How reaching kinematics differ between a low-cost 2D virtual environment and the real world

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***Abstract*— Virtual reality interventions are increasingly used in rehabilitation to target sensorimotor impairments in various populations. To verify that the movements practiced in virtual reality applications are similar to the movements to be retrained when performing everyday activities, it is important to understand if movements performed in a virtual and a physical environment (real-life) are similar. The aim of this study is to estimate the extent to which unilateral reach to grasp movements performed in a 2D low-cost virtual environment are kinematically similar to movements performed in a comparable physical environment in healthy individuals. Using a cross-sectional design, 12 right-handed, healthy participants performed reaching to grasp movements with the dominant arm in a low cost 2D virtual and a comparable physical environment. Each movement was repeated 20 times in each environment. Arm and trunk kinematics were recorded using the Optotrak motion analysis system (13 markers; 120 Hz) and 3D kinematics were reconstructed. Temporal and spatial characteristics of the endpoint trajectory and arm and trunk movement patterns were compared between environments using ANOVAs. In the virtual environment, movements were slower, more segmented and the endpoint trajectory was straighter. Ranges of motion of arm and trunk movements did not differ between environments. When using 2D virtual environments for upper limb rehabilitation, differences in movement performance between virtual and physical environments should be taken into account.**

Keywords— reaching, virtual environment, upper limb, movement quality, rehabilitation

I. Introduction

Virtual reality is a promising intervention in rehabilitation for goal-directed training in a variety of medical conditions. Benefits associated with the use of virtual reality in rehabilitation include patient motivation and engagement, enriched environment and the ability to individualize treatment by modifying task difficulty or the feedback provided [1-3]. Virtual reality can be used to recreate real-life situations and environments that may not be easily done in rehabilitation settings, either due to safety or practicality (e.g. street crossing, grocery shopping or driving) [4]. With the emergence and availability of virtual reality applications designed specifically to meet rehabilitation goals and commercial off-the-shelf video games adapted for rehabilitation, virtual environments are increasingly used in hospital settings [3].

One of the frequent uses of virtual reality for rehabilitation purposes is sensorimotor skills training. However, an important limitation of traditional rehabilitation interventions is that the observed improvements during therapy sessions may not translate into improvements in functional independence and increased performance in everyday life activities. Virtual reality could be a promising intervention to facilitate transfer of skills to daily life functioning [5]. To optimize virtual rehabilitation and facilitate generalization of benefits to real-world functioning, there is a need to determine the kinematic validity of movements performed in virtual environments compared to those performed in a real-life setting.

Movement performance and quality can be altered by the viewing environment [6]. For example, Levin et al. [7] compared reaching and grasping movements performed in a 3D virtual environment with haptic feedback offered by a cyberglove and in a physical environment in individuals with stroke. Reaches were less smooth and slower in the virtual environment. However, the environment did not affect wrist, elbow, shoulder and trunk kinematics [7]. In another study with individuals who have had a stroke, pointing kinematics were compared in a physical environment and in a video-capture 2D virtual environment, where participants saw a mirror image of themselves interacting with objects. Viewing the targets in the 2D virtual environment affected overall movement performance and quality. Movements in the virtual environment were slower, shorter, less straight, less accurate and involved smaller ranges of shoulder and elbow joint excursions compared to movements in the physical environment in all participants [8].

Reaching and grasping movements are performed numerous times a day to manipulate and interact with objects in the surrounding environment. While these movements may be perceived as simple, the ability to produce upper limb functional movements relies on the coordination of complex spatial and temporal patterns of muscle activations. To improve motor recovery using tailored rehabilitation interventions, temporal and spatial characteristics of movement should be targeted. Differences in movement performance and quality between a virtual environment and the real world may be detrimental to motor retraining, as it may lead to maladaptive movements.

To date, there is little work investigating the ways upper limb movement kinematics are affected by the attributes of the

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virtual environment. To create ecologically valid virtual rehabilitation interventions and guide clinicians in the selection of virtual environments for motor rehabilitation, there is a need to better understand how virtual environments are influencing movement performance and quality. This is especially of interest in low-cost tracking 2D virtual environments commonly used in hospital settings.

The aim of this study was to estimate the extent to which unilateral reach to grasp movements are kinematically similar when movements are performed in a low-cost virtual environment and a comparable physical environment, in healthy individuals. It was hypothesized that both movement performance and quality would differ between the virtual and the physical environment, due to the difference in object perception between the virtual environment and the physical environment.

II. Methods

A. Design

This study used a cross-sectional design.

B. Participants

Healthy, right-handed individuals were recruited from a list of volunteers and recruitment posters on social media. Participants were excluded if they had a previous neurological condition or if they presented with visual-perceptual impairments determined by a score of <30 on the Motor-Free Visual Perceptual Test [9-11]. The sample size was based on *a priori* sample size calculation. The ethics board of the Center for Interdisciplinary Research in Rehabilitation of Greater Montreal approved the project. All participants were informed of the procedures and provided written consent prior to participation.

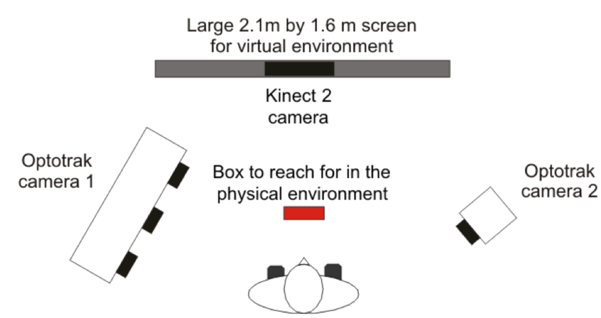
C. Procedures

Participants performed arm reaching movements with the dominant arm to grasp a box located at shoulder level in a virtual environment and a comparable physical environment. Participants were instructed to reach and grasp a virtual or a real box and to move at comfortable speed. The task was performed in standing with the feet shoulder-width apart. The initial position of the dominant arm was alongside the body with the elbow slightly flexed to 10°. The task was demonstrated by the experimenter and a 5-minute familiarization practice period was offered to the participant. Then, the reach-to-grasp movement was repeated 20 times in each environment. The order of presentation of the environment was randomized across subjects.

The virtual environment consisted of an interactive grocery store application developed by our research group to remediate arm motor impairments [12]. The application was developed using Unity Pro software and used the Kinect 2 camera (Microsoft, WA, USA). The virtual environment represented an aisle of a grocery store with three shelves of boxed and canned produce. Avatars of both forearms and hands were displayed on the screen from a first person perspective. The environment was projected in 2D on a large screen (dimensions 2.1 x 1.6 m). Sizes and shapes of the objects, shadows and lighting, texture gradients and motion parallax created the illusion of 3D.

The physical environment consisted of an adjustable height table mimicking a grocery store shelf and a small box (13 x 20 x 5.5 cm). Object locations in the physical environment were calibrated to ensure that the reaching distance and height were equivalent to those in the virtual environment (Fig. 1). In the virtual environment, object sizes were matched to the physical environment by changing the distance between the individual and the screen. The object height in both environments was measured from the object (either the physical object or the object as seen on the screen) to the floor, whereas the object distance was taken from the subjects (mid-sternum) and the object or its projection.

Fig. 1. Experimental set-up for the virtual and the physical environments



D. Data acquisition

Arm and trunk kinematics was recorded using the Optotrak motion analysis system to track the position of 2 rigid bodies composed of 3 non-coaxial infrared emitting markers and 7 additional markers. Rigid-bodies were positioned on the dominant arm and forearm, while single markers were placed on the mid-sternum, both acromion processes, the lateral epicondyle, the wrist (middle of the proximal row of carpals), the head of the second metacarpophalangeal joint and the tip of the index finger of the upper limb. Subjects initiated the movement upon hearing a verbal ‘go’ signal. Data were recorded for 6 seconds, at a sampling rate of 120 Hz.

E. Data processing

Positional data were low-pass filtered at a cut-off frequency of 10 Hz. Movements were analyzed in terms of temporal and spatial characteristics of the endpoint trajectory and arm and trunk movement patterns (elbow and shoulder ranges of motion, elbow/shoulder coordination and trunk displacement). Upper limb 3D kinematics were reconstructed using a custom-made MATLAB program. A linear interpolation program was used for missing data in each trial.

Endpoint tangential velocity was calculated by the differentiation of positional (x, y and z) data of the metacarpophalengeal marker. While the task involved a continuous movement of reaching, grasping and transporting, only the reaching movement was analyzed. For each reaching task, movement onset and offset was determined from the tangential velocity trace of the endpoint marker, where onset/offset was defined as the time at which the trace exceeded/fell below 10% of the peak tangential velocity in that movement. Onset/offset times were then verified by visual inspection.

Kinematic outcomes consisted of temporal and spatial characteristics of the endpoint trajectory (movement performance) and the movement quality (joint angles and interjoint coordination). At the movement performance level, outcome measures were movement time, endpoint peak velocity, time to endpoint peak velocity, trajectory straightness and movement smoothness. Movement time was determined from movement onset to time of grasping (offset) and all other outcomes were computed from movement onset to offset. Trajectory straightness was estimated using the index of curvature (i.e. ratio between the length of the actual movement trajectory and a straight line representing the shortest distance to the target). Endpoint movement smoothness was calculated as the number of movement units or velocity peaks in the endpoint tangential velocity trace. At the movement quality level, outcome measures were ranges of elbow extension, shoulder flexion and horizontal abduction and trunk rotations (pitch, roll and yaw). Flexion/extension range of motion at the elbow was calculated from computing the rotations of the elbow based on segment lengths and the position of the rigid-bodies of the forearm and arm (full elbow extension = 0°). Shoulder flexion/extension and horizontal abduction/adduction ranges of motion were computed from the rotations of the shoulder. The initial position, arm alongside the body, was defined as 0° of flexion and of abduction. Trunk rotation was computed from a rigid body constucted from the shoulder makers and the sternal marker, for which the initial position was equal to 0°.

F. Data analysis

Data were verified for normality using Kolmogorov-Smirnov and Shapiro-Wilk tests. Normally distributed outcomes were compared using one-way analyses of variance (SPSS v20, SPSS Inc, Chicago, IL). For non-parametric data, Wilcoxon Signed Ranks tests were used. Initial significance levels were set at < 0.05 for all statistical tests.

III. Results

Twelve healthy participants (6 females) were recruited (see Table 1 for socio-demographic information). All participants were self-reported right hand dominant and had no visual-perceptual impairments.

TABLE I. Socio-demographic information

Characteristics	***Mean ± SD***
Age (years)	57.3 ± 19.3
Education (years)	16.3 ± 3.8
MVPT[a] score (/36)	34.9 ± 1.38
Visual-processing speed (s)	3.60 ± 1.27

[a.] Abbreviations: MVPT: Motor-Free Visual-Perceptual Test

A. Effect of environment on reaching: comparison between the physical and the virtual environment

At the motor performance level, endpoint peak velocity, endpoint time to peak velocity, trajectory straightness, and movement smoothness differed between the virtual and the physical environment (see Table 2). Specifically, in the virtual environment, participants made slower arm movements, took longer to achieve peak velocity, and there was a tendency to have longer movement times. The reach-to-grasp movement was also more segmented, and participants adopted straighter movements in the virtual environment (see Fig. 2). At the movement quality level, the ranges of motion of the trunk, shoulder and elbow were similar for both environments.

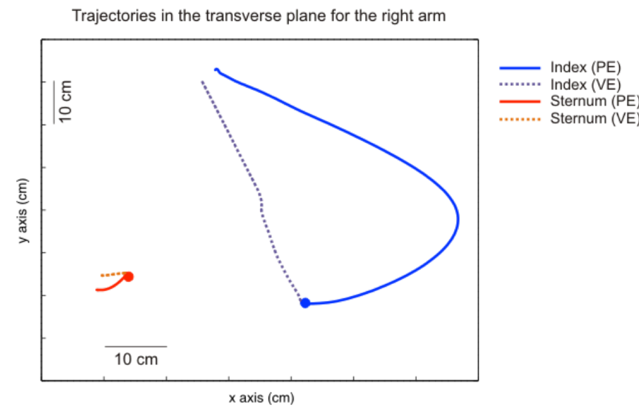


Fig. 2. Example of endpoint and trunk trajectories in the virtual environmnent (VE) and physical environment (PE)

TABLE II. Endpoint, arm and trunk kinematics for reaching movement in the 2 environments

Kinematic variables	**Spatial parameters**			
	VE Mean (SD)	***PE Mean (SD)***	***F***	***P-value***
Number of Peaks*	1.31 (0.48)	1.07 (0.15)	-2.536	0.011
Index of curvature*	1.07 (0.03)	1.15 (0.10)	-2.672	0.008
Shoulder flexion (º)*	47.44 (19.28)	47.02 (13.06)	-0.235	0.814
Shoulder abduction (º)	72.03 (32.69)	73.29 (29.95)	0.010	0.922
Elbow flexion (º)*	35.77 (28.31)	22.39 (17.49)	-1.804	0.071
Trunk pitch (º)	5.39 (4.51)	6.48 (2.66)	0.523	0.477
Trunk yaw (º)	10.39 (7.01)	12.39 (5.29)	0.624	0.438
Trunk roll (º)	5.31 (5.31)	8.51 (4.23)	2.167	0.155
	Temporal parameters			
Movement time (s)	1.86 (0.37)	1.54 (0.40)	4.105	0.055
Peak velocity (mm/s)	966.70 (279.56)	1253.36 (283.43)	6.222	0.021
Time to peak velocity (s)	0.63 (0.13)	0.52 (0.12)	4.504	0.045

* : non-parametric tests used (Z score instead of F score)

IV. Discussion

This study compared reaching kinematics in a low-cost 2D virtual environment and a comparable physical environment in healthy individuals. Temporal aspects of endpoint movement trajectories differed between environments (endpoint peak velocity, endpoint time to peak velocity, trajectory straightness, and movement smoothness). For spatial parameters, only movement smoothness and trajectory straightness differed, while all ranges of motion of the arm and trunk were similar. In the virtual environment, movements were slower, more segmented and endpoint trajectory was straighter.

Altered movement velocity and smoothness in this 2D virtual environment was consistent with results from previous studies using 2D and 3D virtual environments with healthy individuals and clinical populations [7, 8, 13-15]. The slower peak velocity and the longer time to peak velocity in the virtual environment can be explained by the differences in depth perception, the reduced visual cues in the virtual environment and the reduced accuracy of the Kinect 2 motion tracking camera. While the Kinect 2 camera provides full-body 3D motion capture and joint tracking capabilities, inaccuracy in tracking small movements and movements performed in the frontal and sagittal planes have been reported [16-18]. The quality of the 2D viewing environment may also have impacted the number of velocity peaks, as participants may have needed to adjust their movements based on the visual feedback provided by the forearm and hand avatar, hence reducing movement smoothness. The lack of haptic feedback in the virtual environment may also have influenced movement production [19].

To our knowledge, this study is one of the first to report differences in the index of curvature between the virtual and the physical environment. The adoption of straighter endpoint trajectories in the virtual environment suggests that participants may not have taken into consideration the changed object affordances in the virtual environment. Indeed, actions are determined by how the actor perceives the possible movements of the body that will allow him/her to interact with the object in the intended way. The interaction between the actor and the object is determined by the 'affordances' of the object. Object interactions are related to the object's location in space, its orientation, its relative distance from the body, its properties such as its texture, shape, size, weight, etc., as well as the properties of the environment in which the movement will occur (surface height, type of surface, etc.). This interaction is referred to as 'perception/action coupling'. This coupling may have been altered in the 2D virtual environment used in this study as evidenced by differences in how the object was grasped in each environment. In the virtual environment the object could be grasped by placing the whole hand over the object, whereas in the physical environment, the subject had to close their hand over the object. Indeed, in the virtual environment, participants first reached towards the virtual object (reaching the middle of the virtual box) and once the arm avatar was over the object, they opened their hand to grasp it. In contrast, in the physical environment, participants reached for the right side of the box and made a more curved endpoint trajectory to orient the hand to grasp the box.

At the movement quality level, our results differ from the results obtained by Liebermann et al. [8], in which both healthy participants and participants with stroke had a decrease in overall movement quality for reaches in a 2D virtual environment. The difference in the movements compared (reach-to-grasp vs. reaching to 3 targets), as well as the view in the virtual environment (first-person vs. third-person perspective) may explain this discrepancy. Indeed, kinematics of reach-to-grasp task differ from those of a reaching task [20], which may be explained by differences in perception-action coupling. When reaching for an object, the arm, hand and fingers are positioned according to the size, shape, orientation, location and affordance of the object. When pointing, the arm, hand and fingers are not required to be positioned in the same way. Also, in contrast to our study, in the Liebermann et al. [8] study, third-person interactions with the environment may have involved visuospatial transformations [21], which may have impacted movement quality in the 2D virtual environment.

V. Conclusion and Practice implications

This study provides new information about the validity of reach to grasp movements in a low-cost 2D virtual environment using a Kinect 2 motion tracking camera. The reduced visual cues in the virtual environment and the reduced accuracy of the Kinect 2 motion tracking camera may have affected reaching kinematics at the movement performance level. Differences in kinematics between virtual and physical environments should be taken into account when using 2D virtual environments for upper limb rehabilitation. The provision of a better 2D or 3D virtual viewing environment can help to overcome some of the problems in perception when interacting with 2D virtual environments.

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