance, found that subjects tended to show a more curved trajectory in VR. However, this pattern was present only when reaching toward contralateral targets. Such behavior was explained by saying that reaching targets crossing the body midline was more complex and that those targets were at the edge of the participant's FoV. In our case, none of the targets could probably be considered to be in the peripheral FoV. Rather, the limited distance from the midline could have influenced our outcomes in the opposite way (i.e., with almost no significant position effects).

The current technological advancement of VR devices, which still conserve reduced FoV with respect to the human eye, may mask other factors possibly inducing kinematic differences in VR. Nonetheless, this effect might be reduced with some expedients. A recent study investigating how reduced FoV affected the comprehension of a video showed that if the focus is on the region of major interest, the user can still adequately describe what is happening (Costela & Woods 2020). Therefore, applying the same principle to immersive VR, it may be advantageous to place the interactable objects in the foveal vision area (except for applications dedicated to patients with vision problems as neglect and hemiopia) to avoid an excessive trajectory curvature and promote the execution of more natural movements.

Having no difference in the trajectory curvature was also in contrast to previous studies employing 2D VR systems (Liebermann et al. 2012; Viau et al. 2004). Therefore, our study supports the evidence that 3D VR represents a key factor in making the reaching movements more similar to those made in physical reality and encourages the future development of rehabilitative applications using immersive VR.

In terms of hand dominance, no differences occurred in MTs and peak velocities between the hands in our study, i.e., when performing a non-precise reach at a self-selected velocity. This agreed with the results of Xiao et al. (2019), though they also reported reduced curvature for the dominant hand, resulting from a more efficient torque pattern occurring at the level of the elbow joint (Bagesteiro & Sainburg 2002), which we did not find. It is also true, however, that reliance on (visual) feedback is a parameter influencing the efficiency of task execution (Gershon et al. 2015), and this may be more limited in VR than in RW.

None of the variables we examined were influenced by hand dominance alone, and the interactions were sparse. Clear tendencies did not emerge, neither for condition (thorax rotation was different when using the dominant or the non-dominant hand, but in RWC only), nor for position (MT_R and V_T were different depending on the hand side, but for a few targets only). Therefore, no conclusion could be drawn without further investigations. Also at neural level, the mechanisms underlying handedness are still a matter of investigation: Different models have been outlined (e.g., brain right hemisphere relying on sensory feedback, left on pre-planning in aimed reaching task; or right hemisphere controlling the position of body segments, and left controlling trajectory), but evidence both supporting and contrasting these hypotheses has been found (Bagesteiro & Sainburg 2002; Gershon et al. 2015; Haaland et al. 2004; Mieschke et al. 2001). The search for a neural control model that explains our results goes beyond the scope of this work. Still, future studies may also try to investigate further aspects related to hand dominance, which had not been considered up to now (e.g., different control strategies occur when comparing the two hands also in VR conditions (Bagesteiro & Sainburg 2002)). These findings, though empirical, could be of help in informing rehabilitation therapists about potentially different behaviors exhibited between the dominant and non-dominant sides.

Finally, our work did not highlight any influence of the targets' position on movement variables in all three conditions. This means that, among conditions, the same reaching and transport strategies were possibly applied across all targets. Irrespective of condition, the target placed in the contralateral bottom (CB) position was the only one for which we identified a pattern that was (in most of the comparisons) different from the others: It was quicker to reach and slower to transport with the dominant hand; also, it required more shoulder abduction, less shoulder flexion, and less elbow flexion than other targets. Previous studies exploring reaches toward targets in contralateral and ipsilateral position in both VR (Levin 2020; Viau et al. 2004) and RW only (Xiao et al. 2019) reported a less efficient movement strategy when reaching across the midline. However, once again, this principle did not apply to our outcomes. As already mentioned, the reduced distance of our targets from the midline may not have been sufficient to make differences emerge.

Specifically regarding CB, possible explanations may be attributed to the different hand accommodation required to grasp the item with the right hand (e.g., from the top or the side). However, this would contrast what was reported by Magdalon et al. (2011) and theories about asymmetries between the two brain hemispheres (Bradshaw et al. 1990).

In general, comparing the performance of our participants in VR condition, we found results that were slightly better than what was reported in previous studies with older HMDs (Knaut et al. 2009; Magdalon et al. 2011): Differences in MTs were over 50%; curvature was different; joint RoMs were influenced in the case of precise grips. Instead, our outcomes were worse than those reported for a comparable visualization device (Furmanek et al. 2019). This may go in the direction of denying the superiority of ecological environments in eliciting natural behaviors. Nonetheless, it is also true that such a study was focused on grasping parameters and implied a completely different environmental setting. Thus, no exact comparison could be made. Future studies focusing on the comparison of ecological vs. non-ecological virtual environments may shed further light on this topic. Nonetheless, the advantages of ecological settings—in terms of users' engagement and transfer of the acquired capabilities to real life (Parsons 2015; Rizzo & Kim 2005)—should encourage VR developers to focus on these, even in the absence of an overt superiority from the kinematic point of view.

5.1 Limitations

We acknowledge that this work has a few limitations, as we intended to conduct a preliminary trial investigating the potentialities of VR in eliciting natural behaviors in an ecological scenario. First, the sample was small (but comparable to previous studies' samples), the age range was narrow, and gender was not adequately balanced. All these elements did not allow generalizing the results to the entire population. Specifically for handedness, minor differences may be due to one left-handed participant: All previous studies investigating hand dominance included only right-handed participants. However, previous findings suggested that dominance is the parameter primarily influencing the upper limb's kinematics, rather than using the left or right arm per se (Diffendaffer et al. 2019; Przybyla et al. 2012).

Second, we used a within-subject design, which, on the one hand, has the advantage of allowing for a better comparison but, on the other, may introduce learning effects and fatigue. However, we expect these two effects to be null or negligible given the involvement of a healthy population, the randomization of the three conditions, and the relatively short duration of the whole experiment.

Third, in our intent of creating an unconstrained ecological environment, we are aware that we have reduced the control over our scenarios. However, we tried to make the conditions the most comparable as possible by aligning both vertically and horizontally the positions of the target items, and placing the virtual cart and the table in the same spot and with the superior edge at the same height. Given the volume of the real items, it was impossible to define a clear release point without affecting the experience. Few possibilities for increasing control over the setting (but reducing ecological validity) would be: (i) to set a starting point for each reach, (ii) to define a precise point in which the grabbed item should be released (and removed by a third person), and (iii) to use items requiring the same hand accommodation.

Also shelves structure may be rendered more similar: The presence of vertical bars in the real setup (needed to adjust the heights of the shelves) may have influenced the reaching behavior by providing a slightly different visual feedback. The real shelf was, however, left in place also for the performance of the VR condition: Neither unwanted collisions nor brushes against the shelf unit were recorded. This is reassuring in terms of items' placement: They were correctly aligned and far enough from vertical shelf edges.

Our study neglected to investigate variables that may further explain how VR influence the kinematic behavior of different users (e.g., jerk, number of peaks in the velocity profiles, EMG analysis) or the application of known models (e.g., Fitt's law (Zimmerli et al. 2012)), but given its nature of a pilot investigation, we believe that our outcomes are sufficient to reach adequate, though preliminary, conclusions.

Finally, we used the simple VR setup as possible, keeping in mind that this would ease both the potential future development of rehabilitative VR-based applications and the configuration of the VR devices, especially considering that they will be used in a clinical scenario and not in a research laboratory. Future studies addressing the topic of kinematics in VR could include better rendering of proprioception (e.g., showing an arm of a human avatar Connolly & Goodale 1999; Schettino et al. 2003)), and the use of cyber-gloves and haptic devices (Furmanek et al. 2019; Magdalon et al. 2011; Viau et al. 2004).

6 Conclusions

The aim of this study was to provide new information about the kinematics of reaching and transport movements performed in ecological immersive VR. We found that movement times and peak velocities were affected by VR, but not by the fact of holding the controller. Also, we showed that trajectory curvature and joint RoMs (with the exception of trunk rotation) were mostly not affected by the fact of wearing an HMD. According to previous studies (Furmanek et al. 2019; Knaut et al. 2009; Magdalon et al. 2011), this could be considered as a promising result, as movement pattern and joint angle synergies were preserved.

Our conclusions were promising, but the influence of having introduced ecological elements in the testing setup has still to be clarified. Nonetheless, this element remains fundamental for rehabilitation in order to facilitate the transferring of the capabilities acquired during rehabilitation to real life (Levin et al. 2015).

Another point that remains open to investigation is the extent to which movements performed in VR must be similar to those performed in VR to obtain functional gains by means of recovery during the rehabilitative intervention. Future studies should try to unveil this issue, also by conducting clinical trials and enrolling end users. Finally, the effectiveness of VR-based interventions remains uncontested, as it is for the benefits this technology provides to rehabilitation treatments (Laver et al. 2017; Mekbib et al. 2020; Yates et al. 2016).

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Author contributions SA, NK, GF, and MS had contributed to conceptualization; SA and NK were involved in methodology; SA and GP took part in software and investigation; SA prepared the original draft; NK, GP, GF, and MS wrote, reviewed, and edited the manuscript; NK and MS helped with resources; and GF and MS carried out supervision.

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Data availability Data are available upon request to the corresponding author.

Declarations

Conflict of interest The authors have no conflict of interest to declare.

Consent to participate All participants signed an informed consent form.

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