Virtual Reality Environments to Enhance Upper Limb Functional Recovery in Patients with Hemiparesis

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Abstract. Impairments in reaching and grasping have been well-documented in patients with post-stroke hemiparesis. Patients have deficits in spatial and temporal coordination and may use excessive trunk displacement to assist arm transport during performance of upper limb tasks. Studies of therapeutic effectiveness have shown that repetitive task-specific practice may improve motor function outcomes. Movement retraining may be optimized when done in virtual reality (VR) environments. Environments created with VR technology can incorporate elements essential to maximize motor learning, such as repetitive and varied task practice, performance feedback and motivation. Haptic technology can also be incorporated into VR environments to enhance the user's sense of presence and to make motor tasks more ecologically relevant to the participant. As a first step in the validation of the use of VR environments for rehabilitation, it is necessary to demonstrate that movements made in virtual environments are similar to those made in equivalent physical environments. This has been verified in a series of studies comparing pointing and reaching/grasping movements in physical and virtual environments. Because of the attributes of VR, rehabilitation of the upper limb using VR environments may lead to better rehabilitation outcomes than conventional approaches.

Keywords. Stroke, Kinematics, Validation, Reaching, Grasping.

Introduction

The motor recovery of the upper limb in patients following congenital or acquired brain injury remains a persistent problem in neurological rehabilitation. More than 80% of the approximately 566,000 stroke survivors in the United States experience hemiparesis resulting in impairment of one upper extremity (UE) immediately after stroke and in 55-75% of survivors, impairments persist beyond the acute stage of stroke. Important from a rehabilitation perspective is that functional limitations of the upper limb contribute to disability and are associated with diminished health-related quality of life [1, 3].

Despite a growing number of studies, there is still a paucity of good quality evidence for the effectiveness of upper limb motor rehabilitation techniques for patients

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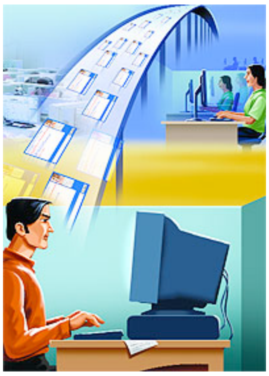

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with stroke-related hemiparesis [4]. Current rehabilitation practice is based on movement repetition of targeted tasks in the clinical setting. Not all motor improvements gained in clinical settings however have been shown to carry over into real world situations when patients are discharged home after therapy [5]. For example, even patients with well-recovered upper limb function as judged by clinical tests may not make full use of their arm in everyday activities [6]. One possible reason for the tendency to under use the affected arm may be the lack of recovery of higher order motor control functions resulting in an inability to perform rapid, accurate and coordinated movement and the perception of arm movements as being clumsy and slow [7]. This suggests that greater attention should be paid to retraining upper limb coordination or the ability of the arm and hand to interact with the environment rapidly and efficiently in order to improve the real world relevance of practice in the clinical setting. Indeed, an important component of dexterous movement, if such a term can be applied to whole arm movement, is coordination between different body segments - an element that has been largely neglected in rehabilitation approaches to movement recovery.

1. Deficits in the coordination of reaching and grasping movements in patients with stroke

The arm motor deficit in stroke is complex and can be described at all levels of the International Classification of Functioning (ICF, World Health Organization, http://www.who.int/classifications/icf/en/). At the Body Structure and Function (impairment) level, stroke-related hemiparesis is characterized by sensorimotor deficits such as spasticity [8] and pathological synergies in the limbs contralateral to the hemispheric lesion [9]. The ability to activate and inactivate appropriate muscles [9, 15] is also compromised as well as the abilities to compensate elbow and shoulder torques [12, 16] and to coordinate movements between adjacent joints [17, 18]. Impairments may be related to altered mechanical properties of motor units [19, 20], abnormal agonist motor unit activation [21, 22] and deficits in segmental reflex organization, including the ability to appropriately regulate stretch-reflex threshold excitability [23, 27]. Previous studies have shown that patients have deficits in both spatial and temporal aspects of interjoint coordination during 3D reaching to stationary targets, placed within [18, 28, 30] and beyond the reach [31]. They also have coordination deficits when synchronizing hand orientation with hand opening and closing during reach-to-grasp movements to stationary targets (Figure 1) [32, 33].

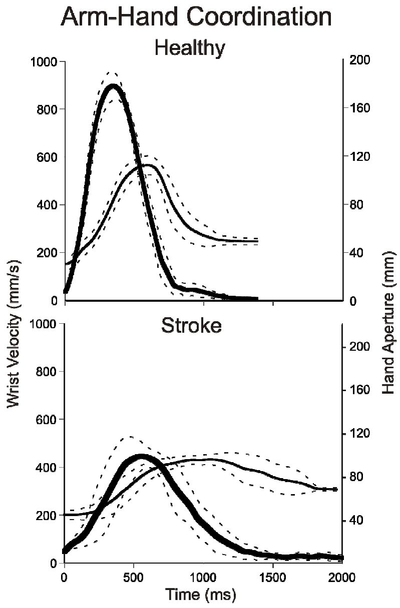

Figure 1. Arm and hand coordination during a reach-to-grasp task in one healthy subject (*top*) and one individual with stroke-related hemiparesis (*bottom*). The mean peak hand aperture (thin solid lines) generally occurs after the mean peak hand velocity (thick solid lines) as seen in both examples but the movement is slower and hand opening is delayed in the individual with hemiparesis. Dotted lines indicate ± one standard deviation of the mean traces.

For more complex movements, individuals with hemiparesis may have several deficits when attempting to produce coordinated arm, trunk and hand movements. For example, during trunk-assisted reaching (reaching to objects placed beyond arm's length), patients may have deficits in the timing of the initiation of arm and trunk movement characterized by delays and increased variability [34, 35]. In addition, Esparza et al. [35] found differences in the range of trunk displacement between patients with left and right brain lesions and documented bilateral deficits in the control of movements involving complex arm-trunk co-ordination.

We are only beginning to understand how complex movements are controlled and the role of perception-action coupling in the healthy and damaged nervous system. The healthy nervous system is able to integrate multiple degrees of freedom of the body and produce invariant hand trajectories when making pointing movements with or without trunk displacement (Figure 2). In trunk-assisted reaching, Rossi et al. [36] compared the hand trajectories when healthy subjects reached to a target placed beyond the reach on a horizontal surface. In some trials, the trunk was free to move and thus contributed to the endpoint trajectory. In some other trials however, the trunk movement was unexpectedly arrested before the movement began. They showed that the initial contribution of the trunk movement to the hand displacement was neutralized by appropriate compensatory rotations at the shoulder and elbow. Trunk movement began to contribute to hand displacement only after the peak velocity of the hand movement was reached. Results such as these highlight the elegant temporal and spatial coordination used by the healthy nervous system to produce smooth and effective movement.

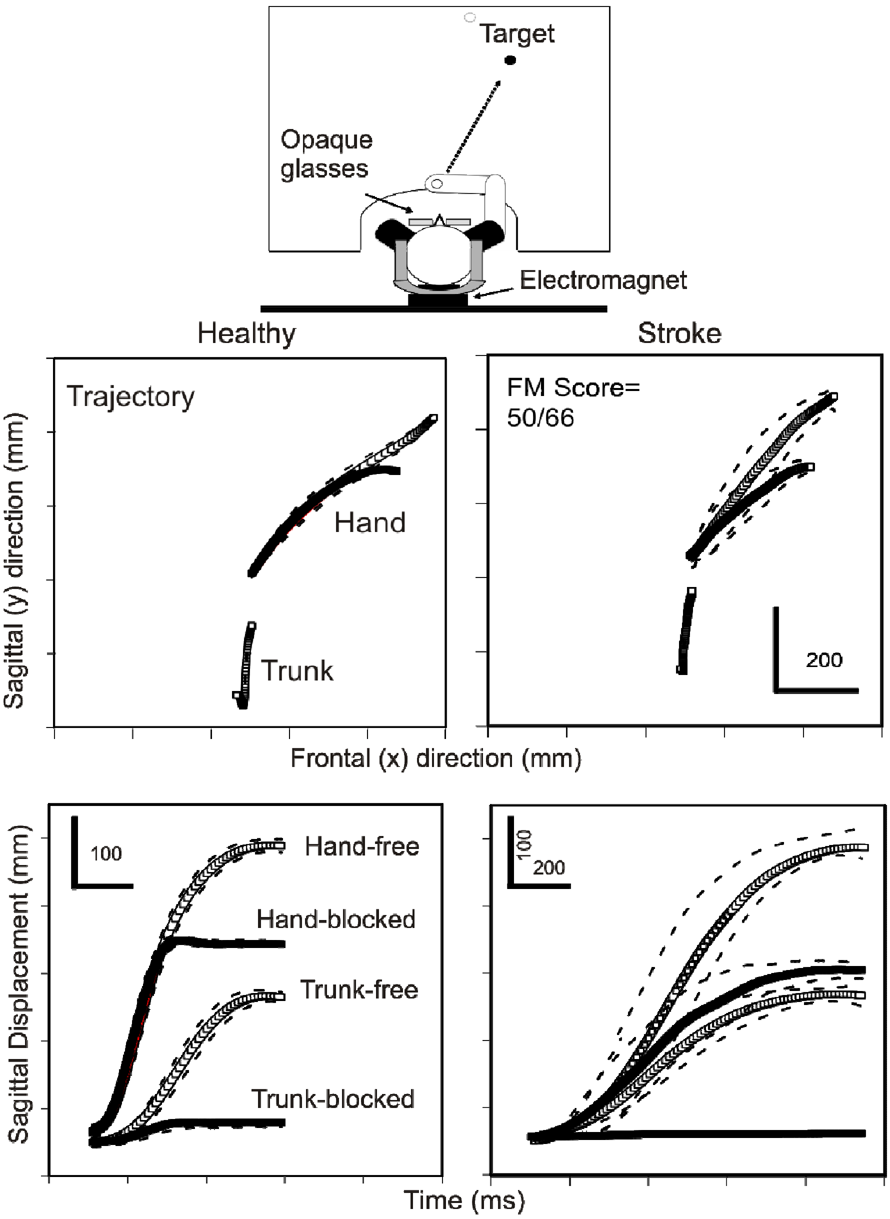

Figure 2. Top. For beyond-the-reach experiments, subjects sat in a cut-out section of a plexiglass table. Goggles obstructed vision of the hand and target after the go signal. Hand starting position was located 30 cm in front of the sternum. A metal plate attached to the back of the trunk, and an electromagnet attached to the wall were used to arrest the trunk movement in 30% of randomly selected trials. Middle and lower panels: Mean hand and trunk trajectories for one healthy (*left*) and one stroke subject (*right*) in trunk-blocked (solid lines) and trunk-free (open lines) movements. The stroke subject had a moderate motor impairment as indicated by the Fugl-Meyer (FM) Arm Score of 50 out of 66. Despite differences in the trunk motion between conditions, hand trajectories for blocked-trunk trials initially coincided with those for free-trunk movements. Hand trajectories for trunk-blocked trials diverged earlier in participants with stroke indicating that they could not fully compensate for the trunk movement by adjusting their arm movement.

After stroke, control of movement in specific joint ranges is limited and trunk movement makes a larger and earlier contribution to hand transport for reaches to objects placed both within and beyond the arm's length [26, 29]. The neurologically damaged system also has deficits in the ability to make appropriate compensatory adjustments of the arm joints to maintain the desired hand trajectory during trunk-assisted reaching. This was tested using the same paradigm described above for the study by Rossi et al. [36]. We compared hand trajectories and elbow-shoulder interjoint coordination during "beyond-the-reach" pointing movements in healthy and hemiparetic subjects when the trunk was free to move or when it was unexpectedly arrested [31]. In approximately half the participants with hemiparesis, hand trajectory divergence occurred earlier (Figure 2, right panels) while the divergence of interjoint coordination patterns occurred later than the control group suggesting that compensatory adjustments of the shoulder and elbow joints were not sufficient to neutralize the influence of the trunk on the hand trajectory. Arm movements only partially compensated the trunk displacement and this compensation was delayed. This suggests a deficit in intersegmental temporal coordination that may be partly responsible for the loss of arm coordination even in well-recovered patients.

Individuals with hemiparesis also have spatial and temporal coordination deficits between movements of adjacent arm joints such as the elbow and shoulder [12, 16, 17, 18, 37], between the transport phase of reaching and aperture formation in grasping [38, 40] and in precision grip force control [39, 41]. For example, using a mathematical analysis of kinematic variability during whole arm reaching movements, Reisman and Scholz [42] found that individuals with mild-to-moderate hemiparesis had deficits in specific patterns of joint coupling, and that they had only partial ability to rapidly compensate movement errors. This suggestion had previously been proposed for single joint arm movements by Dancause et al. [43] who further related the error compensation deficits to impairments in executive functioning in patients with chronic stroke.

The reduced capacity to produce and coordinate the movements of the arm, hand and trunk into coherent action [see 44, 45] may lead to clumsy and slow movement making it less likely that individuals would use their upper limb in daily life activities. Rehabilitation efforts are aimed at reducing the effects of impairments through repeated practice of targeted movements, tasks or activities in controlled clinical environments [46].

2. Environments for upper limb rehabilitation interventions

The environment in which movement is practiced may be crucial to maximize motor recovery. Recently, Kleim and Jones [47] summarized some of the outcomes of the IIIStep meeting held in Salt Lake City in 2005, and outlined 10 principles of experience-dependent plasticity related to recovery from stroke. Of these, several principles directly or indirectly relate to the environment in which movement is practiced. These include the importance of specificity, repetition, intensity and salience of practice. All of these factors can be creatively manipulated using virtual reality technology to make the most of the practice environment and to add the novelty of gaming to make activities more challenging. Virtual reality (VR) is a multisensorial experience in which a person is immersed and can interact with a computer-generated environment [48]. VR offers the user a practice environment that can be ecologically valid and has the potential to enhance patient enjoyment and compliance [49], important factors in successful rehabilitation [50, 52].

2.1. Advantages of virtual environments

In virtual reality environments (VE), real-world situations can be mimicked while precisely and systematically manipulating environmental constraints (tasks, obstacles). Indeed, task difficulty can be manipulated without danger to the user. Consequently, VEs have been used in a number of movement analysis studies [53, 61]. One advantage of using VEs is that sensory parameters can be adapted and scaled to the abilities of the user. In so doing, responses to a larger number of situations in a shorter amount of time than is possible in real-world laboratory experimental set-ups can be measured. For example, in a VE, several object locations and orientations can be reliably and rapidly reproduced and object properties can be manipulated (i.e., obstacles can be introduced by quickly changing properties and orientation of the object or the environment). VEs are especially suited to the study of how individuals interact with objects or situations that unexpectedly change. Thus, questions about dexterity and coordination that are not easily accessible in a real-world environment can be more easily addressed. This is of particular importance in the study of arm functional recovery in post-stroke patients.

Many stroke survivors lack the ability to reliably use the arm and hand during interactions with objects within changing environments: e.g. catching a ball or picking up an object while walking. These types of experimental set-ups are difficult to recreate in the laboratory. Finally, another advantage of using VR is the possibility of studying movement production in situations that, in the real world, may compromise the safety of the individual. For example, in obstacle avoidance tasks, the ability to anticipate and reach around a static obstacle such as the table ledge can be evaluated as well as the ability to move in a constrained environment without danger of incurring injury due to impact of the hand with an object.

2.2. The question of haptics

When the arm and hand interact with objects in the physical world, in addition to proprioceptive feedback related to limb movement, the individual perceives sensory information about collision of the hand with the objects being manipulated. This sensory information combined with task success, provides feedback to the individual about the adequacy and effectiveness of his or her movement in the virtual environment. However, haptic information is not easily incorporated into VR environments created for motor control studies or rehabilitation studies of upper limb reaching and object manipulation. The use of relevant haptic interfaces is important because it enhances the user’s sense of presence within VEs [62]. Many existing VEs do not include haptics or include haptic information limited to sensations felt through a joystick or mouse [63, 64]. These do not provide the nervous system with the most salient movement-related sensory information. Given this reality, the essential question is whether movements made in VR environments that lack haptic sensory cues usually available in physical environments, can be considered valid. In other words, are they spatially and temporally kinematically similar to equivalent movements made in physical environments? In order to address this question, several studies have been done to compare the kinematics of movements made in different types of VEs to those made in physical environments [65, 69]. The following section of this chapter will summarize the results of these validation studies.

3. Are movements made in virtual and physical environments kinematically similar?

Viau et al. [69] compared movement kinematics made by 8 healthy adults and 7 stroke survivors with mild left hemiparesis who performed near identical tasks in both a physical and in a virtual environment. In both tasks, seated subjects grasped a real or virtual 7 cm diameter ball, reached forward by leaning the trunk and then placed the ball within a 2 cm x 2 cm yellow square on a real or virtual target. The initial conditions for the task and the tasks themselves were carefully matched so that movement extent and direction were as similar as possible. Thus, in both environments, the initial position of the arm was about 0° flexion, 30° abduction and 0° external rotation (shoulder), 80° flexion and 0° supination (elbow) with the wrist and hand in the neutral position. The fingers were slightly flexed. The initial position of the ball was 13 cm in front of the right shoulder, 7 cm above and 3 cm to the left of the subject’s hand. The target was placed 31 cm in front of the shoulder, 12.5 cm above and 14 cm to the right of the initial position of the ball. The VR environment was displayed in 2 dimensions (2D) on a computer screen placed 75 cm in front of subject’s midline. The ball and hand were displayed on the screen inside a cube. The task was to place the ball in the upper right far corner of the cube. The virtual representation of the subject’s hand was obtained using a 22 sensor fibre optic glove (Cyberglove, Immersion Corp.) and an electromagnetic sensor (Fastrak, Polhemus Corp.) that was used to orient the glove in the 2D environment. Data from these devices were synchronized in real time. To enable the subject to "feel" the virtual ball, a prehension force feedback device (Cybergrasp, Immersion Corp.) was fitted to the dorsal surface of the hand. The Cybergrasp delivered prehension force feedback in the form of extension forces to the distal phalanxes of the thumb and each finger. Forces applied to the fingers were calibrated for each subject while he/she was wearing the Cyberglove and all subjects perceived that they were holding a spherical object in their hand. To better compare the performance of participant in each of the two environments, the glove and grasp devices were worn on the hand in both conditions (Figure 3).

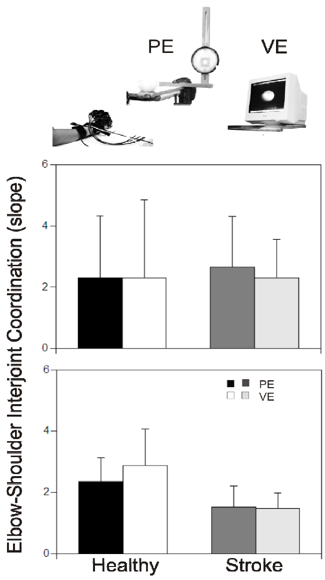

Figure 3. Top: Experimental set up for reaching, grasping and placing experiment in 2D virtual (VE) and physical (PE) environments. Elbow-shoulder interjoint coordination in the reaching (middle) and transport (bottom) phase of the task was similar between environments in healthy and stroke subjects.

Kinematics of functional arm movements involving reaching, grasping and releasing made in physical and virtual environments were analyzed in two phases: 1) reaching and grasping the ball and 2) ball transport and release. Temporal and spatial parameters of reaching and grasping were determined for each phase. Using this 2D VR environment, individuals in both groups were able to reach, grasp, transport, place and release the virtual and physical ball using similar movement strategies. In healthy subjects, reaching and grasping movements in both environments were similar in terms of spatial and temporal characteristics of the endpoint and joint movements. Healthy subjects however, used less wrist extension and more elbow extension to place the ball on the virtual vertical surface.

As has been well-documented [17, 37], reaching movements made by individuals with hemiparesis are different from those made by healthy control subjects. Compared to healthy subjects, participants with hemiparesis made slower movements in both environments and during transport and placing of the ball, trajectories were more curved and interjoint coordination was altered. Despite these differences, however, participants with hemiparesis also tended to use less wrist extension during the whole movement and they used more elbow extension at the end of the placing phase for the movement made in VR.

The finding that both groups of subjects used less wrist extension and more elbow extension in the virtual compared to the physical environment suggested that the movements made in VR might have been influenced by differences in perception of the target location and the absence of haptic feedback when the target was touched by the ball. We addressed these questions in a second study in which we compared the spatial and temporal characteristics of reaching to targets located in different parts of the workspace in a 3D environment [65, 66]. If the problem of target localization was related to the quality of depth perception, then movements made in a 3D environment should be more like those made in a physical environment than those made in the 2D environment of the computer screen.

We created a 3D VE consisting of two rows of three targets arranged so that they were in different parts of the arm workspace (Figure 4). The virtual environment, created on CAREN software (Motek, Inc) was viewed through a head-mounted display (HMD, Kaiser XL50, resolution 1024 x 768, frequency 60Hz) and arm and hand movements were recorded with an Optotrak Motion Capture System (Northern Digital). In lieu of haptic feedback, when a target was ‘touched’ by the virtual hand, auditory or visual feedback was provided.

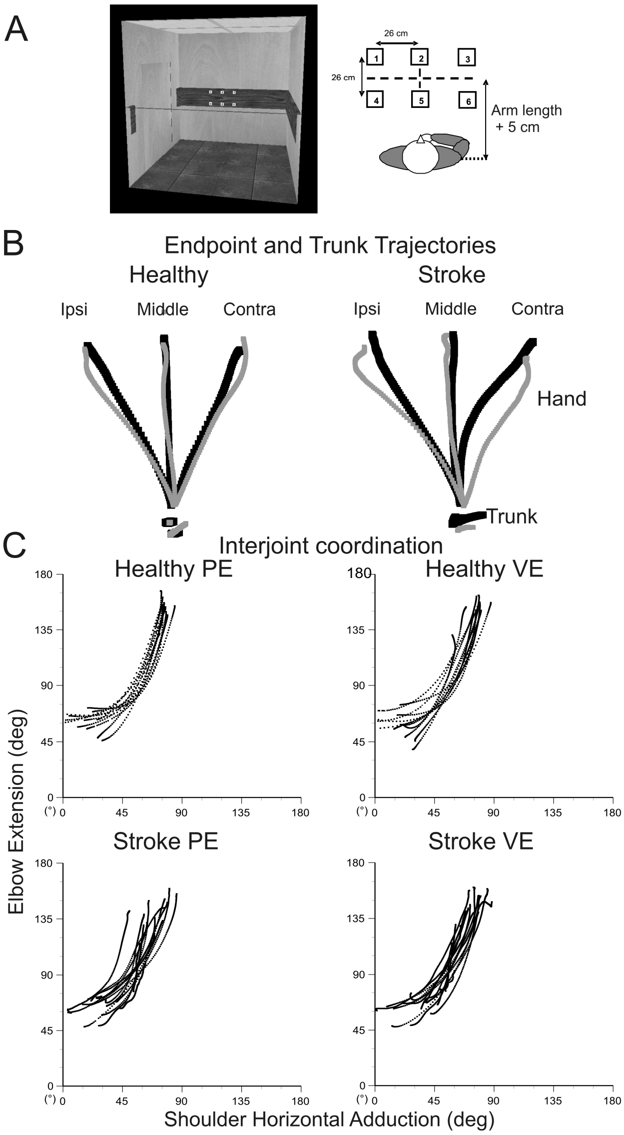

Figure 4. A. Experimental set-up for comparison of pointing in the physical environment and equivalent 3D virtual environment. The virtual environment (VE) was designed as two rows of three elevator buttons. The distances between the buttons and from the body were the same in both environments. B. Examples of endpoint (hand) and trunk trajectories for pointing movements to three lower targets in one healthy and one stroke subject. C. Examples of elbow/shoulder interjoint coordination for movements made to middle lower target in healthy and stroke subjects in the physical (PE) and virtual (VE) environments.

The VE was designed to exactly reproduce a physical environment that also consisted of 2 rows of targets. Thus, the VE was not designed to take advantage of the attributes of virtual environments for movement retraining. Rather, it was designed to be an exact replica of the physical environment in order to be able to compare the movement kinematics made to similarly placed targets. The location of the targets required the subject to use different combinations of arm joint movements for successful pointing. The center-to-center distance between adjacent targets was 26 cm in both environments and targets were displayed at a standardized distance equal to the participant's arm length.

Fifteen adults (4 women, 11 men; aged 59 ± 15.4 years) with chronic poststroke hemiparesis participated in this study. They had moderate upper limb impairment according to Chedoke-McMaster Arm Scores which ranged from 3 to 6 out of 7. A comparison group of 12 healthy subjects (6 women, 6 men, aged 53.3 ± 17.1 years) also participated in the study.

The task was to point as quickly and as accurately as possible to each of the 6 targets (12 trials per target) in a random sequence in each of the two environments. Movements were analyzed in terms of performance outcome measures (endpoint precision, trajectory and peak velocity) and arm and trunk movement patterns (elbow and shoulder ranges of motion, elbow/shoulder coordination, trunk displacement and rotation). There were very few differences in movement kinematics between environments for healthy subjects. Overall, there were no differences in elbow and shoulder ranges of motion or interjoint coordination for movements made in both environments by either group (Figure 5). Healthy subjects however, made movements faster, pointed to contralateral targets more accurately and made straighter endpoint paths in the PE compared to the VE. The participants with stroke made less accurate and more curved movements in VE and also used less trunk displacement. Thus, the results of this study suggested that pointing movements in virtual environments were sufficiently similar to those made in physical environments so that 3D VEs could be considered as valid training environments for upper limb movements.

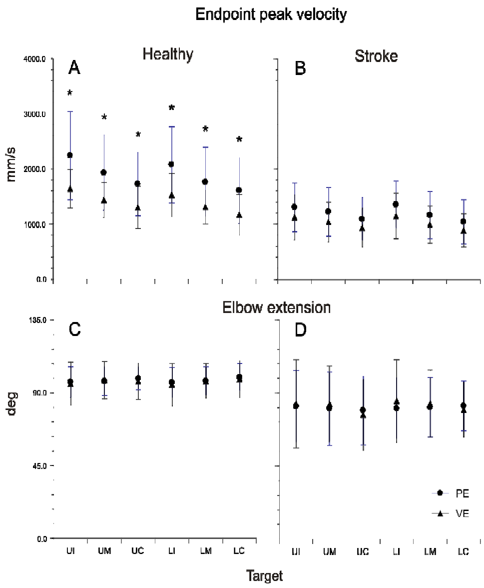

Figure 5. Results of comparison of pointing movements made in two environments described in Figure 4. Healthy (A) but not stroke (B) subjects made movements more slowly in the virtual environment (VE) compared to the physical environment (PE). There were no differences in joint ranges used in either healthy or stroke subjects in the two environments (C,D).

The appearance of more curved trajectories and the use of less trunk movement were also features of grasping movements made in a virtual environment while subjects wore a haptic device on the hand (Cybergrasp, Immersion Corp.). In a study of 12 adults with chronic stroke-related hemiparesis (age 67±10 yrs), reaching and grasping kinematics to three different objects in a VE and a PE were compared [68]. The 3D virtual environment was displayed via a HMD as in the previous study and the task was to reach forward, pick-up and transport a virtual/physical object from one surface to another (Figure 6). Three objects were used that required different grasp types – a can (diameter 65.6 mm) that required a spherical grasp, a screwdriver (diameter 31.6 mm) requiring a power grasp and a pen (diameter 7.5 mm), requiring a precision finger-thumb grasp. In the VE, the virtual representation of the subject's hand was obtained using a glove (Cyberglove, Immersion Corp.) and haptic feedback (prehension force feedback) was provided via an exoskeleton device placed over the glove (Cybergrasp, Immersion Corp.).

As for the comparison of reaching movements, comparable movement strategies were used to reach, grasp and transport the virtual and physical objects in the two environments. Similar to what was found for pointing movements, reaching in VR took approximately 35% longer compared to PE. This was true especially for the cylindrical and precision grasps. Thus, reaching and grasping movements that were accomplished in around 1.5 seconds in PE, took up to 2.2 seconds in the VE. The increase in movement time was reflected in all the temporal variables compared between the two environments such as the peak velocity, the time to peak velocity, the time to maximal grip aperture and the deceleration time as the hand approached the object. In addition to the temporal differences, movement endpoint trajectories were also more curved in VE. Overall, participants used more elbow extension and shoulder horizontal adduction in VE compared to PE and there were slight differences in the amount of supination and pronation used for reaching the different objects. Despite these differences, subjects were able to similarly scale hand aperture to object size and the hand was similarly oriented in the VE compared to the PE.

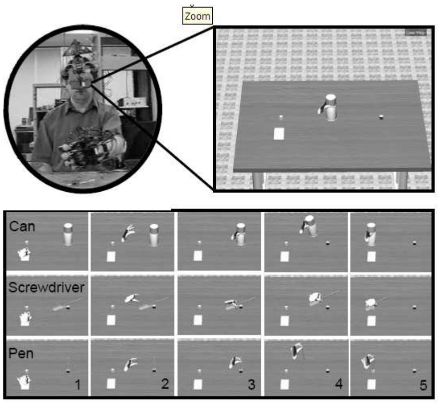

Figure 6. Representation of virtual environment for comparison of reaching and grasping kinematics in physical and virtual environments. Inset (upper right) shows the scene as viewed by the subject wearing the head-mounted display. Bottom: Sequence of movements (1-5) for picking up and moving the can, screwdriver and pen.

4. Conclusion

Results of these validation studies are encouraging for the incorporation of VEs into rehabilitation programs aimed at improving upper limb function. They suggest that movements made in virtual environments can be kinematically similar to those made in physical environments. This is the first step in the validation of VEs for rehabilitation applications. A question remains as to how similar movements made in VEs have to be to movements made in the physical world in order for real functional gains to occur. Research on the effectiveness of task-specific training versus conventional or non-specific training suggests that rehabilitation outcomes are better when practice is task-oriented and repetitive [4, 46, 70]. Better outcomes are also expected when the learner is motivated to improve and when the movements practiced are judged to be salient to the learner [47]. These variables can be optimized in novel environments offered by virtual reality technology to maximize rehabilitation outcomes.

VR is one of the most innovative, potentially effective technologies that during the past decade has begun to be used as an assessment and treatment tool in the rehabilitation of adults and children [49, 50, 52, 71, 72]. Some progress has been made in the demonstration of the transfer of abilities and skills acquired within VE to real world performance [50, 69, 73, 75]. Training in virtual reality environments has the potential to lead to better rehabilitation outcomes than conventional approaches because of the attributes of VR. Future research is still needed to firmly establish that motor gains made in VEs are transferable to and will improve functioning and arm use in the physical world.

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