Reaching, thinking, moving: virtual reality for upper limb rehabilitation

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Statement of Authorship

I, Marika Demers, certify that I am the primary author of this thesis and all the manuscripts contained in this thesis. I claim full responsibility for the content and study of the text included herein.

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Abstract

Virtual reality (VR) is a promising intervention for sensorimotor rehabilitation following a stroke. To date, increasing evidence supports the use of virtual interventions for paretic upper limb rehabilitation of patients in the chronic phase of stroke recovery. Still, evidence is limited in the sub-acute phase of stroke recovery, where most rehabilitation occurs. To address this gap, our research team developed a functional game-based virtual reality intervention designed to remediate arm motor impairments in sub-acute stroke rehabilitation. Before the effectiveness of this virtual reality-based intervention can be tested in a planned intervention study, it is crucial to determine the feasibility of the virtual reality intervention with potential users. Specifically, it is necessary to determine the validity of movements made in a two-dimensional (2D) VR environment by comparing motor performance and quality of movement variables of reaching movements made in the two environments. This is important to ensure that movements practiced in the virtual environment match real-life situations and to avoid reinforcing maladaptive compensatory movements.

The overall aim of the thesis is to determine the feasibility of using a virtual reality intervention as a therapeutic option for improving upper limb function in individuals who have had a stroke. This thesis is comprised of three manuscripts - one review paper and two experimental studies.

The first manuscript is a mixed-methods study aimed at determining users' satisfaction and safety of incorporating the developed virtual rehabilitation intervention as an adjunctive therapeutic option for sub-acute stroke rehabilitation. Clinicians' perspectives were assessed in a focus group interview. Satisfaction with, ease of use and difficulty level of the VR intervention, fatigue and occurrence of adverse events were assessed using semi-structured interviews and standardized assessments. The main findings were that both clinicians and individuals with sub-acute stroke were highly satisfied with the virtual reality intervention and perceived that it would be useful in clinical practice. The duration

and intensity of a single session of virtual reality were well tolerated. The intervention was also considered safe, with no participants experiencing major adverse events.

The second manuscript is a structured review. The objective was to determine the extent to which upper limb movement quality is assessed by commonly used neurological outcome measures. Outcome measures assessing arm/hand function and recommended by neurological clinical practice guidelines were reviewed. This manuscript highlighted the need to incorporate the assessment of movement quality into clinical practice and research. The results suggested that most upper limb measures poorly capture how well a person moves, limiting their ability to distinguish recovery from compensation and to adequately track changes over time. Only one measure, the Reaching Performance Scale for Stroke, was found to assess both movement quality and motor performance. The use of observational kinematics with or without motion tracking technology could help to incorporate movement quality into clinical assessment.

The third manuscript focuses on the kinematic validity of upper limb functional movements performed in the 2D VR environment. The aim was to determine whether upper limb movements made in a low-cost 2D were similar to those made in a comparable physical environment, in healthy individuals and in individuals who have had a stroke with and without visual perceptual impairments. Participants performed unimanual and bilateral reach-to-grasp movements in a virtual environment and a similar physical environment. Arm and trunk kinematics were recorded using the Optotrak motion analysis system. For unimanual reaching movements, movement speed, hand orientation when grasping the object and trunk kinematics were unaffected by the environment. However, in the virtual environment, unimanual reaches were less smooth and time to peak velocity was longer. These differences were more pronounced in individuals with stroke. Greater visual perceptual impairments resulted in longer movement duration and slower time to peak velocity in only in the virtual environment. For bilateral reach-to-grasp movements, healthy individuals made generally simultaneous and symmetrical movements in both environments. In contrast, movements in stroke subjects were less symmetrical in the virtual environment. The similarity of endpoint spatial variables of movements and most movement quality variables made in the virtual and the physical environments suggest that using the low-cost 2D virtual environment may be a valid approach for sensorimotor rehabilitation following a stroke. This work supports the feasibility of using a low-cost VR intervention for supplementing stroke rehabilitation in individuals with a large spectrum of motor, cognitive and perceptual impairments.

Abrégé

La réalité virtuelle est une modalité thérapeutique prometteuse pour la réadaptation sensorimotrice à la suite d'un accident vasculaire cérébral (AVC). À ce jour, de plus en plus de données probantes appuient l'utilisation de la réalité virtuelle comme intervention pour la réadaptation du membre supérieur hémiparétique dans la phase chronique de récupération à la suite d'un AVC. Néanmoins, les preuves sont limitées dans la phase subaigüe de la réadaptation, où l'essentiel de la réadaptation a lieu. Pour combler cette lacune, notre équipe de recherche a mis au point une intervention fonctionnelle de réalité virtuelle conçue pour remédier aux déficiences motrices du bras dans le cadre de la réadaptation en phase subaigüe. Avant de pouvoir tester l'efficacité de cette intervention de réalité virtuelle, il est essentiel de déterminer la faisabilité de l'intervention de réalité virtuelle avec les utilisateurs potentiels. Plus précisément, il est nécessaire de déterminer la validité des mouvements effectués dans un environnement virtuel en deux dimensions en comparant la performance et la qualité des mouvements d'atteinte effectués dans les deux environnements. Ceci est important pour s'assurer que les mouvements pratiqués dans un environnement virtuel correspondent à des situations réelles et éviter, ainsi, de réentrainer des mouvements compensatoires non-désirables.

L'objectif général de la thèse est de déterminer la faisabilité d'utiliser une intervention de réalité virtuelle comme modalité thérapeutique pour améliorer la fonction du membre supérieur chez les personnes qui ont subi un AVC. Cette thèse comprend trois manuscrits, une revue narrative et deux études expérimentales.

Le premier manuscrit est une étude à méthodes mixtes visant à déterminer la satisfaction des utilisateurs et la sécurité face à l'incorporation d'une intervention de réalité virtuelle, offerte en ajout aux soins habituels, spécifiquement développée pour la réadaptation à la suite d'un AVC en phase subaigüe. Les perspectives des cliniciens ont été évaluées lors d'un groupe de discussion. La satisfaction, la facilité d'utilisation et le niveau de difficulté de l'intervention de réalité virtuelle, ainsi que le niveau de fatigue et la présence d'évènements indésirables ont été évalués à l'aide d'entrevues semi-structurées et d'évaluations

standardisées. Les principales conclusions de cette étude étaient que les cliniciens et les personnes ayant subi un AVC étaient très satisfaits face à l'intervention de réalité virtuelle et ils percevaient l’utilité de cette intervention dans la pratique clinique. La durée et l'intensité d'une seule session de réalité virtuelle furent bien tolérées. L’intervention a également été considérée comme étant sécuritaire, puisqu’aucun participant n’a connu d’effets indésirables majeurs.

Le deuxième manuscrit est une revue narrative. L'objectif était de déterminer dans quelle mesure la qualité de mouvement du membre supérieur est évaluée à l'aide des outils de mesure couramment utilisés en neurologie. Les outils de mesure évaluant la fonction du bras et/ou de la main et recommandés par les guides de pratique clinique en neurologie ont été passés en revue. Ce manuscrit a mis en évidence la nécessité d'intégrer l'évaluation de la qualité du mouvement dans la pratique clinique et en recherche. Les résultats suggéraient que la plupart des outils de mesure du membre supérieur ne reflètent pas la façon dont une personne bouge, ce qui limite la capacité de distinguer la récupération motrice de la compensation et de mesurer de façon adéquate les changements au fil du temps. Une seule mesure, le *Reaching Performance Scale for Stroke*, évalue à la fois la qualité de mouvement et la performance motrice. L'utilisation de la cinématique d'observation avec ou sans l’incorporation de technologies de capture du mouvement pourrait aider à intégrer la mesure de la qualité de mouvement à l'évaluation clinique.

Le troisième manuscrit porte sur la validité des mouvements fonctionnels du membre supérieur effectués dans un environnement de réalité virtuelle. Plus précisément, l’objectif était de comparer la performance motrice et la qualité des mouvements effectués dans l’environnement virtuel par rapport à celle des mouvements effectués dans un environnement physique similaire, chez des individus sains et chez des individus ayant subi un AVC avec ou sans atteinte de la perception visuelle. Les participants ont effectué des mouvements unimanuels et bilatéraux dans un environnement virtuel et un environnement physique similaire. La cinématique des bras et du tronc a été enregistrée à l'aide du système d'analyse de mouvements Optotrak. Pour les mouvements unimanuels, la vitesse de déplacement, l'orientation de la main au moment de prendre l'objet et la cinématique du tronc n'ont pas été affectées par l'environnement. Toutefois, dans l’environnement virtuel, les mouvements unilatéraux étaient plus segmentés et le temps nécessaire pour atteindre la vitesse maximale était plus long. Ces différences étaient plus prononcées chez les personnes ayant subi un AVC. Les atteintes de la perception visuelle étaient associées avec une plus longue durée de mouvement et un délai plus long pour atteindre la vitesse maximale dans l'environnement virtuel. Pour les mouvements bilatéraux, les individus sains ont effectué, en général, des mouvements simultanés et symétriques dans les deux environnements. En revanche, les mouvements des individus ayant subi un AVC étaient moins symétriques dans l'environnement virtuel. La similitude des variables spatiales des mouvements au niveau de la main et de la plupart des variables de qualité des mouvements effectués dans les environnements virtuel et physique suggère que l'utilisation de l'environnement virtuel en deux dimensions peut constituer une approche valable pour la rééducation sensorimotrice après un AVC. Ces travaux confirment la possibilité d'utiliser une intervention de réalité virtuelle à faible coût pour la réadaptation après un AVC chez des personnes présentant un large spectre de déficiences motrices, cognitives et perceptuelles.

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"*The whole purpose of education is to turn mirrors into windows."* Sydney J. Harris

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List of abbreviations

2D: Two-dimensional

3D: Three-dimensional

ADL: Activity of daily living

AMAT: Arm Motor Ability Test

ARAT: Action Research Arm Test

AVC: Accident vasculaire cérébral

BBT: Box and Blocks

CAHAI: Chedoke Arm and Hand Activity Inventory

CAVE: Cave Automatic Virtual Environment

CMSA: Chedoke McMaster Stroke Assessment

CUE: Capabilities of Upper Extremity

CRIR: Center for Interdisciplinary Research in Rehabilitation of greater Montreal

FAT: Frenchay Arm Test

FMA: Fugl-Meyer Assessment

Hem: Hemorrhagic

HMD: Head-mounted display

ICC: Inter-correlation coefficient

ICF: International Classification of Functioning, Disability and Health

IREX: Immersive Rehabilitation Exercise

Isc: Ischemic

Jebsen: Jebsen Hand Function Test

MAL: Motor Activity Log

MCA: Middle cerebral artery

MESUPES: Motor Evaluation Scale for Upper Extremity in Stroke Patients

Mo: months

MoCA: Montreal Cognitive Assessment

MVPT: Motor-Free Visual Perception Test

NHPT: Nine-Hole Peg Test

PCA: posterior cerebral artery

PE: Physical environment

RPSS: Reaching Performance Scale for Stroke

SD: Standard deviation

SIS: Stroke Impact Scale

Sollerman: Sollerman Hand Function Test

TEMPA: Test d'Évaluation des Membres supérieurs des Personnes Âgées

UL: Upper limb

VE: Virtual environment

VR: Virtual reality

WMFT: Wolf Motor Function Test

Yr: year

Contribution to original knowledge

This thesis contains no material that has been published elsewhere, except where specific references are provided. The work presented in this thesis emerged from my clinical experience as an occupational therapist working in stroke rehabilitation. I witnessed the challenges of delivering effective upper limb rehabilitation interventions and simulating functional tasks mimicking daily life situations in a setting as realistic as possible. Hence, this led to me to contribute to the development of an adjunctive virtual reality intervention specifically designed for sensorimotor rehabilitation in the sub-acute phase of stroke recovery. This thesis focuses on the feasibility of incorporating this novel virtual reality intervention in clinical settings for sub-acute stroke rehabilitation.

The novel contributions of this thesis to the knowledge base of stroke rehabilitation are: a) developing a low-cost virtual reality application simulating grocery shopping; b) determining the acceptability and the safety of the newly-developed virtual reality intervention from the viewpoint of important stakeholders, namely patients receiving rehabilitation services following a stroke and clinicians working in stroke rehabilitation; c) identifying the best upper limb outcome measures to assess motor recovery and movement quality (at the *Activity* level of the International Classification of Functioning, Disability and Health); d) highlighting the similarities and differences in motor performance and movement quality between movements performed in a low-cost two-dimensional (2D) virtual environment and in a matched physical environment; e) identifying that patients with visual perceptual impairments following a stroke can benefit from using a low-cost virtual reality application for sensorimotor upper limb rehabilitation. These contributions are important, because they inform clinical practice about the selection of upper limb outcome measures to capture changes over time and the use of compensatory movements. The results also inform clinical practice on the feasibility, the advantages and the limitations of using a low-cost virtual reality application for sensorimotor rehabilitation for individuals who have had a stroke. This work will contribute evidence towards the validity of arm movements performed in 2D virtual reality environments to guide clinicians in their choice of virtual reality interventions for stroke rehabilitation.

All data presented in this thesis were collected at the Center for Interdisciplinary Research in Rehabilitation of greater Montreal (CRIR) - site Feil & Oberfeld Research Centre of the Jewish Rehabilitation Hospital. The research center is affiliated with McGill University. The Ethics Board of the CRIR approved all studies involving research participants (consent forms used are found in the Appendix 2).

Preface and contribution of authors

This thesis is manuscript-based and is prepared according to the McGill Graduate and Postdoctoral studies guidelines of thesis preparation. Following these guidelines, this thesis consists of a collection of three original manuscripts, in addition to a literature review and a conclusion describing the implication of this work and its limitations. Two manuscripts were published in peer-reviewed journals and one is in preparation for submission to a peer-reviewed journal. Each manuscript represents a step towards the overall aim of this project. Because of the nature of these requirements, it is inevitable to have material duplication.

This thesis contains seven chapters.
Chapter 1 outlines the rationale for the work presented in this thesis, and introduces to the need to develop and assess the feasibility of an ecologically-valid virtual reality intervention to target essential components of motor learning.

Chapter 2 is a comprehensive literature review and is composed of five sections. The first section covers the consequence of stroke on sensorimotor and visual perceptual function. The second section describes the theoretical frameworks of movement production, with a specific focus on perception and action. The third section presents an overview of how upper limb movement kinematics differ between healthy individuals and individuals who have had a stroke. The fourth section reviews the evidence and the challenges of using common rehabilitation interventions, including virtual reality applications, to remediate upper limb sensorimotor impairments. The fifth section describes the current gap in knowledge related to the use of virtual reality applications for stroke rehabilitation and how movements may differ in virtual reality environments, especially after a stroke.

Chapter 3 describes the objectives and hypotheses of the thesis.

Chapter 4 consists of Manuscript 1 entitled "*Feasibility of incorporating functionally relevant virtual rehabilitation in sub-acute stroke care: perception of patients and clinicians*".

This study assesses the feasibility of incorporating a virtual reality intervention as a therapeutic option for improving arm motor impairments in individuals who have had a stroke by assessing four factors: 1) clinicians' level of satisfaction with the virtual reality intervention in targeting upper limb motor impairments, 2) participants' tolerance of the duration and intensity of the virtual reality intervention, 3) participants' satisfaction with the virtual reality environment and the intervention, and 4) the level of risk (occurrence of adverse events).

Chapter 5 consists of Manuscript 2 entitled: "*Do activity level outcome measures commonly used in neurological practice assess upper limb movement quality?*" This structured review highlights the need to incorporate movement quality assessments in clinical practice. It also determines the extent to which 15 outcome measures used in neurological practice assess upper limb movement quality. Potential solutions to incorporate movement quality measures into clinical assessment are also discussed.

Chapter 6 consists of Manuscript 3 entitled: "*Kinematic validity of a low-cost 2D virtual environment for arm rehabilitation in stroke*". This study assesses the feasibility of the virtual reality intervention by determining the kinematic validity of the upper limb functional movements performed in the virtual reality application. The motor performance and movement quality of unimanual and bilateral reach-to-grasp movements performed in the virtual environment and in a matched physical environment are compared in healthy individuals, and in individuals who have had a stroke with and without perceptual impairments.

Chapter 7 summarizes and synthesizes the results of all three manuscripts. The clinical implications of the results obtained, the limitations of this work and the directions for futures studies are also discussed.

Tables and figures are displayed at the end of each chapter. Reference lists for all chapters are merged and compiled at the end of the thesis. The appendices include the focus group and the individual interview questions, and the English consent forms used for the recruitment of the study participants.

The manuscripts included in this thesis are the work of Marika Demers with the guidance of Dr. Mindy F. Levin. For all three manuscripts, the following steps were conducted by the doctoral candidate under the direct supervision of Dr. Mindy F. Levin: study conception and design, data acquisition, analysis and interpretation, and manuscript preparation. Dr. Levin also oversaw all aspects of the thesis, critically reviewed all manuscripts and provided expertise regarding research methodology, strategies to enhance participant recruitment and statistical analysis. Members of the supervisory committee, Dr. Joyce Fung and Dr. Anouk Lamontagne also provided guidance regarding study conception and design.

For Manuscript 1 (Chapter 4), Daniel Chan Chun Kong provided assistance with the data collection (note-taking, co-facilitation of the focus group and verbatim transcription) and analysis. Franceen Kaizer provided assistance for the recruitment of study participants. Noémie Mbiya made technical modifications to the virtual reality program. For Manuscript 3 (Chapter 6), Réjean Prévost and Vira Rose provided assistance with the recruitment of study participants. Mr. Prévost also performed the clinical assessments. Dr. Melanie Baniña assisted with the data collection. Dr. Valeri Goussev wrote custom-made Matlab programs for the data analysis. Shaheen Ghayourmanesh assisted with the statistical analysis.

Chapter 1 - Background

Upper limb paresis is one of the most common impairments following a stroke, which impacts everyday life activities, social participation and quality of life (Mayo et al., 1999). To improve upper limb motor recovery, there is a need to target the underlying factors driving neuroplasticity. These include the type and intensity of practice, the salience of practice and the motivation of the individual (Kleim & Jones, 2008). Recent technological advances in the fields of engineering, information technology and neuroscience have led to the development of new rehabilitation technologies to better access the neuroplastic potential of the damaged nervous system (Burridge & Hughes, 2010). New technologies allow the opportunity to create individualized and enriched practice environments, specifically designed for rehabilitation purposes. Thus, there is considerable interest in developing enhanced environments to engage in challenging therapeutic tasks using new technologies such as virtual reality for stroke rehabilitation. Virtual reality is a promising intervention for upper limb sensorimotor recovery, as this technology can be used to encourage more movement repetitions, to motivate the individual to practice and to provide an ecologically valid environment in which feedback components of the training can be manipulated (Levin, 2011). Virtual reality-based interventions may provide the opportunity for the individual to perform activities of everyday life and to engage in activities within environments that replicate real-life situations, so as to facilitate the transfer of learning to everyday activities (Weiss, 2009). Increasing evidence supports the use of virtual reality in upper limb rehabilitation of patients in the chronic phase of stroke recovery. However, there is only limited evidence, mostly from small and uncontrolled studies of its effectiveness for rehabilitation in the sub-acute phase of post-stroke recovery, when most rehabilitation services occur (Laver et al., 2015).

To take advantage of the potential of virtual reality-based interventions to target upper limb recovery, an innovative, salient, low-cost virtual reality-based intervention was developed by our research team. The intervention was purposefully designed to supplement usual care in the sub-acute phase of stroke recovery, increase treatment intensity and remediate upper limb sensorimotor impairments. Although the use of low-cost virtual reality-based interventions is showing potential to supplement usual stroke care, there are factors that could limit the usability and eventual adoption of the developed virtual reality-based intervention. Hence, there is a need to ensure the feasibility and validity of using such treatment interventions in clinical practice with potential users, as part of the development process of new virtual reality interventions (Laver et al., 2017). Understanding the perspectives of clinicians and individuals who have a stroke may provide greater insight into user's needs as well as issues of implementation and motivation (Lewis & Rosie, 2012; Thomson et al., 2014). Identifying the most appropriate outcome measures to capture movement quality and performance changes is also needed to determine the feasibility and inform future effectiveness studies. Another crucial step prior to testing the effectiveness of this virtual-reality based intervention is to ensure the validity of the movements performed in this virtual environment. Comparing the motor output congruence between physical and virtual environments can inform on the potential of virtual reality for retraining lost motor elements. This is important to ensure that individuals who have had a stroke are not developing undesirable habits promoting maladaptive plasticity, which could ultimately result in decreased possibilities for motor recovery. It is also unclear how perception of how someone can interact with an object may be affected by the projection of a virtual environment onto a screen and how it may impact action, especially in individuals with visuo-perceptual impairments after a stroke.

The overall aim of this thesis is to determine the feasibility of using a low-cost virtual reality intervention as a therapeutic option for improving upper limb function in individuals who have had a stroke.

Chapter 2 - Literature review

2.1 Stroke - definition, cause and prevalence

Stroke is a leading cause of long-term disability worldwide (World Health Federation, 2015). In Canada, the number of adults aged 20 and older who are currently living with a stroke is over 740 000 (Government of Canada, 2017). Of this number of stroke survivors, more than 400 000 individuals are currently living with long-term disabilities associated with stroke, and are requiring services and support as they recover (Heart and Stroke Foundation, 2017). With the aging of the population, the prevalence of stroke survivors is projected to almost double in the next 20 years, as age is the strongest risk factor for stroke and the percentage of stroke survivors is continually increasing (Heart and Stroke Foundation, 2017).

Stroke, also called cerebrovascular accident, is a heterogeneous disease that can be characterized as a neurological deficit attributed to an acute focal injury of the central nervous system by a vascular cause, including cerebral infarction, intracerebral hemorrhage, and subarachnoid haemorrhage (Sacco et al., 2013). The diagnosis is based on pathological imaging or other objective evidence of cerebral focal infarction in a defined vascular distribution, or on clinical evidence of cerebral focal infarction based on symptoms persisting for more than 24 hours or until death (Sacco et al., 2013). Ischemic stroke, the most common type of stroke, occurs when a clot restricts blood flow leading to the brain and the brain region to which a vessel supplies blood is deprived of oxygen and nutrients (Grysiewicz et al., 2008). Haemorrhagic stroke refers to a focal collection of blood within the brain parenchyma or ventricular system that is not caused by trauma, and includes intracerebral haemorrhage (bleeding within the brain tissue itself) and subarachnoid haemorrhage (bleeding within the subarachnoid space; Sacco et al., 2013).

Epidemiological studies have established numerous risk factors for stroke, some of which are modifiable, while others are not. Well-established modifiable risk factors associated with stroke include high blood pressure, dyslipidemia and lifestyle-related risk factors, such as tobacco use, physical inactivity, overweight/obesity and nutrition. Age, gender, race, ethnicity, and heredity have also been identified as markers of risk for stroke. Other health risk factors include metabolic syndrome, diabetes mellitus, arterial fibrillation, cardiac disease and chronic kidney disease (Grysiewicz et al., 2008; Mozaffarian et al., 2016; Sacco et al., 1997).

2.2 Common sequelae following a stroke based on the International Classification of Functioning, Disability and Health

Stroke is a complex and multifaceted medical condition. The consequences of stroke and the severity of the symptoms are heterogeneous with possible motor, sensory, cognitive, perceptual and psychological sequelae, impacting activity and participation. The International Classification of Functioning, Disability and Health (ICF) of the World Health Organization (2002) provides a multi-dimensional framework that can be used to describe disability associated with stroke (see Figure 2-1). The ICF classifies health and health-related domains and describes changes in body function and structure, the level of capacity and the level of performance, in relation to the environment. Impairments are defined as significant deviations or losses occurring at the body function and structure level. Difficulty in accomplishing a functional task is defined as an activity limitation, while participation restrictions are problems an individual may experience when involved in life situations.

2.3 Consequences of stroke on upper limb sensorimotor function

2.3.1 Upper limb paresis – definition and prevalence

The damage to different cortical areas caused by a stroke can result in motor and sensory deficits, impacting voluntary movement production and fine manipulation. One of the most common impairments following a stroke is upper limb (UL) paresis affecting more than 80% of individuals in the acute stage of stroke recovery. Impairments persist in 55-75% of the cases beyond the acute stage of stroke, despite intensive and prolonged rehabilitation (Chen & Winstein, 2009; Hendricks et al., 2002). Paresis is characterized by muscle weakness, altered muscle tone, decreased sensation and impaired voluntary, well-coordinated, and effective movements (Alt Murphy & Häger, 2015; Bourbonnais & Vanden Noven, 1989; Cirstea & Levin, 2000; Lang et al., 2005). Sensorimotor deficits in the UL after a stroke can range from mild to severe (i.e. complete UL paralysis, referred to as 'plegia'). Arm paresis is most apparent in the limb contralateral to the side of unimanual brain lesion

(Levine et al., 1978; Trombly, 1992). However, sensorimotor deficits are also common on the UL ipsilateral to the brain lesion, generally considered as the non-affected side. Specifically, a decrease in strength, dexterity, motor performance (speed, smoothness) and movement quality can be observed in the ipsilateral UL of individuals who have had a stroke when compared to healthy control (Bustrén et al., 2017; Kitsos et al., 2013; Metrot et al., 2013; Sunderland, 2000). In a drinking task, it was observed that these motor deficits of the ipsilateral UL were more prominent for individuals with moderate motor impairments compared to mild motor impairments (Bustrén et al., 2017).

2.3.2 Implications of upper limb sensorimotor impairments for activity limitations

The UL makes an important contribution to the accomplishment of everyday activities. Unimanual and bimanual reaching and grasping movements are performed numerous times a day to manipulate and interact with objects in the surrounding environment. Beyond motor impairments, UL paresis may limit a person's ability to perform activities of daily living (e.g. washing, dressing, eating, etc.) and instrumental activities of daily living (e.g. cooking, gardening, housekeeping, etc.), as well as impact social participation and quality of life (Desrosiers et al., 2003; Mayo et al., 1999). While UL movements to accomplish everyday tasks can be perceived as simple, the ability to produce UL functional movements relies on very complex spatial and temporal patterns of muscle activation and depends on the ability to coordinate the control of movements of the trunk, shoulder, scapula, elbow, forearm, wrist and fingers used to position and orient the hand (Lang & Beebe, 2007; Santello & Lang, 2015).

Only approximately 65% of individuals with hemiparesis following a stroke incorporate their more impaired UL into their usual activities (Dobkin, 2005). For those using their paretic arm in everyday activities, the daily use of the more affected UL is approximately 35% of the less affected UL at 12 months post stroke (Rand & Eng, 2015). Despite good UL motor recovery, individuals who have had a stroke do not spontaneously incorporate their more affected UL to accomplish activities in natural environments (Mayo et al., 2002). For example, 71% of patients with maximal scores to the Fugl-Meyer Assessment, a measure of UL impairments, reported persistent difficulty with hand movements or reduced hand use in daily activities (Stewart & Cramer, 2013). The discrepancy between motor capability and daily UL use can be partly attributable to the learned non-use phenomenon (Taub et al., 2006). This phenomenon is defined as the difference between what the individual can do when constrained to use the paretic UL and what the individual does when given a free choice to use either UL, for example outside of therapy (Andrews & Steward, 1979). The high complexity and large variability of the movements performed to manipulate objects in the environment may explain why UL motor improvements may not directly translate into increased UL use behaviour in the natural environment (Aprile et al., 2014; Higgins et al., 2006). Other factors that may influence UL use behaviour are pain in the paretic UL, one's limited expectations for task success, decreased self-efficacy and perceived negative social interactions (Hidaka et al., 2012; Jones & Riazi, 2011).

2.4 Theoretical frameworks of movement production (how is normal movement produced)

There are several theories of how normal movement is produced including physical (dynamical systems, ecological approach, equilibrium-point approach) and biomechanical approaches (internal models). While there is no consensus on which theory best describes normal movement production, the use of motor control theories can help guide research and clinical practice to remediate sensorimotor impairments. This thesis will focus on physical approaches to understanding movement, more specifically, the ecological theory.

2.4.1 Perception and action

To better understand the perception of the environment around us, the ecological theory, originating from psychology, describes the importance of the interaction between the person, the surrounding environment and the action (Gibson, 1979). Motor planning and execution tasks are guided by the perception of objects, the environment and the goal of the intended task (Gibson, 1954; Mark et al., 1997). 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 and is referred to as 'perception/action coupling'.

Affordances are defined as the action possibilities available in the environment to an individual (Gibson, 1979). The affordances of an object 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.). Perception is defined as "the ability to organize, process and interpret incoming visual information, tactile-kinesthetic information, or both, and to act appropriately on the basis of the information received" (Titus et al 1991, p. 410). More specifically, visual perception is a process that integrates vision with other sensory input (i.e. proprioception, kinesthesis, vestibular and auditory information; Warren, 2006) to adapt actions to the environment and the situational context. Vision plays an important role in the detection of obstacles or changes in the environment, motor planning, spatiotemporal orientation, visual-motor activities, motor and postural adjustment, among others. The sensory/perceptual systems provide information about the state of the body (e.g. position in space) and features of the environment critical to regulate movement (Rosenbaum, 1991). The context and constraints of the task, such as object properties, orientation and location with respect to the body and the goal of the task, impact motor planning and performance (Alt Murphy & Häger, 2015; McCrea et al., 2002; Rosenbaum et al., 2012; Trombly & Wu, 1999). For example, the UL kinematics of a pointing task differ from those of a reaching task that includes grasping. Kinematics also differ according to whether the object to be grasped is simulated or real, or whether the action is performed with the eyes open or closed or when movement speed varies (Armbrüster & Spijkers, 2006; Grafton, 1996; Marteniuk, 1987). These differences can be explained by the nature of the task being performed within a specific environment, thereby influencing the organization of action and the resultant kinematics. During unimanual and bimanual reach-to-grasp tasks, the orientation of the arms, hands and fingers reflects the perceived object affordances and the object physical composition (Rosenbaum et al., 2012). How someone plans to use an object also influences how the object will be grasped. Thus, a knife will be grasped differently if the intention is to butter a piece of toast, place the utensil in the dishwasher or give it to someone else. The way a knife will be handled will also vary whether the knife is a plastic butter knife or a cleaver. In a seminal study by Cohen & Rosenbaum (2004) with healthy individuals, the height at which a plunger shaft was grasped was linearly related to the height of the target surface to which the plunger had to be moved, such that the higher the target surface, the lower the initial grasp height on the plunger shaft. The relationship between preferred grasp height and the height of target platform height was called the grasp-height effect (Rosenbaum et al., 2012). Alt Murphy et al. (2017) replicated this study with healthy participants and with individuals who had a stroke with and without visual impairments. In all participants, there was a significant interaction between grasp and target height. In individuals with visual-perceptual impairments following a stroke, the grasp-height effect was decreased in the more affected and the less affected UL when compared to healthy controls.

In everyday activities, UL movements are performed in social contexts, which involve object manipulation to give or receive an object from another person. The impact of social factors on object manipulation was explored in different studies where participants had to hand objects with various purposes to another person. Participants were aware of what the recipient would do with the object. How objects were grasped when the intention was to hand the object to another person depended on the context in which the task is performed and what the other person would do with the object (Gonzalez et al., 2011; Ray & Welsh, 2011; Rosenbaum et al., 2012).

A consideration of perception/action coupling is important in the context of the present thesis since it affects how patients may interact with objects in a virtual environment. Perception/action coupling is important for UL movements that are influenced by veridical information about the environment such as reaching and grasping (Jeannerod, 1999; Smeets & Brenner, 1999). Due to the interaction between perception and action, alterations in the ability to process visual information after a stroke can impact movement planning and execution.

2.4.2 Basic concepts of motor control

Knowledge of the basic concepts of motor control and the properties of the central nervous system involved in movement production, such as redundancy and movement variability, is essential to guide stroke rehabilitation interventions. The human body is characterized by a large number of muscles and joints that must be coordinated in order to produce functional movement (Bernstein, 1967; Latash, 2012a). Redundancy implies that to produce movement, the musculoskeletal system has the potential to combine individual joints in a large number of different ways to find multiple solutions to a motor task (Latash, 2012a; Latash & Zatsiorsky, 2016). The UL is composed of seven axes of joint rotation, called degrees of freedom (three at the shoulder joint, one at the elbow, two at the wrist and one shared between the elbow and the wrist for pronation/ supination), in addition to the degrees of freedom of the trunk, scapula, hand and fingers. Similarly, at the muscle level, each joint has more muscles than what is required to perform a movement (e.g., a simple joint like the elbow is crossed by several flexor and extensor muscles, such as the biceps, the brachialis, the brachioradialis, the triceps brachii and the anconeus) and each muscle consists of hundreds of motor units that can be recruited in different patterns for the same overall level of force output. At the kinematic level, during movement production, despite using different movement trajectories, velocities and accelerations, the same goal or motor task can be achieved. The redundancy of the system allows the individual to develop multiple adaptive solutions for a given task (Latash, 2012c). The ability to adopt multiple ways to accomplish a task relies on the active exploration of the task and the environment in which the task is performed.

Despite the apparent motor redundancy, human motor patterns show some typical behaviors; i.e. when comparing multiple trials, movement patterns show a high degree of consistency across both tasks and persons (Latash, 2012b). This attribute of the central nervous system is called *synergy* and can be defined as "a neural organization of a multi-element system that (1) organizes sharing of a task among a set of *elemental variables*; and (2) ensures co-variation among elemental variables with the purpose to stabilize *performance variables*" (Latash et al., 2007). For example, when reaching for a cup, the rotation of individual joints are *elemental variables* and endpoint characteristics may be viewed as *performance variables* (Latash & Anson, 2006). One muscle can be part of multiple muscle synergies and one synergy can include multiple muscles. Muscle synergies provide motor stability by preventing errors in individual motor components from affecting the task itself (Latash et al., 2002).

In summary, this section highlights the importance of the interaction between the person and the environment to organize and execute actions such as visually-guided reaching. The clinical implications are that individuals can combine movement with active problem-solving to discover the best solutions for performing a task. This is especially relevant after a stroke, because the redundancy of the system allows the individual to use alternative movement patterns to accomplish a functional task. Disruption of visual perceptual function after a stroke may alter the perception-action coupling, consequently, impacting movement planning and execution. The next section will describe the neural substrates involved in visual perception and how visual perceptual skills are developed within the central nervous system. Then, the way in which visual perceptual function may be disrupted after a stroke and the associated consequences on activity limitations and participation will be discussed.

2.5 Consequences of stroke on visual perceptual function

2.5.1 Physiology of visual perception

Visual perception and visual control of actions may have distinct neural substrates. Indeed, Milner and Goodale (1992; 2012) proposed a model to explain the various components of visual-spatial perception and visual-motor function. In this model, it is suggested that two distinct, but complementary higher neural processing pathways, namely, the dorsal stream and ventral stream, carry information about the objects and the environment. The ventral stream passes from the primary visual cortex (V1) through the inferior parts of the temporal lobe. The ventral stream is hypothesized to be pivotal for visual object information and recognition. The purpose of the ventral processing pathway is to identify objects and classify them (Warren, 2006). In contrast, the dorsal stream, passing from V1 through to various areas in the posterior parietal lobe, plays an important role in the control of actions directed at (or with respect to) an object, encompassing the location of the object and its particular disposition and motion with respect to the observer. The dorsal stream allows visually guided movements based on the visual image in the mind, which may constitute an internal and subconscious egocentric spatial representation of the multidimensional external world (Ting et al., 2011). After a stroke, lesions in the brain areas involved in the dorsal or the ventral stream may impact visual perception function. Depending on the location of a brain injury (whether ventral or dorsal stream structures are involved), the consequences will differ. For example, dysfunction of dorsal stream results in impaired visual guidance of movement, called optic ataxia, while dysfunction in ventral stream structures impacts the recognition of visual stimuli (i.e. visual agnosia; Ting et al., 2011). While both streams can be perceived as distinct, recent work from human neuropsychological and neuroimaging research highlights the interconnections between the two visual streams themselves for mediating complex and flexible visual-motor skills and three-dimensional perceptual function (Milner, 2017).

2.5.2 Visual perceptual skills with the central nervous system

Warren (1993a; 1993b) introduced a hierarchical framework for visual perceptual skill development within the central nervous system suggesting that visual perception can be conceptualized as a hierarchy of skill levels, in which skills at the lowest level form the foundation for each successive level. Specifically, higher-level skills in the framework evolve from the integration of lower level skills and are subsequently affected by disruption of the lower level skills (Warren, 1993a). The skills in this hierarchical framework consist of: visual cognition, visual memory, pattern recognition, visual scanning, and visual attention. The highest order visual perception skill is *visual cognition*, defined as the ability to mentally manipulate visual information and integrate it with other sensory information to solve problems, formulate plans, and make decisions. The next level in the hierarchy is *visual memory*, which encompasses the encoding, storage and retrieval of a visual stimulus. The ability to store and recall a visual image is dependent on *pattern recognition*, which refers to the identification of the salient features of an object. Pattern recognition is also dependent on both the identification of the configurable and holistic aspects of the object, as well as its specific features to distinguish the object from its surroundings or from one another. The next order of visual perceptual skills is the *scanning* of the environment. Visual scanning consists of moving the eyes from object to object in an organized, systematic, and efficient way to extract information critical to pattern recognition. The organization and accuracy of visual scanning is based on *visual attention*, a critical prerequisite for visual cognitive processing and decision-making. It refers to the process of focusing on the object under study, disengaging to shift the focus to a new object and then, comparing both objects for similarities and differences. Three basic skills, *oculomotor control, visual fields, and visual acuity,* form the base of the hierarchical framework on which all higher-level skills depend*.* These three basic skills are needed to generate adequate images and allow a higher level of visual processing (Warren, 1993a). While each skill is described above individually, they are highly interdependent. The ability to use visual perception to adapt actions to the environment relies on the interaction of all the processes in the hierarchy (Warren, 2006). However, damage to the central nervous system can disrupt visual perception at any level of the hierarchy, consequently impacting all higher-level skills. Due to the interaction between perception and action, visual perceptual impairments may limit the ability of stroke survivors to extract and process salient information to produce appropriate motor actions (Bolognini et al., 2016).

2.5.3 Visual perceptual impairments – prevalence and functional impact

The prevalence of visual perceptual impairments is estimated to be up to 76% in individuals with right or left hemispheric lesions (Edmans & Lincoln, 1989). Visual perceptual impairments include difficulties in perceiving and understanding the shapes and locations of objects (form perception/constancy: inability to judge variations in form; spatial relations: inability to perceive the position of two or more objects in relation to self and to each other), inability to judge depths and distances (depth perception) and inability to separate objects from their background (figure-ground discrimination; Edmans & Lincoln, 1989; Jutai et al., 2003). Visual perceptual impairments can also impact the ability of an individual to perform activities of daily living (Titus et al., 1991). More specifically, in a study of the impact of motor, cognitive, and perceptual impairments on functional autonomy, visual perceptual impairments contributed 16-31% of the variance of 2 outcome measures of functional independence, the Functional Autonomy Measurement System and the Assessment of Motor and Process Skills (Mercier et al., 2001). In another study, Titus et al. (1991) found positive and significant correlations between scores on visual perceptual tests and basic activities of daily living such as dressing ($r = 0.55$), hygiene ($r=0.42$) and feeding (*r*=0.50), stressing the importance of visual perceptual abilities in activities of daily living.

Another frequent symptom associated with visual perceptual deficits following a stroke is unilateral spatial neglect, characterized by the inability to orient or respond to stimuli appearing on the side or hemispace contralateral to the brain lesion (Stone et al., 1998). Unilateral spatial neglect should be distinguished from hemianopsia, which refers to a decrease or blindness in one half of the visual field of one or both eyes contralateral to the brain lesion (Hellerstein, 1997). The prevalence of unilateral spatial neglect is estimated to between 23-46% and it is more frequent in right hemispheric lesions (Buxbaum et al., 2004; Jutai et al., 2003; Ringman, 2004). Lesions in the right temporoparietal junction, the inferior parietal lobule, the superior/middle temporal cortex and underlying insula, and the ventrolateral prefrontal cortex are often associated with unilateral spatial neglect (Karnath & Rorden, 2016). Unilateral spatial neglect can be divided into three different types, and patients can have one or a combination of these types with varying degrees of severity: 1) Personal neglect: neglect of one side of one's body (e.g. combing hair only on half of the head), 2) Near extrapersonal neglect: neglect of the environment within reaching distance (e.g. leaving food on half of the plate), and 3) Far extrapersonal neglect: Neglect of the space beyond reaching distance (e.g. colliding with an object on the more impaired side when ambulating). While approximately 20–45% of unilateral spatial neglect resolves spontaneously within the acute stage of post-stroke recovery, neglect, in the long-term, can have an impact on rehabilitation outcomes and lead to activity limitations and participation restriction (Gillen et al., 2005; Paolucci et al., 2001).

2.6 Upper limb kinematics following a stroke

2.6.1 Levels of movement description

Movements can be described at two levels: endpoint movement in external space and movements in body space. At the external space level, movement variables, such as movement smoothness, trajectory speed, precision, and straightness, can be quantified (i.e., endpoint characteristics). At the body space level, joint angles, spatial and temporal interjoint coordination, and arm muscle activity can be measured (i.e., movement quality variables; Levin et al., 2009). Describing movement at those two levels can provide more information about how a person accomplishes a functional task, the compensatory strategies used, missing task elements and other specific deficits to guide clinical decisions. Kinematic analysis can objectively evaluate movement patterns, quality, and strategies underlying a given task (Alt Murphy et al., 2011; Chen et al., 2015).

2.6.2 Unimanual movements in healthy subjects

Multiple studies have described kinematic characteristics of unimanual reaching behaviour in healthy individuals, such as hand trajectory formation, velocity and acceleration/ deceleration profiles, movement smoothness and temporal and spatial relationships between movements of multiple joints and muscles. Understanding "normal" behaviour is crucial to understand how movement performance and quality are disrupted after an insult to the central nervous system, such as a stroke. Upper limb movements encompass various tasks such as reaching or pointing to a target (hereafter referred to as reaching) and reaching-to-grasp to lift or transport an object. Reaching involves movements of the shoulder, scapula, elbow and wrist, when the target is within arm length, and the addition of trunk and hip movements when targets are beyond arm's length. Reaching-to-grasp additionally involves movements of the hand and fingers to position and orient the hand in order to grasp an object. The reach-to-grasp task can be broken down into several phases, all interrelated: a) locating the target, which can involve visual perception, b) reaching for the object, which involves the transportation of the arm and hand to the object and the anticipatory stabilization of the trunk for perturbations generated by the movement, and c) grasping, which involves hand orientation, positioning and grasp. Previous studies of UL reaching movements in healthy participants have described some typical behaviour for specific tasks. Healthy individuals can produce smooth reaching movements with straight endpoint movement paths finishing accurately on the intended target, despite a great variability in the joint rotations during movement performance (Bernstein, 1968). The redundancy of the system allows a large variability in the configuration of body segments and joints organized in a task-specific way (Latash & Zatsiorky, 2016). Other characteristics of UL reaching movements are that hand tangential velocity profiles are smooth and bell shaped, with only a single major peak (Cirstea et al., 2003). Task demands (e.g. reaching vs. reaching-to-grasp or a task requiring precision) can impact the acceleration and deceleration phases of the trajectory associated with UL movement (Marteniuk et al., 1987). In summary, despite the many available degrees of freedom in the UL, the kinematic characteristics of UL reaching movement in healthy individuals are similar from one trial to the next. The reaching movement is characterized by a smooth, bell shaped hand velocity profile.

2.6.3 Bimanual movements in healthy subjects

Basic and instrumental activities of daily living require the use of not only simple reaching-to-grasp actions, but also involve complex movements of both UL in a highly coordinated and efficient manner. While the term bilateral movement and bimanual movement are often used interchangeably, UL involvement differs for these two types of movements. Bilateral movements involve symmetrical movements of both ULs and engage homologous muscles, while bimanual movements involve asymmetric movements of both ULs and engage non-homologous muscles either simultaneously or in different temporal relationships (Kantak et al., 2017). It is also imperative to distinguish between bimanual movements in which both ULs achieve common or independent task goals. For example, when opening a jar, both arms work collaboratively towards the same goal (i.e. opening a jar), but each hand accomplishes a different task (stabilizing the jar or turning and removing the lid). When reaching for two different objects placed at two different locations, both arms can move independently. In healthy individuals, functional imaging has shown that the neural substrate for symmetric actions of both arms is distinct than asymmetric actions (Duque et al., 2010). Specifically, when both ULs were coordinated, the superior temporal gyrus, the supplementary motor area and the primary motor cortex (M1) in the right hemisphere showed a greater activation than when both ULs performed in independent tasks.

2.6.4 Unimanual movements and compensations in stroke survivors

UL kinematics characteristics can also help identify the differences between individuals with arm paresis following a stroke and healthy individuals. In contrast to healthy individuals, UL movements in individuals who have had a stroke are slower and less smooth. For individuals who have had a stroke, UL movements are characterized by larger variability in the end-point trajectory, lower accuracy and a decrease in movement efficiency in multi-joint reaching such as longer endpoint trajectories or deviations from smooth straight lines (Alt Murphy & Häger, 2015; Archambault et al., 1999; Cirstea et al., 2003; Collins et al., 2018; Levin, 1996; McCrea & Eng, 2005). UL motor impairments may affect movement speed, movement smoothness, accuracy and coordination. Specifically, movements of individuals with more severe arm motor impairments are more segmented, less accurate and the variability of velocity profiles and end-point trajectory are higher than those of individuals with mild-moderate impairments (Cirstea & Levin, 2000; Cirstea et al., 2003). Thus, individuals with more severe motor impairments may recruit new degrees of freedom to compensate for motor deficits (Cirstea et al., 2003). In multijoint reaching for individuals who have had a stroke, UL movements are characterized by a larger variability in endpoint trajectories, such as longer trajectories and more pronounced deviations from straight lines (Alt Murphy & Häger, 2015; Archambault et al., 1999; Cirstea & Levin, 2000; Levin, 1996). Furthermore, when reaching beyond arm length, alterations in coordination between arm and trunk, as well as between shoulder abduction/adduction or flexion/extension and elbow flexion/extension are common (Archambault et al., 1999; Cirstea & Levin, 2000; Levin et al., 2002; Roby-Brami et al., 2003). The use of compensatory movement patterns, such as excessive trunk displacement when reaching or grasping objects placed well within the reaching extent of the arm, is also common following a stroke to compensate for arm motor impairments (Cirstea & Levin, 2000; Collins et al., 2018; Levin, 1996; Levin et al., 2016; Levin et al., 2002). Other frequently described alterations of movement patterns following a stroke include reduced elbow joint extension, shoulder joint flexion and increased compensatory shoulder abduction (Alt Murphy & Häger, 2015). The adoption of compensatory strategies may be considered maladaptive if compensations limit recovery of independent movements of the more affected arm, contribute to secondary complications such as pain, joint contracture and discomfort (Ada et al., 1994), and lead to a pattern of learned maladaptive behaviour impeding long-term functional recovery of the UL (Alaverdashvili et al., 2008; Kleim & Jones, 2008). In addition, the use of maladaptive compensatory strategies may limit the person's ability to generalize movements to a wider array of tasks (Aprile et al., 2014) and may contribute to incipient decline after the end of active therapy (Winstein et al., 2014).

2.6.5 Bimanual movements in stroke survivors

In individuals with arm paresis, the ability to execute coordinated bilateral or bimanual movements can be affected due to impairments in the contralateral and the ipsilateral arm (Schaefer et al., 2009). As a result, the ability to perform daily tasks involving both ULs is frequently diminished. During bilateral movements or bimanual movements towards a common goal, it is suggested that the less impaired UL must adapt its movements to the constraints brought about by the more affected limb to retain temporal coupling between limbs (Gosser & Rice, 2015; Kantak et al., 2016a; 2017; Messier et al., 2006; Rice & Newell, 2001). In a task involving oscillations of the UL at the elbow in asymmetric patterns with one limb oscillating at twice the frequency of the other, Rice and Newell (2004) observed that individuals who have had a stroke used a greater number of in-phase movement patterns than the healthy control group. This suggested that individuals who have had a stroke might perform better in tasks requiring symmetrical movement of both ULs, which can be explained by the inherent spatial and temporal dependencies between limbs (Carson, 2005; Cauraugh et al., 2010). When both UL are moving symmetrically in homologous actions, similar neural networks are activated (Carson, 2005). Gosser & Rice (2015) compared unimanual and bilateral reaching movements performed at the participants' preferred speed in healthy individuals and in individuals who have had a stroke. For both groups, the less affected UL displayed shorter movement time, faster peak velocity and time to peak velocity and smoother movement during unimanual reaches than bilateral reaches. However, movement time, peak and time to peak velocity and movement smoothness did not differ between the unimanual and bilateral conditions for the more affected UL. These results were also observed in other studies where unimanual and bilateral movements were performed at preferred speed (DeJong & Lang, 2012; Rice & Newell, 2001). When bilateral movements (reaching for a box) compared to unimanual movement were performed at the fastest speed possible, improvement in some movement performance variables for the paretic UL was noted. More specifically during bilateral movements, the paretic UL showed faster peak velocity and peak acceleration, but movement time or smoothness did not differ between unimanual and bilateral conditions (Harris-Love et al., 2005). In an asymmetrical bimanual task involving opening a drawer and pressing on a button, individuals who had a stroke adopted a sequential approach to executing the bimanual task, showing difficulty coordinating both arms, unlike healthy participants (Kantak et al., 2016b). In another study by the same research group comparing symmetric and asymmetric movements (Kantak et al., 2016a), participants displayed greater difficulties performing asymmetric movements than symmetric movements, with significantly poorer spatial and temporal coordination of both ULs. When looking at the contribution and timing of both UL during common goal actions, temporal coupling of both ULs was maintained for symmetrical movements, but impaired cooperative coordination between both ULs were observed (Kantak et al., 2016a). When investigating the correlation between paretic UL impairments and impaired bimanual performance, studies have consistently failed to report strong relationships between motor impairments or performance of the paretic arm and deficits in different aspects of bimanual coordination (Kantak et al., 2016b; 2017).

To summarize this sub-section, in comparison to healthy adults, individuals who have had a stroke make slower, less coordinated and more segmented reaching movements. Movement limitations such as reduced elbow extension or shoulder flexion, excessive trunk displacement or shoulder abduction are also common. UL impairments also affect the ability to coordinate both ULs to accomplish bimanual movements with common or independent task goals, with greater difficulties when performing asymmetric movements. Knowledge of how movement is performed in healthy individuals and how it may be disrupted due to sensorimotor impairments after a stroke is important to guide targeted rehabilitation interventions to promote motor recovery.

2.7 Background concepts in stroke rehabilitation

Great progress has been made in the past decades to better understand the brain mechanisms that can be exploited to enhance recovery after an injury to the central nervous system. The brain’s inherent ability to reorganize cortical representations, to form new connections between neurons, and to bypass damaged circuits by using secondary pathways can be exploited by using therapeutic approaches encouraging the restorative capacity of the brain and its neural networks (Winstein & Kay, 2015). Rehabilitation can help to remediate impairments, maximise functional independence and participation for individuals who have had a stroke. Rehabilitation can be defined as ‘‘a process of by which a person who has become disabled acquires the knowledge and skills needed for optimum physical, psychological and social function’’ (Turner-Stokes & Wade, 2004).

2.7.1 Distinction between recovery and compensation

Restoration of sensorimotor function is a key goal of post-stroke rehabilitation. To facilitate the discussion between disciplines and distinguish between motor recovery from the use of compensatory movement patterns, Levin et al. (2009) suggested a common terminology, in accordance with the International Classification of Functioning, Disability and Health framework, for the concepts related to recovery and compensation in individuals who have had a stroke. At the *Health condition* (neuronal) level, recovery refers to restoring the functionality in damaged neural tissues. The restoration of lost neurons is not anticipated after a stroke, due to the nature of the insult following a stroke. Compensation, at the neuronal level, refers to the acquisition of a function that neural tissue did not have prior to injury (e.g. activation in alternative brain areas). At the *Body function/structure* level, recovery, also called restitution, is defined as the performance of a movement in the same manner as it was performed before the stroke. For example, someone may use premorbid movement patterns similar to those that were used before the injury to reach for a cup located at shoulder height. Compensation, also called substitution, is defined as performing a movement in a new way. Taking the same example of reaching for a cup, someone who had a stroke may use alternative motor strategies, such as elevating the shoulder or leaning forward (using more trunk flexion) to compensate for lost motor patterns in the elbow and shoulder. Finally, at the *Activity* level, recovery refers to successful task accomplishment using limbs or end effectors typically used by nondisabled individuals (e.g. turning on a light by pressing the switch with the finger), while compensation refers to successful task completion using different techniques (e.g. using the elbow on the switch to turn on the light; Levin et al., 2009).

2.7.2 Optimal time window for recovery and principles guiding experience-dependent plasticity

Evidence from large observational studies indicate that recovery in UL function is most rapid during the first three to six months after stroke (Langhorne et al., 2009; Teasell et al., 2008). Thus, the first six months post-stroke is a critical time to intervene to reduce impairments and maximize function in the paretic UL. In their seminal paper, Kleim and Jones (2008) identified ten principles for experience-dependent plasticity, based on work from animal studies (see Table 2.1). While findings from animal models do not translate directly to humans, fundamental principles can guide rehabilitation. Among the ten principles described, the role of repetition, intensity and salience to drive neuroplasticity is critical for rehabilitation targeting motor recovery of the UL. More specifically, rehabilitation interventions should focus on practicing tasks used in daily life, in settings that are as realistic as possible. Rehabilitation interventions should also be delivered at a high intensity (dose, frequency, and duration of training) and involve challenging practice (Plautz et al., 2000). Studies from animal stroke models have established that animals need to engage in hundreds of repetitions of motor tasks to induce lasting neural changes (Kleim et al., 1998; Nudo et al., 1996). In humans, the definitive number of repetitions needed for optimal learning is unknown. It can be assumed that a large number of repetitions that is progressive and adaptive is needed to engage plastic mechanisms, and obtain a level of improvement and brain reorganization sufficient for stroke survivors to continue to incorporate their more affected UL in the natural environment after therapy ends. In addition to the principles postulated by Kleim and Jones, practice should be progressive and optimally adapted to the individual's capability and the environmental context (Lee & Wishart, 2005; Winstein & Kay, 2015), and solicit intrinsic motivation and active participation (Lee et al., 1991; Lewthwaite & Wulf, 2012). Another key component in improving motor relearning post-stroke is the provision of meaningful feedback during or after the task on the outcome of the movement and the elements of the motor performance (Cirstea & Levin, 2007; Levin et al., 2010).

2.8 Common rehabilitation interventions, evidence and challenges

The principles for experience-dependent plasticity can be translated to clinical practice by designing salient and intensive training approaches that involve a high number of movement repetitions and that are delivered early after a stroke. To minimize the impact of UL impairments on activities and participation, a wide range of rehabilitation interventions are used for retraining the impaired arm, hand and fingers. Rehabilitation interventions may be aimed at particular impairments or activity limitations, and can be combined to address the multi-factorial nature of the deficits post-stroke (Pollock et al., 2014). Interventions targeting the UL can be supervised or not by a therapist, and offered in groups or individually, at various stages of stroke recovery, in different settings, such as hospitals, in- or out-patient rehabilitation centers or in the community. Occupational and physical therapists are more commonly responsible for delivering UL rehabilitation interventions, but other healthcare professionals, caregivers or family members can also be involved in delivering rehabilitation interventions (National Institute of Neurological Disorders and Stroke, 2018).

Conventional approaches used in rehabilitation of the paretic arm include constraint induced movement therapy, functional electrical stimulation, bilateral arm training, Bobath or Neurodevelopmental techniques, mental practice, mirror therapy, interventions for sensory impairment and repetitive task-oriented or task-specific training. In a Cochrane review synthesizing evidence about stroke rehabilitation interventions on UL function (Pollock et al., 2014), moderate-quality evidence suggests that constraint-induced movement therapy, mental practice, mirror therapy, and a relatively high dose of repetitive task-oriented practice may be beneficial in the treatment of UL function after stroke. Moderate-quality evidence also indicates that bilateral arm training, which consists of practice of bilateral arm movements in symmetrical or alternating patterns, might not be more effective than unimanual arm training. Bobath/Neurodevelopmental techniques are approaches widely used in clinical settings, despite strong evidence (Level 1a) suggesting that these approaches are not more effective than other conventional approaches for retraining the paretic UL post-stroke (Hiraoka, 2001; Teasell et al., 2003). High quality evidence from a recent systematic review and meta-analysis also support the use of functional electrical stimulation to improve UL function after a stroke (Monte-Silva et al., 2019). Small beneficial effects on UL motor impairments were also reported in systematic reviews and meta-analyses of robotic training (Veerbeek et al., 2017) and transcranial direct current stimulation when combined with rehabilitation interventions for the UL (Tedesco Triccas et al., 2015). For many commonly used interventions, such as strength training and task-specific training, the evidence remains of low quality, making it impossible to conclude on their relative effectiveness (Pollock et al., 2014).

2.8.1 Challenges with stroke rehabilitation targeting the upper limb

Despite evidence supporting various treatment modalities for the paretic UL, the rehabilitation of the more affected UL post-stroke remains a challenge. UL rehabilitation is challenging due to different health system constraints, such as the early focus on improving lower limb mobility and gait, and the limited available treatment time (Barreca et al., 2003). For these reasons, the treatment of the paretic UL might not be delivered at the right intensity and might not include a sufficient number of repetitions for optimizing post injury neuroplasticity (Burke et al., 2009). Lang et al. (2007) observed the amount of daily movement practice provided in occupational and physical therapy in seven rehabilitation centers in Canada and the United-States, for individuals post-stroke. The average number of repetitions per session in the paretic arm was only 32 (95% confidence interval: 20–44). In addition, only 51% of the sessions focussed on practice of functional UL movements. As discussed previously, while the exact number of movement repetitions needed to induce brain plasticity is unknown in humans, a large number of movement repetitions that are progressive and adaptive, probably higher than 32 repetitions per session, is needed to engage plastic mechanisms. Due to the repetitive nature of traditional post-stroke interventions, conventional therapy can be considered monotonous and does not present enough challenge, contributing to the lack of treatment adherence (Burke et al., 2009), which can play an important role in determining he outcome of therapy (Maclean & Pound, 2000). Another limitation of traditional post-stroke interventions is that the observed improvements achieved in therapy might not be maintained or generalized into real-world situations in the natural environment after therapy (Hidaka et al., 2012; Higgins et al., 2006; Rand & Eng, 2015; Winstein et al., 2014). This section highlights the importance of salient and progressive UL stroke interventions delivered at high intensity and adapted to the individual's capability and the environmental context to drive neuroplasticity. However, challenges with traditional therapies to deliver high treatment intensity, to engage stroke survivors and to generalize skills to real-world situations have also been identified. To address the main challenges facing traditional UL interventions, the advent of new technologies can allow the development of innovative adjunctive rehabilitation interventions providing more intensive learning experiences and the opportunity to manipulate the learning environment (Levin, 2011).

2.9 Virtual reality for upper limb rehabilitation

In recent years, the emergence of virtual reality (VR) and off-the-shelf video games has shown promise for targeting key mechanisms for experience-dependent plasticity such as intensity of practice of functional movements, precise real-time feedback provision, motivation and engagement of the learner (Burridge & Hughes, 2010). VR can be described as "use of interactive simulations created with computer hardware and software to present users with opportunities to engage in environments that appear and feel similar to real-world objects and events" (Weiss et al., 2006). VR can provide a rich, multi-modal and stimulating environment shown to be important in neurological rehabilitation (Biernaskie & Corbett; 2001; Sale et al., 2009). The use of VR interventions for sensorimotor rehabilitation may enable simulated practice of functional tasks at a higher dosage than traditional therapies, because of the inherent features of the virtual environment and the task novelty may increase interest and engagement with the virtual intervention (Adamovich et al., 2009; Lewis & Rosie, 2012; Merians et al., 2006). Another key feature of VR is its ability to recreate, in a safe environment, some activities that may be impractical or could not be performed in clinical settings, such as grocery shopping (Weiss et al. 2006). VR also enables sensory manipulations that are not possible in the real-world (i.e. change in auditory input, color, brightness, object location or shape, etc.; Cheung et al., 2014). For example, when used as a treatment modality for stroke rehabilitation, a therapist may be able to playback movements to provide meaningful feedback to focus the learner's attention on elements of movement performance. The availability of commercial video games by the entertainment industry for home use and low-cost game-like systems for rehabilitation has contributed to the deployment of VR in hospital settings (Weiss et al., 2009). However, there is a need to distinguish between VR applications specifically designed for rehabilitation purposes and off-the-shelf video games, which have been designed for recreation purposes, but adapted for rehabilitation. The advantages of VR-based interventions over off-the-shelf video games is the possibility of tailoring virtual environments (VE) to optimise motor learning by manipulating the task difficulty and the feedback provided to offer individualized treatment (Burke et al., 2009; Holden, 2005; Weiss et al., 2009).

The findings from a recent Cochrane review on the efficacy of VR on UL post-stroke suggested that VR and interactive video gaming have a small but significant effect on improving UL impairments (measured by the Fugl-Meyer Assessment) when compared to conventional rehabilitation therapy (mean difference: 2.85, 95% confidence interval: 1.06 to 4.65, 599 participants; Laver et al., 2017). When VR was used in addition to usual care to increase overall therapy time, the effect of providing additional intervention using VR was moderately significant (standardized mean difference of the upper limb composite score: 0.49, 95% confidence interval: 0.21 to 0.77, 210 participants; Laver et al., 2017). The potential benefits of VR on improving function in everyday activities were also identified when used as an adjunct to usual care (Laver et al., 2017). Increasing evidence supports the use of adjunctive VR in UL rehabilitation of patients in the chronic phase of stroke recovery. Nevertheless, evidence for the effectiveness of supplemental VR-based interventions in this critical time period is limited (Adamovich et al. 2009; Laver et al., 2015; Saposnik & Levin, 2011). To facilitate the clinical application of VR-based intervention to supplement usual care, it is imperative that future research involves individuals in the sub-acute phase of stroke recovery. While VR-based interventions are promising for adjunctive UL rehabilitation, the difference in how the VEs are perceived by individuals with stroke, especially for those with visual perceptual impairments, may impact motor learning. For example, some visual or auditory cues, such as the color of an object or an auditory sound to indicate the use of maladaptive compensatory strategies, can be enhanced in the VE to facilitate motor relearning. However, the absence of cues present in the physical world may be detrimental to movement production, especially in individuals with visual perceptual impairments. The next section will focus specifically on how vision and perception are influenced by VEs and how it may impact movement production.

2.10 Vision and perception in virtual environments and how they may be affected by stroke

VE displays create the illusion that the users are in a place other than where they physically are (Kenyon & Ellis, 2014). VEs are not constrained by the physics of the real-world, however they may not contain all the visual, tactile, auditory and other sensory cues present in the physical world (Kenyon & Ellis, 2014). The perception/action coupling may be altered in VE because of differences in the viewing environment compared to the 3D real-world. To perceive the distance of an object in a 2D VE, a person needs to rely on the detection and the simultaneous use of multiple visual cues (e.g.: motion parallax, binocular vergence, height in the visual field, size of object in relation to others in the surrounding scene, texture) and the exploitation of predictive hypotheses about actions needed to interact with the object (Gregory, 1980; Mon-Williams & Bingham, 2008). Predictive hypotheses of the possible ways to interact with an object are based on the use of visual cues to extrapolate the location and time the movements towards the perceived 3D object (Liebermann et al., 2012). The background surfaces and horizon lines can also play a role in the judgement of the position, distance and size of an object in a 3D scene (Ozkan & Braunstein, 2010; Ooi et al., 2001). More specifically, in a series of experiments in which virtual objects were placed at varied heights and distances with respect to the horizon in a virtual scene, participants appeared to use the location of the objects relative to the perceptual horizon to make judgements about the size of the objects, whereas height of objects in the image was used for judging distances (Ozkan & Braunstein, 2010). To minimize problems in perception-action coupling in 2D environments, most game-like systems offer an enriched 2D environment where depth perception is enhanced via cognitive and sensory cues mimicking stereovision, such as texture gradients, lighting, shadows, and the declination of the object with respect to the horizon line (Ooi et al, 2001). Movement performance and quality can be altered by the different attributes of the VE, such as the resolution of the display medium, the viewer's perspective, the co-existence of physical and virtual objects, and the provision of multiple visual cues (Kenyon & Ellis, 2014). Specifically, reduced visual information and smaller target size can result in longer movement times and more asymmetrical hand velocity profiles (Berthier et al., 1996). The viewing environment can also affect reaching performance. In a study comparing reaching kinematics in two different viewing environments, UL movements performed in a 3D VE viewed through a head-mounted display were less precise with larger vertical directional errors compared to those made when the VE was projected on a large screen in healthy individuals and in individuals with stroke (Subramanian & Levin, 2011; Subramanian et al., 2011). Moreover, Thomas et al. (2016) investigated the impact of viewing environments (3D VE projected on a television or in a head-mounted display) when playing virtual Dodge ball or reaching for physical balls, involving full-body reaching tasks to static targets. In the VE, significantly greater excursions of the ankle, knee, hip, spine, and shoulder were observed, as well as significant differences in the forward and downward displacements of the whole-body center of mass. The results suggested that visual display type influences motor behaviour.

2.11 Comparison of movement performance and quality in virtual and in physical environments

2.11.1 Similarities and differences in kinematics between virtual and physical environment in individuals with stroke

Understanding perception/action coupling is useful to interpret the differences that may be present in a virtual environment, for example, compared to a physical environment. When using VR in stroke rehabilitation to decrease motor impairment, it is therefore important to understand if the quality of the movements made in a VE is similar to that made in the physical environment (PE) in which everyday activities are accomplished. This is crucial to facilitate the transfer of skills to real-life activities and to ensure stroke survivors are not developing undesirable habits promoting maladaptive plasticity, which could ultimately result in decreased possibilities for motor recovery. It is also important to understand if individuals with specific visual perceptual impairments can benefit from the practice of movements in game-based VR applications since this might impact on the potential benefit to be gained by practice of movements in such environments. Previous studies have compared UL kinematics performed in a 2D and 3D VEs to movements performed in a comparable PE, with different populations such as typically developing children, children with cerebral palsy, neurologically intact adults, older adults, individuals who have had a stroke, a traumatic brain injury or Parkinson's disease (Chen et al., 2014; Knaut et al., 2009; Kuhlen et al., 2000; Levin et al., 2015; Liebermann et al., 2012; Lin & Woldegiorgis, 2018; Magdalon et al., 2011; Robert & Levin, 2018; Schafer & Ustinova, 2013; Viau et al., 2004; Wang et al., 2011). The results of these studies are summarized in Table 2.2. Specifically, Viau et al. (2004) compared reaching and grasping movements made in a 2D VE and a PE of equivalent dimensions in healthy adults and in adults with mild right hemiparesis due to stroke (chronic phase). The 2D VE was displayed on a computer screen that included minimal depth cues. Haptic feedback was provided with a Cyberglove (Immersion Corp., CA, USA). In both environments, spatial and temporal aspects of arm movement trajectories were similar for individuals with stroke and healthy adults. However, participants with stroke tended to use more elbow extension and less wrist extension in the VE compared to PE, due to the absence of depth perception in the 2D VE and the lack of tactile feedback at the end of the reach. In another study, Liebermann et al. (2012) compared pointing kinematics to three targets made in a PE and in a video-capture 2D VE (IREX, GestureTek Inc., ON, Canada) with the same populations. The VE was viewed on a large monitor where individuals saw a mirror image of themselves interacting with objects. Viewing the targets in the 2D VE affected overall movement performance and quality. Movements in the VE were slower, shorter, less straight, less accurate and involved smaller ranges of shoulder and elbow joint excursions compared to movements in the PE in all participants. To better understand the role of depth perception on kinematics in VEs, other studies compared effects of the quality of the viewing environment (3D VE vs. PE) on reaching and grasping movements. Knaut et al. (2009) studied reaching to six targets performed in a fully immersive 3D VE viewed through a head-mounted display in comparison to reaching movements in a PE. For healthy adults and individuals with stroke, motor performance and quality were similar for midline targets. However, for healthy adults, movements were slower for all targets in VE, and precision and trajectory straightness were higher in VE when pointing to contralateral targets compared to the PE. Movements performed by individuals who have had a stroke were less accurate and more curved compared to healthy subjects and participants used less trunk displacement and had altered elbow/shoulder coordination in VE compared to PE when pointing to the lower ipsilateral target. Levin et al.

(2015) compared reaching and grasping of three objects (a can, a screwdriver and a pen) in a 3D VE and in a PE in individuals who have had a stroke (chronic phase). The immersive VE was displayed in 3D via a head-mounted display and a virtual representation of the hand was obtained using a Cyberglove. A prehension force-feedback device (Cybergrasp, Immersion Corp., CA, USA) also provided haptic feedback. Reaching trajectories were similar in both environments. In VE, reaching movements were less smooth and slower compared to PE. However, the environment did not affect wrist, elbow, shoulder, or trunk kinematics. These studies and others suggest that endpoint performance and joint kinematics are affected by the quality of the viewing environment (Marathe et al., 2008; Subramanian & Levin, 2011; Thomas et al., 2016; Ustinova et al., 2010). The differences between movements performed in virtual environments compared to the real-world can be explained by differences in the perception of the affordances in each environment.

2.11.2 Similarities and differences in kinematics between virtual and physical environment in individuals with visual perceptual impairments

To date, there is a limited research on the impact of visual perceptual impairments on motor performance and quality in a VE. Schafer & Ustinova (2013) conducted a study with healthy individuals and with individuals who have had a traumatic brain injury with and without visual perceptual impairments. Participants were asked to reach forward as far as possible for in a VE viewed from 3 different angles (10° above horizon, resembling a real-world viewing angle; 50° above horizon, or 90° above horizon, directly overhead). For all participants, movement time was slower, peak velocity was lower and movements were more segmented (multiple velocity peaks) in the VE compared to the PE. For both groups, viewing angle influenced reaching amplitude. From the 50° viewing angle, the reaching amplitude was the greatest (~9% farther arm displacement than during PE reaches), while from the 10° viewing angle, arm displacement in the VE was shorter than in the PE. Furthermore, visual perceptual impairments were moderately correlated with performance (i.e. movement time, $r = 0.62$-0.63, $p < 0.05$) of virtual reaches, suggesting that visual perception in the VE differs from real-world perception (Schafer & Ustinova, 2013). The results of this study suggest that visual perceptual impairments may impact motor performance in the VE for individuals with traumatic brain injury. However, the role of visual perceptual impairments in individuals who have had a stroke and how these impairments may impact reaching performance and quality is unclear, as the results may not be directly translated to stroke rehabilitation. This knowledge is critical to be able to identify what are the characteristics of participants who can effectively benefit from using VR-based interventions to enhance motor recovery after a stroke, instead of maladaptive compensatory movements.

2.12 Methodological considerations - accuracy of motion tracking

The accuracy of motion tracking is also important for assessing how motor improvements occur, and in particular, whether patients improve function through motor recovery or compensation. Thus, it is of interest to compare functional movements performed in game-like VEs, where the quality of the viewing environment may be lower and movement tracking may be less precise. For example, the low-cost markerless tracking system Kinect (Microsoft, Redmond, WA, USA) provides full-body 3D motion capture and joint tracking capabilities by relying on an infrared-based depth sensor technology and a color (RGB) camera (Chang et al., 2012; Zhang, 2012). However, the Kinect camera does not accurately track movements performed in the frontal and sagittal planes (Chang et al., 2012; Huber et al., 2015), or track finger and other small movements (Li et al., 2015). During reaching, Tao et al. (2013) found an average error of 6.3 cm in the accuracy of arm endpoint tracking. In addition, large discrepancies in shoulder angle measurement (> 10° for all ranges) were observed with the Kinect camera when compared to a 3D motion analysis system and goniometry (Huber et al., 2015). In low-cost game-liked VEs commonly used in hospital settings, the reduced accuracy of the movement tracking technology may, therefore, impact movement quality and performance. Precisely how UL kinematics may be affected in individuals who have had a stroke by the reduced precision of the motion tracking system is unknown.

2.13 Rationale

Our research team developed a VR-based intervention using a low-cost motion tracking system, the Kinect II camera. The VR intervention was elaborated to be offered as an adjunctive therapy for individuals undergoing rehabilitation following a stroke to remediate arm motor impairment in a VE simulating a functional task: grocery shopping. Before the effectiveness of a VR-based intervention can be tested in a planned intervention study and ultimately be implemented in clinical practice, it is crucial to determine the usability and validity of the VR-intervention by both clinicians and patients, as part of the development process of new VR interventions (Laver et al., 2017). Feasibility studies focus on the process of developing and implementing an intervention by evaluating participant safety, intervention implementation, and acceptability (Orsmond & Cohn, 2015). According to the Technology Acceptance Model developed by Davis (1989), a model that has been widely applied to a diverse set of technologies and users to predict and explain use, acceptability refers to suitability of the use of a new technology. In this model, two important determinants of acceptance have been identified: the perceived usefulness and the perceived ease of use of the technology. Perceived usefulness can be defined as the "the degree to which a person believes that using a particular system would enhance his or her job performance" (Davis, 1989, p.320), whereas perceived ease of use can be defined as "the degree to which a person believes that using a particular system would be free of effort" (Davis, 1989, p. 320).

Previous feasibility studies using VR have established, from the perspective of researchers, that participants with different levels of sensorimotor severity were able to engage in VR-based interventions (Burdea et al., 2011; Kim et al., 2016; Stewart et al., 2007) and that commercial videogames and VR systems are feasible and safe for individuals with chronic stroke (Schuster-Amft et al., 2015; Subramanian et al., 2007). Only a few studies have evaluated patient (Lewis & Rosie, 2012) and/or clinician perspectives (Nguyen et al., 2019) for stroke rehabilitation. These perspectives may provide greater insight into user's needs as well as issues of implementation and motivation, which are important for eventual clinical uptake (Lewis & Rosie, 2012; Thomson et al., 2014). Furthermore, the occurrence of adverse events has not consistently been reported (Laver et al., 2015; Thomson et al., 2014). In brain injury rehabilitation, uptake of VR has met with some barriers such as poor client motivation, enjoyment or interest and time constraints (Glegg et al., 2013). Another barrier is that not all platforms and activities are adapted to the target population (Lewis & Rosie, 2012), hence the need to determine the usability of a newly developed VR-based intervention with the targeted population.

In order for a VR-based intervention to be used in clinical practice to remediate UL motor impairments, it is also essential to know whether motor performance and the quality of movements performed in a given VE are similar to movements performed in the real-world. While previous studies contributed to the validation of VR for retraining arm movements in individuals who have had a stroke, they focused only on unimanual reaching and grasping movements performed in sitting. However, to accomplish functional activities, humans use bilateral and bimanual movements, as well as unimanual ones, and movements are also made while standing. The potential role of visual perceptual impairments after stroke has not been fully investigated. Moreover, most previous studies have compared UL kinematics for reaching or grasping performed in PE and in VE using viewing environments of high quality and high-end motion capture systems that may not be similar to the low-cost tracking commonly used in game-based rehabilitation applications.

Figure 2.1: Consequences of stroke using the International Classification of Functioning, Disability and Health

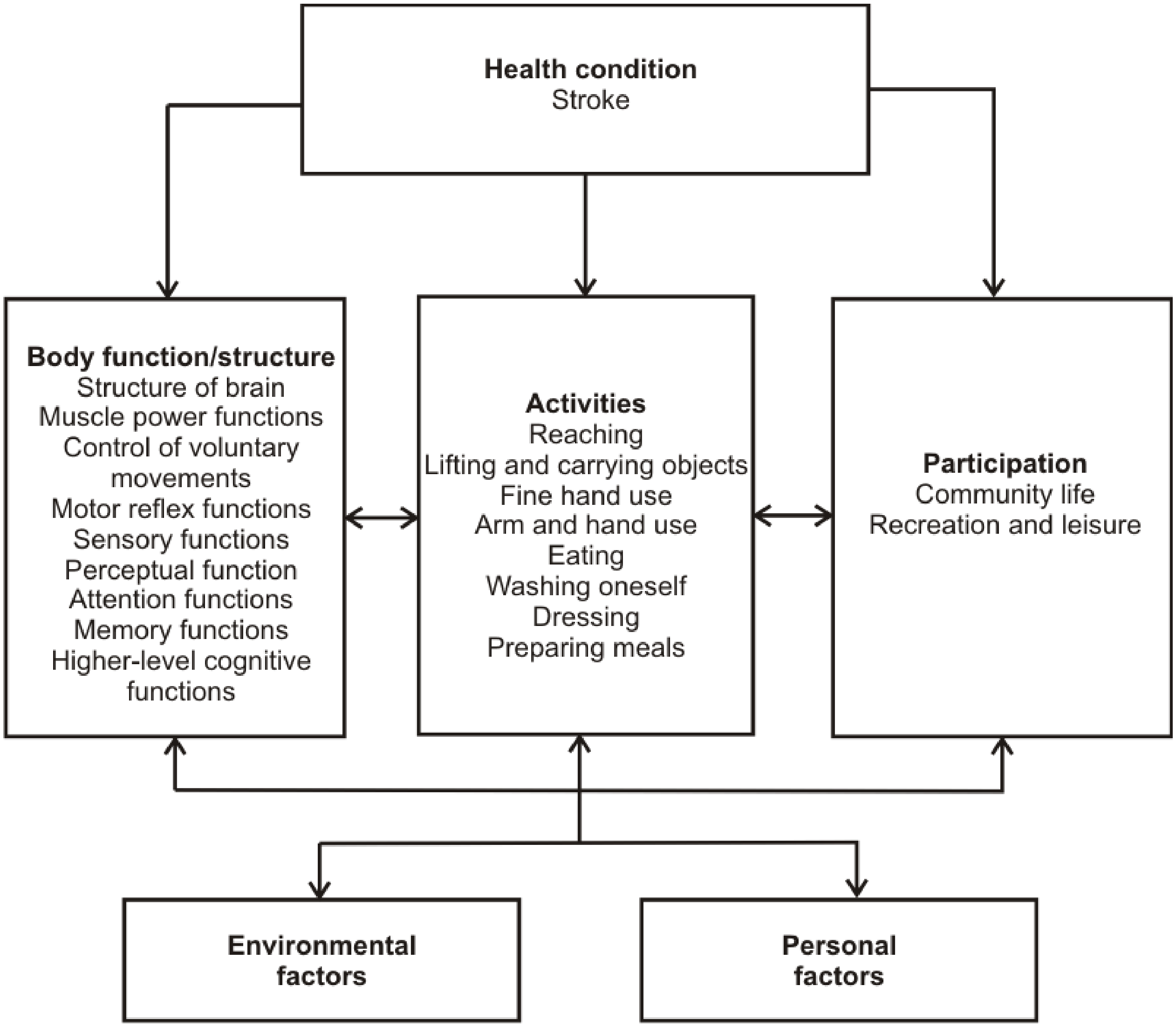

Table 2.1: Principles of experience-dependent plasticity

(adapted from Kleim & Jones, 2008)

Principle	**Description**
1. Use It or Lose It	Failure to drive specific brain functions (e.g. by not actively engaging neural circuits for an extended period of time) can lead to functional degradation.
2. Use It and Improve It	Specific training leads to an enhancement of function. For example, motor skill training can improve motor performance and optimize restorative brain plasticity after brain damage.
3. Specificity	The nature of the training experience dictates the nature of the plasticity.
4. Repetition Matters	Repetition of a newly learned (or relearned) behavior is required to induce lasting neural changes.
5. Intensity Matters	Induction of plasticity requires sufficient training intensity.
6. Time Matters	Different forms of plasticity occur at different times during training. The time after a brain damage may be even more critical given the dynamic changes in the neural environment that are occurring independent of any rehabilitation.
7. Salience Matters	Induction of plasticity requires that the training experience be sufficiently salient to the participant.
8. Age Matters	Training-induced plasticity occurs more readily in younger brains. Neuroplastic responses are altered in the aged brain.

9. Transference	Plasticity in response to one training experience can enhance the acquisition of similar behaviours.
10. Interference	Plasticity in response to one experience can interfere with the acquisition of other behaviours.

Table 2.2: Studies comparing upper limb movements performed in a virtual and in a physical environment

Authors	Movements compared	PE	VE	Population	Kinematic studied	Results	Similarities	Differences
(Chen et al., 2014)	Reaching movements while standing	Reaching for corners of 3 boxes of different sizes using a handheld wand	3D VE using a CAVE system and a handheld wand; virtual boxes	Healthy adults (college students)	Movement time, endpoint precision, and approach toward corners of the boxes (wand rotation angle)	In VE, accuracy and time was significantly poorer. Wand approach angles for the same corner of a box were similar in both environments.	Wand approach angles for the same corner of a box	In VE, accuracy was lower and movement time was greater.
(Knaut et al., 2009)	Pointing movements while sitting	Pointing 6 targets	3D VE using a HMD, simulating elevator buttons	Individuals with chronic stroke and arm paresis, healthy adults	Endpoint (tip of index) precision, peak velocity, trajectory straightness, elbow and shoulder ranges of motion, trunk displacement and rotation, interjoint coordination between elbow extension and shoulder horizontal	**Healthy:** in VE, precision and trajectory straightness were higher when pointing to contralateral targets; movements were slower for all targets. **Stroke:** in VE, movements were less accurate, more curved and used less trunk displacement. Elbow/shoulder	Motor performance and movement patterns for midline target	**Healthy:** in VE, precision and trajectory straightness were higher. **Stroke:** in VE, movements were less accurate, more curved and used less trunk displacement. Elbow/shoulder coordination differed when pointing to the

					abduction/ adduction	coordination differed when pointing to the lower ipsilateral target. There were no group-by environment interactions.		lower ipsilateral target.
Kuhlen et al., 2000	Reaching-to-grasp movements for a cube	Reaching-to-grasp for a red wooden cube	3D VE viewed with stereo shutter glasses; virtual cube	Healthy individuals	Movement time, end-point acceleration/ deceleration, maximum aperture, aperture velocity	**Healthy:** Movement times were similar in both environments, but lower peak velocities were noted in the VE.	Movement time	In VE, peak velocities were lower.
(Levin et al., 2015)	Reaching and grasping 3 objects (can, screwdriver, pen) while sitting	Reaching and grasping 3 objects (can, screwdriver, pen)	3D VE with haptic feedback (cyberglove)	Individuals with chronic stroke and arm paresis	Movement time, peak hand velocity, time to peak velocity, deceleration time, trajectory straightness, movement smoothness, trunk displacement, range of joint movements	In VE, reaches were less smooth and slower. Wrist, elbow, shoulder and trunk kinematics were unaffected by either the environment.	Wrist, elbow, shoulder and trunk kinematics	In VE, movements were slower, and apertures were wider for the medium and small objects (aperture scaled to the largest object).
(Liebermann et al., 2012)	14 reaching movements towards 3 targets (84	Reaching to targets (semi-transpare	2D VE using the IREX video-	Right-handed individuals with left	Endpoint peak velocity, path length, trajectory straightness,	Movements were slower, shorter, less straight, less accurate and involved smaller		In VE, movement speed was slower, path trajectory was shorter, less straight

	movements in total) while sitting	nt squares (33 cm) suspended from the ceiling)	capture system, mountain scenery and colored balls to reach	subacute or chronic stroke and right arm paresis, healthy adults	endpoint precision, final angles of elbow extension and shoulder flexion, sagittal trunk displacement	ranges of shoulder and elbow joint excursions for target reaches in the virtual environment compared to the physical environment in all subject		and accuracy. Ranges of shoulder and elbow joint excursion were also smaller.
(Lin & Woldegiorgis, 2018)	Pointing movement with the tip of a pointing stick towards targets at 9 different locations while sitting; 2 conditions: vision-based and from memory	Pointing 3 green Styrofoam balls with the tip of a pointing stick	3D stereoscopic VE viewed with NVIDIA 3D glasses, green balls	Young healthy adults	Movement time, reaction time (movement onset), confirmation time (movement offset), endpoint peak velocity, movement smoothness	Reaction time, peak velocity or movement smoothness did not differ between environments. In the VE, movement and confirmation time were longer. In vision-based condition: Movements were initiated faster, but movement time was longer.	Initiation of movement, peak velocity, number of peak velocities	In VE, overall movement and confirmation time were longer.
(Magdalon et al., 2011)	Reaching and grasping 3 objects (can, screwdriver, pen) while sitting	Reaching and grasping 3 objects (can, screwdriver, pen)	3D VE with haptic feedback (cyberglove)	Individuals with chronic stroke and arm paresis	Movement time, peak hand velocity, time to peak velocity, deceleration time, trajectory straightness,	Movements were slower and grip apertures were wider when wearing the glove in both the PE and the VE compared to movements made in the PE without the glove.	Reaching trajectories in both environments	In VE, movements were slower and had longer deceleration times, elbow extension was greater when reaching to the smallest object and

					movement smoothness, trunk displacement, range of joint movements	Similar reaching trajectories in the VE and the PE. In VE movements were slower, longer deceleration times, elbow extension greater when reaching to the smallest object and apertures were wider for the power and precision grip		apertures were wider for the power and precision grip tasks
(Robert & Levin, 2018)	Sagittal, frontal, or vertical arm reaching movement while sitting	Tracing 3 different trajectory paths showed by targets positioned on a wooden frame (participants instructed not to touch the targets)	2D VE with 3D rendering (no haptic feedback)	Typically developing children and children with cerebral palsy	Movement time, time to peak velocity, distance, trajectory straightness, shoulder abduction/ flexion, elbow extension, trunk flexion/rotation	Trajectories were more curved in VE for all 3 gestures compared to PE in all children with cerebral palsy. Trajectories were only more curved for the vertical gesture in VE in all typically developing children.	**Typically developing children:** path straightness, shoulder flexion (frontal movement), elbow extension (vertical movement) **Children with cerebral palsy**: movement time	**Typically developing children:** In VE, movements were slower, less trunk flexion and rotation were used. **Children with cerebral palsy**: in VE, trajectories were more curved, and less trunk movement was used.

(Schafer & Ustinova, 2013)	Reaching movement while standing	Reaching forward while standing for small colored pompons	3D VE viewed through shutter glasses (no haptic feedback) Visual scene presented at 3 different viewing angles, flower bed	Individuals with traumatic brain injuries and healthy individuals	Movement time, peak velocity, time to peak velocity, movement smoothness, endpoint displacement (hand), displacement of the center of mass (COM) of the whole body	Healthy participants and participants who have had a traumatic brain reached ~9% farther in the VE presented at a 50° angle than the PE. Arm displacement in the VE at the more natural 10° angle was reduced by the same 9-10% compared to the PE. Virtual reaches were slower than reaches performed in the PE.		In VE, movement time was slower, peak velocity was lower and movements were more segmented (multiple velocity peaks). At 50° viewing angle, the reaching amplitude was the greatest (~9% farther arm displacement than during PE reaches). At 10° viewing angle, the VE reaches were about 9-10% shorter than PE reaches in both participant groups.
(Viau et al., 2004)	Reaching, grasping and releasing a ball while sitting	Reaching for a ball in an environment of equivalent dimensions	2D computer screen and haptic force feedback from a virtual ball	Individuals with chronic left stroke and mild right hemiparesis, healthy adults	Movement time, time to peak wrist velocity, time to maximal hand aperture, delay between peak wrist velocity and maximal hand aperture, trajectory straightness,	Similar arm movement trajectory between healthy and stroke (spatial and temporal), subjects tended to decrease wrist extension	Smooth arm movement trajectories, paths for movements, trajectory lengths	In VE, wrist extension was decreased, and elbow extension increased.

					maximal grip aperture, angular ranges of joint motion and elbow-shoulder interjoint coordination			
Wang et al., 2011	Reaching-to-grasp movements to stationary and moving targets	Reaching-to-grasp for a ball placed on an inclined ramp	3D VE projected to a large screen and viewed with polarized glasses	Healthy adults, individuals with Parkinson's disease	Movement time, peak velocity, deceleration, success rate	For both groups, reaching movements were slower and had longer deceleration phases in the VE for static targets. For moving targets, the success rate was lower in the VE, especially at faster speed.		In VE, movement speed was slower, and the deceleration phases were longer for the static targets. The success rate was also lower in the VE for moving targets.

Abbreviations: CAVE: cave automatic virtual environment; HMD: Head-mounted display; IREX: Immersive Rehabilitation Exercise; PE: physical environment; VE: virtual environment

Chapter 3 - Objectives of the thesis

The overall aim of the thesis is to determine the feasibility of using a low-cost virtual reality intervention as a therapeutic option for improving UL function in individuals who have had a stroke.

The specific aims of the thesis are:

I. To determine user satisfaction and safety of an adjunct virtual reality intervention for individuals with stroke undergoing rehabilitation, from the point of view of clinicians and individuals with stroke.

II. To inform the selection of outcome measures capturing upper limb motor performance and movement quality.

III. To estimate the extent to which unimanual and bilateral movements are kinematically similar when movements are performed in a low-cost virtual reality environment and a comparable physical environment, in individuals who have had a stroke and in healthy individuals.

IV. To estimate the extent to which motor performance and movement quality variables of movements performed in a physical and a virtual environment are affected by visuo-perceptual deficits in individuals who have had a stroke.

The first objective is addressed by a mixed-methods study presented in Chapter 4. The second objective is addressed by a structured review presented in Chapter 5. The third and fourth objectives are addressed by an experimental study described in Chapter 6.

3.1 Hypotheses

For specific objective I, it is hypothesized that:

1) The intervention would be enjoyed by the majority of the participants with stroke;
2) Few participants with stroke would experience minor adverse events and no participant would experience major adverse events;

3) Clinicians would be highly satisfied with the virtual reality intervention and perceive it as useful in their clinical practice.

To guide our hypotheses for specific objectives III and IV, it is assumed that the perception of objects in 2D VE is different than in physical environments. For specific objective III, the hypothesis is:

4) For unimanual reach-to-grasp, endpoint performance variables and hand orientation would be affected by the viewing environment in healthy individuals and individuals with stroke;
5) For unimanual reach-to-grasp, differences in endpoint and hand orientation variables would be greater in individuals with stroke than healthy individuals;
6) For bilateral reach-to-grasp, arm movement symmetry and synchronicity would be affected in VE in both groups.

For objective IV, it is hypothesized that:

7) Endpoint and hand orientation variables would be correlated with visual perceptual impairments in the stroke group, in which slower, more segmented and less wrist flexion would be correlated to greater visual impairments.

Chapter 4 – Feasibility of incorporating functionally relevant virtual rehabilitation in sub-acute stroke care: perception of patients and clinicians

4.1 Preface

Virtual reality can target key elements of motor learning for stroke recovery, such as massed practice, augmented feedback, motivation, and observational learning. However, some features of virtual reality systems may also be detrimental to motor learning, particularly in individuals who have had a stroke (Levac & Sveistrup, 2014). Specifically, the manipulation of feedback provision and task difficulty may not be possible, which may make the tasks too challenging for those with cognitive, perceptual or sensorimotor impairments. Certain virtual environments may provide inaccurate, discouraging or excessive visual and auditory feedback perceived as overwhelming (Deutsch et al., 2011, Lange et al., 2012, Levac et al., 2011). The literature review presented in Chapter 2 highlighted the need to determine the feasibility of a newly developed virtual reality intervention for sub-acute stroke rehabilitation. The process of determining the feasibility of an intervention involves the evaluation of the sample characteristics, the acceptability and suitability of the intervention, as well as the evaluation and refinement of data collection procedures and outcome measures (Orsmond & Cohn, 2015). It has been recognized that the development and implementation of virtual reality applications for rehabilitation depends on the close collaboration between end-users, clinicians, researchers and industry (Rizzo & Kim, 2005). To ensure that the virtual reality intervention can meet the desired rehabilitation goals and is appropriate for the population receiving sub-acute stroke rehabilitation care, there is a need to gather the perspectives of potential stakeholders (i.e. clinicians and individuals receiving rehabilitation services following a stroke). Understanding the perspectives of individuals who have had a stroke can provide greater insight on the needs and motivation of the targeted population, as well as the safety of the intervention, which are important for eventual clinical uptake (Lewis & Rosie, 2012; Thomson et al., 2014). The clinicians' perspective is also valuable to identify how the application can be improved to address rehabilitation goals and overcome common barriers to the adoption of virtual reality interventions cited in the literature (Glegg et al., 2013; Hughes et al., 2014; Levac et al., 2012 and 2016; Nguyen et al., 2018).

This manuscript aims to determine the satisfaction and safety of incorporating a low-cost virtual rehabilitation intervention as an adjunctive therapeutic option for the rehabilitation of individuals with sub-acute stroke, from the point of view of clinicians and patients. Feasibility is determined by: a) assessing the perceptions of different users regarding the satisfaction towards the virtual reality intervention to address rehabilitation purposes, the ease of use in rehabilitation, and the usefulness in clinical practice, and b) measuring the perceived level of difficulty, fatigue and reactions to the virtual reality intervention in individuals receiving rehabilitation services following a stroke. The level of enjoyment of participants who interacted with the virtual reality intervention and the presence of adverse events is also presented. Suggested modifications to improve the virtual reality intervention for stroke rehabilitation are discussed.

Feasibility of incorporating functionally relevant virtual rehabilitation in sub-acute stroke care: perception of patients and clinicians

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4.2 Abstract

Purpose: To determine user satisfaction and safety of incorporating a low-cost virtual rehabilitation intervention as an adjunctive therapeutic option for cognitive-motor upper limb rehabilitation in individuals with sub-acute stroke.

Methods: A low-cost upper limb virtual rehabilitation application incorporating realistic functionally relevant unimanual and bimanual tasks specifically designed for cognitive-motor rehabilitation was developed for patients with sub-acute stroke. Clinicians and individuals with stroke interacted with the intervention for 15-20 or 20-45 minutes respectively. The study had a mixed-methods convergent parallel design that included a focus group interview with clinicians working in a stroke program and semi-structured interviews and standardized assessments (Borg Perceived Exertion Scale, Short Feedback Questionnaire) for participants with sub-acute stroke undergoing rehabilitation. Occurrence of adverse events was also noted.

Results: Three main themes emerged from the clinician focus group and patient interviews: Perceived usefulness in rehabilitation, Satisfaction with the virtual reality intervention and Aspects to improve. All clinicians and the majority of participants with stroke were highly satisfied with the intervention and perceived its usefulness to decrease arm motor impairment during functional tasks. No participants experienced major adverse events.

Conclusion: Incorporation of this type of functional activity game-based virtual reality intervention in the sub-acute phase of rehabilitation represents a way to transfer skills learned early in the clinical setting to real world situations. This type of intervention may lead to better integration of the upper limb into everyday activities.

4.2.1 Implications for Rehabilitation

- Use of a cognitive-motor low-cost virtual reality intervention designed to remediate arm motor impairments in sub-acute stroke is feasible, safe and perceived as useful by therapists and patients for stroke rehabilitation.

- Input from end-users (therapists and individuals with stroke) is critical for the development and implementation of a virtual reality intervention.

4.3 Introduction

Stroke is a leading cause of disability worldwide (World Health Federation, 2015) with persistent upper limb (UL) hemiparesis impacting activities of daily living, social participation and quality of life (Desrosiers et al., 2003, Mayo et al., 1999). Current practice to improve UL function is based on principles of enhancing neural plasticity such as movement repetition and task salience (motivation and task validity; Kleim & Jones, 2008). However, due to different health system constraints such as the early focus on improving lower limb mobility and the limited available treatment time, UL mobility targets are not being met (Lang et al., 2013). Another issue is that UL mobility gains have not shown to completely carry-over into real world situations when patients are discharged home after therapy (Kwakkel et al. 1999; Rand & Eng, 2012).

Virtual rehabilitation (VR) is a promising intervention for reducing UL motor impairment and increasing function, as it may encourage more movement repetitions, and provide motivating and ecologically-valid environments for feedback delivery (Levin, 2011; Weiss et al., 2003). VR may increase overall therapy time when used as an adjunct to usual care (Laver et al., 2015). Increasing evidence supports the use of VR in UL rehabilitation of patients with chronic stroke. However, most UL recovery naturally occurs within the first six months after stroke (Skilbeck et al., 1983), a critical time to reduce impairments and maximize function. Nevertheless, evidence for the effectiveness of VR in this critical time period is limited (Laver et al., 2015; Adamovich et al., 2009; Saposkik & Levin, 2011). Thus, there is a need to develop salient UL therapy interventions to increase treatment intensity in the sub-acute phase of stroke rehabilitation that are acceptable to stakeholders.

To this end, new VR-based interventions should be assessed for their feasibility by both clinicians and patients. Feasibility studies focus on the process of developing and implementing an intervention by evaluating participant safety, intervention implementation, and acceptability (Orsmond et al., 2015). Such studies have established, from the perspective of researchers, that participants with different levels of sensorimotor severity were able to engage in VR-based interventions (Burdea et al., 2011; Kim et al., 2016; Stewart et al., 2007) and that commercial videogames and VR systems are feasible and safe for individuals with chronic stroke (Schester-Amft et al., 2015; Subramanian et al., 2007). Only a few studies have evaluated the patient perspective (Lewis et al., 2012) and no studies have evaluated the perspective of clinicians for stroke rehabilitation. These perspectives may provide greater insight into user's needs as well as issues of implementation and motivation, which are important for eventual clinical uptake (Lewis et al., 2012; Thomson et al., 2014). Furthermore, the occurrence of adverse events has not consistently been reported (Laver et al, 2015; Thomson et al., 2014). In brain injury rehabilitation, uptake of VR has met with some barriers such as poor client motivation, enjoyment or interest and time constraints (Glegg et al., 2013). Another barrier is that not all platforms and activities are adapted to the target population (Lewis et al., 2012).

We sought to determine user satisfaction and safety of a new cognitive-motor VR intervention for stroke, from the point of view of both clinicians and patients. We hypothesized that: 1) the intervention would be enjoyed by the majority of participants; 2) few patients would experience adverse events; 3) clinicians would be highly satisfied and perceive the intervention as useful for clinical practice.

4.4 Methods

4.4.1 Design

A mixed-methods convergent parallel design was used including qualitative and quantitative approaches. This design tests feasibility using qualitative methods to gain an in-depth understanding of the perceptions of different users as well as quantitative methods to measure the challenge level and reactions to the VR intervention. First, a focus group was conducted to gather clinician perspectives of the safety and appropriateness of the VR intervention for sub-acute stroke rehabilitation. Then, perception of the VR intervention, occurrence of adverse events and fatigue were assessed in individuals undergoing post-stroke rehabilitation using standardized assessments and a semi-structured interview.

4.4.2 Study participants

Clinicians: Using a purposive sampling strategy (Barbour, 2001), nine Stroke Program occupational therapists were invited to participate. There were no exclusion criteria. The Advanced Stroke Clinical Practice Leader at the site was also recruited because of her expertise in stroke care and VR. The Stroke Program coordinator emailed the project description to all potential participants, who contacted a research team member if interested.

Participants with stroke: The inclusion criteria were: receiving in- or out-patient rehabilitation for a recent unimanual ischemic or haemorrhagic stroke and mild to moderate UL motor deficits (3-6/7 on Chedoke McMaster Hand or Arm Stroke Assessment; Gowland et al., 1993). Participants were excluded if they had severe cognitive disorders (<20/30 on Montreal Cognitive Assessment; Waldron-Perrine et al., 2012), expressive or receptive aphasia limiting the ability to answer questionnaires using Likert Scales, paretic arm pain >4/10 when moving the arm or any other medical conditions interfering with participation or putting participants at risk. The purposive sampling strategy was used to recruit men and women of different ages, with varying levels of physical and cognitive impairments, with and without prior experience with VR/commercial games to facilitate the generalization of results. Eight eligible participants were identified by the stroke program coordinator and then contacted by a third party, after providing general consent to be contacted by research staff. One person refused to participate due to fatigue. Participants were consecutively recruited during two 2-month periods (July-August 2016 and October-November 2016). An initial sample size of ten participants was targeted but revised to seven participants due to data saturation after the fifth participant.

4.4.3 VR intervention

The intervention was developed on Unity Pro Software and a Kinect II camera tracked arm, hand and trunk movements to interact with the VR environment without a game controller. It was projected on a large 2.1x1.6 m screen. Participants played the games in sitting or standing with or without ambulatory aids.

The intervention included two tasks designed to encourage functional UL reaching and grasping of differently shaped objects in different contexts. In the “Smash Blocks” task, participants hit differently sized and coloured squares according to an instructed sequence as quickly and accurately as possible. The second task, "Shopper's Delight", simulated shopping in an interactive grocery store (Figure 4.1). Participants located and retrieved six items from a shopping list displayed on the screen within a specified budget and placed them in a shopping cart. The store included five specialty (i.e., diary, frozen items, etc.) aisles. Participants moved between aisles by holding one hand over a navigation button for three seconds. The task included unimanual, bilateral and bimanual UL movements (e.g., opening a refrigerator door and reaching for an item; reaching-to-grasp a large item with both arms), and challenged decision-making, attention, visual scanning and working memory cognitive processes. The tasks involved reaching and grasping an object, maintaining the arm final position for two seconds, and bringing the arm back towards the trunk to place the object in an unseen shopping cart. Each task had three levels of difficulty with respect to time (both games), block size (Smash Blocks) and involvement of bimanual and bilateral movements (Shopper's Delight). Visual feedback about motor performance was provided by an arm avatar and object collision was signalled by visual cues. Negative auditory and visual feedback was given when excessive trunk displacement occurred. In Smash Blocks, auditory feedback was given when participants hit a block of the wrong colour. Summary feedback was provided after completion of each game as a success score (Smash Blocks: number of hit blocks; Shopper's Delight: respect of the budget, use of trunk compensations and number of items retrieved from the list) and total time.

4.4.4 Procedures

Clinicians: Clinicians played each game at each difficulty level for 15-20 minutes. A user manual with detailed task descriptions including equipment setup was provided after their interaction. Then, clinician level of satisfaction was assessed during a one-hour audiotaped focus-group interview in a closed room, led by one group leader (MD) and one moderator (DCCK), who also made field notes. It consisted of semi-structured open-ended questions on the following topics: familiarity with VR, satisfaction with the VR intervention, ease of use in rehabilitation and usefulness in clinical practice (see Appendix 1 for interview guide). Saturation was reached after 35 minutes. Subsequently, discussion was stopped, and main ideas were summarized by the moderator to ensure that they accurately reflected the opinions expressed (i.e. member checking; Creswell, 1994).

Stroke participants: Patients participated in a single session comprised of a VR intervention trial (20-45 minutes, based on the average time of a single session of adjunctive VR therapy in a rehabilitation setting (i.e., 23 minutes; Perez et al., 2017). They completed the Short Feedback Questionnaire (Kizony et al., 2006), the Borg Perceived Exertion Scale (Borg, 1982) and an individual interview. The Short Feedback Questionnaire assesses enjoyment, immersion, success, control, realism and understandability of computer feedback on 5-point Likert Scales (1– not at all, 5– to a great extent) for a total score of 30 points. Two additional questions assessed the levels of discomfort and difficulty (1– very easy, 5– very difficult). Exertion was monitored between games and at the session end using the Borg Perceived Exertion Scale, which ranges from 6 (no exertion at all) to 20 (maximal exertion). Sessions were videotaped to determine practice intensity by quantifying the number of movement repetitions. A pause in the movement for more than one second signalled the end of one movement and beginning of the next. Movements were counted whether or not they were successful (i.e., resulted in hitting a block or retrieving an item). Movements not targeting completion of a game task were not counted (e.g.: scratching one's nose). The 20-minute semi-structured interview was audio-recorded and focused on overall satisfaction with the VR intervention, occurrence of adverse events, level of difficulty while performing the task and perceived usefulness of the intervention (Appendix 1). When needed, the interviewer (MD) pursued and clarified the meaning of answers. Notes were taken by another team member (DCCK) for summary and member check with each participant.

4.4.5 Research team and reflexivity

MD is a female Ph.D. student with previous experience in focus group facilitation and a former occupational therapist in the Stroke program at the site. This previous work experience allowed her to understand the clinical issues reported by some of her former colleagues and individuals with stroke. However, it might also have impacted negative responses from clinicians, not wanting to disappoint the group moderator. DCCK is a male, undergraduate student in physical therapy. Prior to the focus group and individual interviews, he received training about qualitative methods by the research team. Personal assumptions and reflections throughout the data collection and analysis were noted in a reflective journal and discussed between the three members of the research team.

4.4.6 Ethical considerations

All participants signed consent forms approved by the CRIR Ethics Committee. All information was coded alphanumerically to ensure confidentiality and stored in a locked cabinet accessible only to research team members.

4.4.7 Data analysis

Qualitative and quantitative data were analysed separately and then merged to compare and combine results from both methods (Creswell, 2007). Because the time of interaction with the VR by the participants with stroke varied, movement repetitions were counted for each five-minute period and then averaged. Focus group and interview audio recordings were transcribed into verbatim texts. Inductive thematic content analysis was implemented for interpreting meaning from the context of textual data (Ritchie & Spencer, 2002; Hsieh & Shannon, 2005) using Nvivo 10 software. Meaningful units of text were identified and coded independently by MD and DCC to form a book of codes and their definitions. Similar codes were grouped together, and recurrent codes identified emerging themes. Sources of disagreement were resolved by discussion. An audit trail was kept on the rationale behind the codes, themes and categories, as well as code definitions.

4.5 Results

Seven Stroke Program clinicians, six occupational therapists working with in- and out-patients and one Advanced Stroke Clinical Practice leader (physical therapist) participated in the focus group. All clinicians were female with 10.9 years (range 2-28 years) of clinical experience, and had prior experience playing videogames and using VR interventions occasionally. Seven stroke participants were recruited (Table 4.1) until saturation was reached. Three participants were familiar with commercial videogames prior to their stroke; three were unfamiliar with commercial videogames but used VR interventions during their post-stroke rehabilitation; one was unfamiliar with videogames or computers in general.

4.5.1 Qualitative results

Three main themes emerged from the qualitative data analysis from both groups: Perceived usefulness in rehabilitation, Satisfaction with the VR intervention and Aspects to improve (see Table 4.2 for meaningful quotes).

1. Perceived usefulness in rehabilitation

This theme encompasses the quality and features of the VR intervention as a therapeutic option for individuals following stroke. Both clinicians and patients reported that the intervention was appropriate for the target population. They expressed that the intervention simultaneously addressed motor, cognitive and perceptual impairments. By simulating everyday tasks that would be impractical to retrain in therapy (time for transportation, limited mobility), the VR intervention had the potential to increase treatment efficiency and potentially, help with transfer of skills learned in therapy to real world situations.

Tasks were described as interactive, fun and motivating by both clinicians and individuals with stroke. Therapists perceived the potential of the VR intervention to be used for individuals with language impairments or barriers, since the tasks were easy to understand. Due to the immersive nature of the virtual environment, both games encouraged spontaneous movements. Game accessibility was appreciated, as tasks could be performed in sitting or standing, without a game controller. Clinicians also perceived that the VR intervention could be integrated easily in clinical practice, since equipment set-up was minimal, the menus were easy to select, and both tasks were short.

2. Satisfaction with the VR intervention

All clinicians and all but one patient were highly satisfied with the VR intervention. The realism of the Shopper's Delight task was perceived as a strength, since the task was done within the context of demands of actual grocery shopping, aisles represented a real supermarket and items on shelves were easily recognizable. Many elements, such as the budget, embedded in Shopper's delight, added to task realism. One participant (Stroke 7) did not enjoy the VR intervention, reporting that the tasks were boring. He perceived that the virtual environment was not as appealing as commercial videogames and he did not see the pertinence of practicing a functional task in a virtual environment. He also reported being annoyed by the motion tracking system, which lacked accuracy.

Clinicians and stroke participants differed on their perception of task difficulty. Clinicians felt that difficulty was higher than anticipated (level of precision required to grasp an item, quantity of visual information and the simultaneous requirements of motor, cognitive and perceptual skills) limiting its use with individuals with more severe impairments. Unlike clinicians, participants with stroke perceived that the tasks were a fair challenge, but some perceived that other people with stroke may experience difficulty.

3. Aspects to improve

This theme included ideas or recommendations made by clinicians and participants with stroke regarding specific changes needed to improve the VR intervention and/or make it more suitable for stroke rehabilitation. Suggestions to improve game usability were to display the shopping list constantly in a different screen location to avoid interference with the navigation menu. Stroke participants wanted the items collected displayed at the bottom of the screen and receive more information on their performance. Clinicians suggested having additional levels of difficulty to better individualize treatment. One clinician suggested that the VR intervention could be used as an assessment tool to capture motor, cognitive and perceptual impairments, as well as client's capacity when grocery shopping.

4.5.2 Quantitative results

Participants with stroke played on average 4.7±1.3 games (Table 4.3), with five participants performing the tasks standing and two alternating between sitting and standing. The mean number of repetitions per 5-minute period of game-play was 30.7±14.6 for the more-affected arm and 34.1±22.6 for the less-affected arm. Short Feedback Questionnaire scores ranged from 13-30 (24.0±4.2) points and perceived exertion was minimal (6.3±0.5 points). No adverse events occurred, except for temporary eye fatigue due to concentration in 57% of participants. This was not spontaneously reported by participants when asked about discomfort experienced during the interaction, but only when specific questions were asked about possible symptoms (nausea, dizziness, pain, eye strain, etc.). No participants still perceived eye fatigue when the interview was done (10 minutes after the interaction) and it did not prevent participants to continue. Eyestrain was not experienced by clinicians.

4.6 Discussion

We assessed user satisfaction and safety of salient cognitive-motor VR intervention designed to increase treatment intensity in the sub-acute phase of stroke rehabilitation, from the perspective of not only individuals undergoing rehabilitation, but also clinicians working in a Stroke program. Consistent with our hypotheses, the VR intervention was enjoyed by the majority of the participants with stroke (85.7%); no participant experienced major adverse events and the only minor adverse event was temporary eye fatigue (in 57.1% of participants); clinicians were highly satisfied with the VR intervention and perceived its usefulness in their clinical practice to decrease UL cognitive-motor impairment.

Consistent with previous studies that used low-cost VR systems with individuals in the sub-acute and chronic phases of stroke recovery, the overall Short Feedback Questionnaire score and the enjoyment score were high (Hadad et al, 2012; Rand et al., 2008, 2012). This is also consistent with the postulate that VR environments can increase the participant's level of engagement and motivation in performing motor tasks (Lourenço et al., 2008). The three categories with the highest scores were enjoyment, immersion and realism, which can have contributed to the high satisfaction expressed in the interviews by most participants with stroke. Some attributes of this VR intervention, such as the ability to progress task difficulty, playfulness and feedback provision, have been identified as elements encouraging user engagement for UL stroke rehabilitation (Burke et al., 2009). Nevertheless, one participant with stroke did not enjoy the intervention. Some of this participant's characteristics (young age - 38 years old), frequent previous experience with commercial videogames) may explain his dissatisfaction, as our intervention did not try to duplicate production values of commercial videogames made for entertainment.

The perception of clinicians and participants with stroke were similar, except for the perceived level of difficulty. While clinicians perceived that the games were possibly too complex for individuals with more severe impairments, participants with stroke with various degrees of physical and cognitive impairments rated the level of difficulty as low. Most participants enjoyed the tasks and were engaged in them so that they likely did not perceive that the tasks were difficult. Indeed, exertion was rated as low following the intervention, even when a high number of repetitions were made (>30 repetition with the hemiparetic arm per 5 minutes of play). The high engagement and exercise intensity together with minimal fatigue suggests that VR interventions can target key elements of motor learning (Kleim & Jones, 2008). No adverse events were experienced except for temporary eye fatigue, which may be attributed to the complexity of the visual information in the VR environment. This was mentioned as one aspect that could be better customized for individuals with cognitive or perceptual impairments.

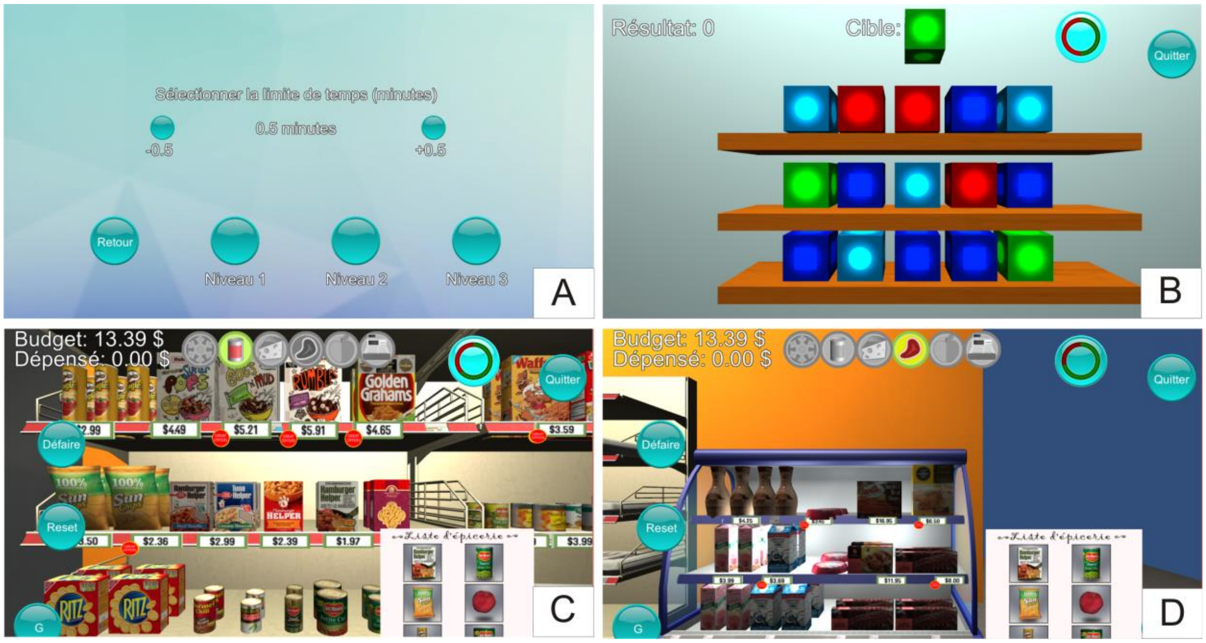
4.6.1 Study Limitations

The intervention was only offered for one session as a first step in the assessment of its effectiveness. We did not assess whether individuals could tolerate more frequent treatment delivery and whether enjoyment would be maintained over time. Therapists' perception was only based on their experience with the VR and not that of their patients. The possibility of a social desirability bias is not excluded since participants may have wanted to please the research team members. The results may have limited generalizability due to the small sample size and perspectives from individuals in only one rehabilitation center.

4.7 Conclusion

Use of this functionally significant cognitive-motor VR intervention was feasible and safe for sub-acute stroke rehabilitation, as an adjunct to usual care to increase overall therapy time. The VR intervention was well-accepted by stakeholders and perceived as being useful for sub-acute stroke rehabilitation. The main strength of the intervention was its ability to realistically recreate a meaningful task, grocery shopping, in a rehabilitation setting. This intervention also targeted motor, cognitive and perceptual impairments, and could be used for individuals with various degrees of severity, familiarity with VR interventions and at different stages in their rehabilitation process (in/outpatient). Future research questions can address whether incorporation of this type of functional VR intervention in the sub-acute phase leads to better transfer of skills learned early in the clinical setting to real world situations by better integration of the upper limb in everyday activities. Modifications were suggested to improve game usability and treatment individualization. Based on the recommendations made by the study participants, the next step is to implement the suggested modifications, using an iterative process involving ongoing consultations between team members and key user stakeholders. This study is a precursor to a large-scale randomized control trial to determine the effectiveness of using an adjunctive VR intervention simulating an ecologically-valid functional task (grocery shopping) to improve UL cognitive-motor impairments with individuals with sub-acute stroke.

Figure 4.1: Virtual reality intervention



Legend: A) Menu selection screen, where clinicians can chose one of the three levels of difficulty for each game and modify the allocated time to complete the task, B) Image of the Smash Blocks game, in which participants are asked to hit blocks of different sizes and colours, as quickly and as accurately as possible, C) Image of the canned items in the Shopper's Delight game, simulating grocery shopping in a supermarket, where participants are asked to find and to retrieve common items located on different shelves of a grocery store by following a shopping list and an allocated budget, D) Image of the meat aisle in the Shopper's Delight game.

Table 4.1: Socio-demographics of participants with stroke

#	Sex	Age (yr)	Diagnosis	Side of lesion	Time since stroke (mo)	CMSA (Arm=7; Hand=7)	MoCA (30)	Ambulation
1	Male	66	Lacunar stroke (internal capsule)	Right	4	Arm: 5 Hand: 3	30	Quad cane
2	Male	58	MCA ischemic stroke	Right	3	Arm: 3 Hand: 3	25	Independent
3	Female	61	Frontal ischemic stroke	Left	5	Arm: 4 Hand: 5	23	Independent
4	Male	73	Fronto-parietal hemorrhagic stroke	Right	8	Arm: 4 Hand: 5	20	Independent
5	Female	70	Caudate nucleus hemorrhagic stroke with intraventricular extension	Left	2	Arm: 6 Hand: 6	23	Simple cane
6	Male	60	MCA ischemic stroke with hemorrhagic transformation	Right	10	Arm: 6 Hand: 6	19	Independent
7	Male	38	MCA ischemic stroke	Right	5	Arm: 5 Hand: 3	29	Independent

Abbreviations: CMSA: Chedoke McMaster Stroke Assessment, MCA: Middle cerebral artery, MoCA: Montreal Cognitive Assessment

Table 4.2: Summary of the main ideas and quotes from clinicians and participants with stroke

Themes	**Quotes**
Perceived usefulness in rehabilitation	**Encourage spontaneous movements:** Therapist 4: "*Seeing as the client is really in the game, sometimes, you will see movements that are more than they were capable of doing with the arm, and also the trunk*... [to herself] *Oh. They are able to do that!"* **Increase treatment efficiency:** Therapist 6: "*Sometimes it is a matter of time… Sometimes we don't have the time to go out. It can be like a first step to simulate a task and then, we can see if we want to go into a real situation to accomplish this particular task. It tells us anyway the things that we need to work on with the patient*." **Target a wide range of impairments:** Stroke 4: "*It forces you to think, it forces you to… control things well, see things well. There are a million things in this* [the game]." **Motivating:** Therapist 6: "*It can also induce interest in people who… sometimes who could be initially skeptical about virtual reality, and it can attract them to it*." **Accessibility:** Therapist 3: "*It creates better access for a lot of patients depending on their limits of mobility, and this is good because it opens up possibilities for many patients*."
Satisfaction with the VR intervention	**Satisfaction:** Stroke 3: "[I liked] t*he fact that it's challenging, the fact that it's fun, the interaction are positive and uh I get to shop and I don't have to pay the bill… yeah it is really, really…4 stars are even 5 maybe… thumbs up!*" **Functional task:** Therapist 3: "*It is about function. That is a strong point*". Therapist 2: "*it is very concrete, and you can bring it back to real life*." **Realism:** Stroke 1: "*What do I like? Reality. Realism. I think that this can be considered as a strong point. And the budget too. These are the two things that I like. Because personally, I always go shopping with a budget*."

	Therapist 4: "*I liked that it was really items that you can find in a grocery store... you know, you can recognize a bag of chips. That's good*." **Level of difficulty:** Therapist 6: "*It was more difficult than what I expected, especially for the grocery shopping part. It's clear that one is not familiar with this technology*."
Aspects to improve	**Game usability:** Therapist 1: "*It is like, um, many more details on, um, elements of shopping, and you know, the* [shopping] *list is small, it does not appear all the time*." Stroke 2: *"the releasing them was difficult and you don't see them in a cart, it's not like you have a cart and you see them* [the items collected]." **Individualization:** Therapist 1: "*But there is a potential to try to improve or maybe to simplify the scene a little, so that it can be a little easier too*." **Use as an assessment tool:** Therapist 5: "*I would almost like to see something in terms of an evaluation, which I know clinically is difficult [laughs] because we can't bring them [the patients] necessarily to the store. So, you are looking at the aspect as, ok the visual scanning, the cognitive component, all the different components which are involved in real shopping and trying to put that into the store*."

Table 4.3: Outcome measures for participants with stroke

Outcome measures (n = 7)	**Mean (± SD)**
Borg Pre (6-20)	6.4 ± 0.8
Post (6-20)	6.3 ± 0.5
Number of games attempted	4.7 ± 1.3
Number of movement repetitions performed in 5 min.	
More affected arm	30.7 ± 14.6
Less affected arm	34.1 ± 22.6
Short feedback questionnaire (/30)	
Enjoyment	4.1 ± 1.6
Immersion	4.3 ± 1.1
Success	4.0 ± 1.0
Sense of control	3.9 ± 0.9
Realism	4.4 ± 1.0
Feedback	3.3 ± 1.4
Discomfort (/5)	1.1 ± 0.4
Level of difficulty (/5)	2.3 ± 1.3
Occurrence of adverse events	0

Chapter 5 – Do activity level outcome measures commonly used in neurological practice assess upper limb movement quality?

5.1 Preface

The previous study confirmed the safety and acceptability by stakeholders of a newly developed VR intervention designed to increase treatment intensity in the sub-acute phase of stroke rehabilitation. The results suggested that this salient VR intervention could be used to supplement usual rehabilitation care and target key components of experience-dependent plasticity. This VR intervention shows potential to be used in rehabilitation to simulate a grocery shopping activity while simultaneously targeting motor, cognitive and perceptual impairments for individuals with various degrees of stroke severity. Before the effectiveness of this VR intervention can be tested, there is a need to determine the appropriate outcome measures to capture subtle, yet important changes in UL movement over time for future planned intervention studies. Indeed, the evaluation and refinement of data collection procedures and outcome measures is an important step of a feasibility study (Orsmond & Cohn, 2015). The assessment of movement quality is imperative, as movement can be classified at two levels of description: the movement quality level and the motor performance level. Conducting assessment at the motor performance level in which only endpoint movements in external space are considered may provide an incomplete picture of how a person can accomplish functional tasks. The incorporation of movement quality measures in clinical assessment can provide information about how a person accomplishes a functional task, the compensatory strategies used, missing task elements and other specific deficits. It is, therefore, useful to assess movement quality in functional activities, to understand underlying motor impairments and to select the appropriate measures to determine the effectiveness of a specific intervention.

This chapter determines how and to what extent UL movement quality is assessed in clinical practice. More specifically, this manuscript presents the rationale for incorporating movement quality assessment in clinical practice and research. The extent to which current outcome measures used in neurological practice capture how UL movements are performed, at two levels of movement description (body space and external space level), is examined. Potential ways to incorporate movement quality measures into clinical assessment are suggested.

Do activity level outcome measures commonly used in neurological practice assess upper limb movement quality?

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5.2 Abstract

Background: Movement is described in terms of task-related endpoint characteristics in external space and movement quality (joint rotations in body space). Assessment of upper limb (UL) movement quality can assist therapists in designing effective treatment approaches for retraining lost motor elements and provide more detailed measurements of UL motor improvements over time.

Objective: To determine the extent to which current *Activity* level outcome measures used in neurological practice assess UL movement quality.

Methods: Outcome measures assessing arm/hand function at the ICF *Activity* level recommended by neurological clinical practice guidelines were reviewed. Measures assessing the UL as part of a general mobility assessment, those strictly evaluating body function/structure or participation and paediatric measures were excluded.

Results: Fifteen *Activity* level outcome measures were identified. Nine measures assess how movement is performed by measuring either endpoint characteristics or movement quality. However, except for the Reaching Performance Scale for Stroke and the Motor Evaluation Scale for Upper Extremity in Stroke Patients, these measures only account for deficits indirectly by giving a partial score if movements are slower or if the person experiences difficulties. Six outcome measures do not assess any parameters related to movement quality nor distinguish between improvements due to motor compensation or recovery of desired movement strategies.

Conclusion: Current *Activity* measures may not distinguish recovery from compensation and adequately track changes in movement quality over time. Movement quality may be incorporated into clinical assessment using observational kinematics with or without low-cost motion tracking technology.

5.3 Introduction

Neurological disorders, a leading cause of disability worldwide (World Health Organization, 2006) can lead to physical, psychological and cognitive impairments impacting activity and social participation (Mayo et al., 1999). One of the most common impairments in individuals with neurological disorders is upper limb (UL) paresis, characterized by muscle weakness, changed muscle tone, decreased sensation and impaired voluntary movement control resulting in slow, imprecise and uncoordinated movement (Alt Murphy et al., 2015; Cirstea & Levin, 2000; Lang et al., 2005). The use of compensatory movement patterns, especially excessive trunk displacement and shoulder elevation and abduction are also common (Cirstea & Levin, 2000; Levin et al., 2015). Following stroke, the incidence of UL impairment is estimated at ~80% (Hendricks et al., 2002; Sommerfeld et al., 2004) with residual impairments persisting into the chronic stage in more than 65% of cases despite intensive and prolonged rehabilitation (Chen & Winstein, 2009). Cervical spinal cord lesions, the most common (75%) site of spinal cord trauma, result in tetraplegia affecting arm/hand sensorimotor functions (Maynard et al., 1997; Pickett et al., 2006). UL paresis affects ~30% of individuals with traumatic brain injury (Katz et al., 1998) and 60% of individuals in the first year following the diagnosis of multiple sclerosis (Kister et al, 2013). UL motor impairment can lead to limitations in activities of daily living (ADLs), such as eating, dressing, using the phone or computer, handling medications or shopping, as well as to decreased social participation and quality of life (Desrosiers et al., 2003; Johansson et al., 2007; Mayo et al., 1999).

Recent reviews of the effectiveness of physical interventions for UL rehabilitation of individuals with stroke concur that current interventions may not be tapping in to the full potential for motor recovery (Byblow et al., 2015; Prabhakaran et al., 2007; Veerbeek et al., 2014). The consensus view is that therapies aimed at remediating specific deficits may be more successful than more general approaches such as repetition, varied practice and feedback only based on task success (Byblow et al., 2015; Stinear et al., 2012). These results may be attributed to the limited potential of current interventions to effect change and/or inadequacies of clinical outcome measures to distinguish between levels of recovery to identify improvement. For example, even if an intervention results in a significant increase in joint range, the improvement may not be noted if the outcome measure only quantifies task accomplishment not involving that range.

To identify true behavioural motor recovery (as opposed to neuronal recovery), measures should be able to distinguish between restitution of premorbid movement patterns and the use of alternative (compensatory) movement patterns during task accomplishment (Table 5.1; Levin et al., 2009). Despite this important distinction, terminology describing how movement changes is inconsistent. Movement can be classified at two levels of description that distinguish between *endpoint movement* in external space in which variables such as trajectory speed, precision, and straightness can be quantified (i.e., endpoint characteristics), and *movements in body space*, in which ranges of individual joints and segments (i.e., trunk), spatial and temporal interjoint coordination, and muscle activation patterns can be measured (i.e., movement quality variables; Levin et al., 2009). Endpoint characteristics may improve either by the use of compensations (e.g., incorporation of trunk movement to assist reaching extent) or by improvement of movements in body space. Thus, only movements in body space (i.e., movement quality variables) can distinguish whether behavioural recovery or compensation has occurred.

Outcome measures that assess movement quality may provide more information about how a person accomplishes a functional task, the compensatory strategies used, missing task elements and other specific deficits. This information can be used to guide clinical decisions about personalizing treatment to optimize motor recovery, such as how to retrain lost motor skills that limit ADL accomplishment while focusing on decreasing maladaptive motor compensations (Levin et al., 2004). In addition, movement quality assessment may help to better capture small changes in movement over time, which can be useful in determining the effectiveness of a specific intervention. However, the ability of current outcome measures at the International Classification of Function (ICF) *Activity* level to capture UL movement quality has been questioned (Jolkonen & Kwakkel, 2016; Kitago & Krakauer, 2013; Levin et al., 2004; 2009). Most UL outcome measures used in neurological practice most often quantify the degree of task completion on an ordinal scale and/or by time to perform a task without considering movement quality (Johansson & Häger, 2012).

Although movement quality may be assessed by recording movement kinematics, kinematic analysis is not widely used in clinical settings due to the high cost and complexity of recording equipment, lack of expertise and time (Kitago & Krakauer, 2013; Subramanian et al., 2010). Thus, if outcome assessment is to continue to be done using clinical scales, it is necessary to determine the extent to which UL movement quality is assessed by current measures at the ICF *Activity* level. For the purpose of this article, the terms outcome measure, assessment, clinical scale and measure are used interchangeably to indicate a method used to capture data in a standardized manner.

5.3.1 Selection of outcome measures used in neurological practice

There is no consensus as to which outcome measures best assess UL movement quality. Therefore, measures recommended by the Evidence-based Review of Stroke Rehabilitation (Salter et al., 2015) and the Academy of Neurologic Physical Therapy Outcome Measures for multiple sclerosis (Potter et al., 2013), spinal cord injury (Kahn et al., 2013), stroke (Zipp et al., 2013) and traumatic brain injury (McCullogh et al., 2013) were extracted. The Canadian Medical Association InfoBase for Clinical Practice Guidelines and the Agency for Healthcare Research Quality's National Guideline Clearinghouse databases were also searched using the key words "multiple sclerosis", "spinal cord injury", "stroke" and "traumatic brain injury" to identify additional clinical practice guidelines recommending UL outcome measures, but no additional guidelines were identified. Measures claiming to assess UL movement quality during activities and reported to be valid and reliable in a neurological population were also included. The inclusion criteria were: measures of arm or hand function at the ICF *Activity* level and developed/used in adult neurological populations. Outcome measures strictly evaluating *Body function/structure* or *Participation* levels, those only used with pediatric populations or only assessing UL function as part of a global assessment of mobility were excluded (Table 5.2). Included measures are listed in Table 5.3. This review was limited to measures at the ICF *Activity* level, since they are often used to determine if rehabilitation interventions result in changes important in daily life. To assess the effectiveness of interventions however, it is desirable to identify if changes occur due to compensation or recovery at this level. Thus, we included measures with items that assess the *Activity* level, even though some items in the scale also assessed other levels.

5.4 Assessment of *Activity* level outcome measures

Outcome measures were divided into 3 categories based on their metrics to facilitate comparisons between scales: therapist ratings based on time; therapist ratings based on a numerical scale; patient self-report measures.

5.4.1 Therapist ratings based on time

Box and Blocks (BBT): The BBT (Mathiowetz et al., 1985a) measures unimanual gross manual dexterity and is composed of a wooden box divided into 2 compartments and 150 wooden cubes. The participant grasps a cube, transports it over a partition and releases it in the opposite compartment. The absolute number of cubes transported by the affected arm from one side of the box to the other in one minute or the number relative to the non-affected arm is measured. The total score is compared to established norms (Mathiowetz et al., 1985a). The BBT has substantial floor effects in individuals without sufficient arm movement, strength and grip function to transport blocks (Salter et al., 2015).

Jebsen Hand Function Test (Jebsen): The Jebsen uses seven timed unimanual tasks to assess fine and gross motor hand function (Jebsen et al., 1969). Each item is scored as the time for task completion. For each task, times are compared to age- and gender-based norms (Jebsen et al., 1969).

Nine-Hole Peg Test (NHPT): The NHPT is one of three components of the Multiple Sclerosis Functional Composite score (Fischer et al., 1999) that tests fine manual dexterity (Mathiowetz et al., 1985b) Participants pick up and place nine wooden pegs into holes on a pegboard and remove them as quickly as possible. The total time required for the task is recorded and compared to age-and gender-specific norms (Mathiowetz et al., 1985b; Grice et al., 2003), with faster times indicating better fine manual dexterity.

5.4.2 Therapist ratings based on a numerical scale

Arm Motor Ability Test (AMAT): The AMAT was developed as a supplement to the Wolf Motor Function Test (described below) to determine the efficacy of constraint-induced movement therapy on improving ADLs (Chae et al., 2003; Kopp et al., 1997). The AMAT is designed for higher functioning individuals with stroke and measures the quality and quantity of UL movement in everyday activities. The evaluation consists of 13 ADLs with 28 subtasks. Unimanual activities are performed with the affected arm. Bimanual tasks are performed using (or attempting to use) the dominant limb in the same role as before the stroke. The AMAT includes two scores for each task: time to complete the task and functional ability. Functional ability considers the actual motor performance of the affected arm and is subjectively rated on a 6-point ordinal scale from 0=no use to 5=normal use. The instructions focus on quality rather than speed of movement, but no clear definition of movement quality is provided.

Action Research Arm Test (ARAT): The Action Research Arm Test assesses specific changes in UL activity limitations in patients with stroke (Hsueh et al., 2002). The ARAT includes 19 items divided into 4 subscales (grasp, grip, pinch and gross movement) grouped according to a hierarchical Guttman scale. Successful task completion implies that subsequent, easier tasks can also be successfully completed (Salter et al., 2015). Similarly, failure on an easier item predicts failure on all items of greater difficulty in the subscale. Items within each subtest are scored on 4-point ordinal scales ranging from 0 to 3: 0=no movement possible; 1=performs test partially; 2=completes the task, but takes abnormally long or has great difficulty; and 3=normal performance of the task. The overall score indicates task completion and is expressed as the sum of subscale scores ranging from 0 to 57. The ordinal scale does not allow tracking small changes in movement quality and does not identify or score compensations used during task completion. Based on a Rasch analysis, Chen et al. (2012) found a disordering of the ARAT threshold measure, indicating that the original four-point scale inadequately differentiates stroke severity. They also suggested a redundancy in the four rating categories since a score of 1 was infrequently used compared to other categories. The authors suggested adopting a 3-point scale: 1=can perform no part of the test or partially perform the test within 60 seconds; 2=completes test but takes an abnormally long time (5-60s) or has great difficulty; and 3=performs test normally within 5s.

Chedoke Arm and Hand Activity Inventory (CAHAI): The CAHAI is intended to complement the Chedoke-McMaster Stroke Assessment that classifies UL impairment into seven recovery stages (Barreca et al., 2004; 2006). It consists of 13 real-life functional tasks involving both ULs and incorporating a range of movements, pinches and grasps reflecting post-stroke recovery stages. Shorter versions of CAHAI are available with seven, eight or nine tasks. All tasks are scored using seven-point quantitative scales, similar to those used in the Functional Independence Measure (Keith et al., 1987). The affected limb is scored according to its positioning and contribution to the task. For individuals who are able to complete the tasks without assistance (score of >5), the scoring scale discriminates between tasks completed normally, without apparent difficulty, and those made with compensations, slower or with safety concerns.

Frenchay Arm Test (FAT): The FAT is a measure of UL gross motor function during ADL performance in patients with neurological disorders (De Souza & Hewer, 1980). The FAT includes 5 tasks completed with the affected arm. Each item is scored as either 'pass=1' or 'fail=0' with total scores ranging from 0 to 5. The FAT measures task accomplishment without accounting for movement quality.

Motor Evaluation Scale for Upper Extremity in Stroke Patients (MESUPES): Unlike the other scales, the stated aim of MESUPES is to measure arm and hand movement quality in individuals with stroke (Johansson & Häger, 2012; Van de Winckel et al., 2006). The MESUPES focuses on "normal" performance, defined as "movements that are painless, made without tremor, and executed with a normal range of motion using adequate muscle contraction and orientations of various body segments". Thus, consistent with our definition, movement quality is assessed by identifying whether a normal range of motion of specific joints occurs. The scale includes 17 items divided in 2 subscales with 6 and 3 response categories for arm and hand function respectively. For the arm subscale, movements are performed in 3 consecutive phases: 1) the therapist moves the arm passively to evaluate muscle tone (scores 0-1), 2) the therapist assists the patient during the movement and evaluates the active contribution through normal muscle contraction (score 2), and 3) the patient performs the task and the therapist evaluates the range of active motion (score 3-5). For hand function (MESUPES-hand test), patients are instructed to actively perform specific hand and finger movements. Range of motion and hand orientation are both scored on 3-point scales. For both subscales, compensations are partially taken into account by giving a score of '0' when there is inadequate tone, abnormal muscle contractions, synergic (flexor/extensor) or mass movement patterns.

Reaching Performance Scale for Stroke (RPSS): The RPSS was designed to address the gap in current outcome measures in assessment of movement quality (Levin et al., 2004). This 6-item measure quantifies movement patterns and compensations on 4-point scales (0-3), used when reaching to grasp a cone located close to and far from the body. Movement components evaluated are: trunk displacement, endpoint movement smoothness, shoulder movements (e.g.: shoulder flexion and horizontal adduction with scapular elevation), elbow movements (e.g.: extension), quality of prehension, and global task performance. The first five items identify deficits in specific aspects of the movement. The global task performance item scores task accomplishment based on the presence or absence of compensatory strategies. The 6 task scores are summed for a total score of reaching performance ranging from 0 to 18 for each target distance.

Sollerman Hand Function Test (Sollerman): The Sollerman was designed to assess hand function and handgrips needed for 20 ADL subtests (Sollerman & Ejeskär, 1995). Most subtests are unimanual tasks. Scoring accounts for the time taken, the level of difficulty and the quality of performance based on the observed use of a correct pinch or grip position. Each subtest is scored on a 5-point scale from 0 (task cannot be performed at all) to 4 (task is completed without any difficulty within the time frame and with the prescribed handgrip of normal quality). Examples of prescribed handgrips are provided for each task to facilitate scoring. The maximal score is 80 obtained by summing scores of the 20 subtests. Scoring the Sollerman is reportly challenging as the assessor must be aware of multiple factors occurring simultaneously (e.g., passage of time, difficulty, correct positioning and quality of performance; Spinal Cord Injury Research Evidence, 2010).

Test d'Évaluation des Membres supérieurs des Personnes Âgées (TEMPA): The TEMPA evaluates 4 unimanual and 5 bimanual tasks related to routine daily activities in individuals over the age of 60 (Desrosiers et al., 1995). Although not specifically designed for individuals with neurological disorders, it has been validated in patients with stroke and multiple sclerosis (Feys et al., 2002). Normative values for execution time are available for people aged between 45-59 years old (Desrosiers, 2002). Three sub-scores evaluate each task: speed of execution, functional rating and task analysis. Speed of execution measures the time taken to complete the task. The functional rating grades the level of autonomy on a 4-level ordinal scale: 0 = task was performed successfully and easily without hesitation; -1 = task completed with some difficulty; -2 = significant difficulty in performing the task, trial-and-error or partial completion of the task; -3 = unable to complete the task despite some assistance. Task analysis identifies and quantifies difficulties encountered during the task by rating five categories on four-point scales: range of movement, strength, control of gross movement, prehension patterns and fine movement.

Wolf Motor Function Test (WMFT): The WMFT was originally developed to qualify the effects of constraint-induced movement therapy in individuals with mild to moderate stroke (Wolf et al. 2001). The WMFT consists of 2 strength-based and 15 function-based tasks, arranged in order of complexity, used to assess UL impairments and activity limitations. Task progression is based on proximal to distal joint involvement (Wolf et al., 2001). Performance is scored both on task completion time and on 6-point ordinal scale (0 =does not attempt with involved arm to 5=arm does participate and movement appears normal), rating the ability to perform the task as well as the presence of synergies influencing movement, required effort, movement speed, precision, fluidity and fine coordination.

5.4.3 Patient self-report measures

ABILHAND: The ABILHAND is a semi-structured questionnaire measuring manual ability according to an individual's perceived difficulty to perform 23 bimanual tasks representing a wide range of complex daily activities (Penta et al., 1998; 2001). Patients rate their perceived level of difficulty on 3-point scales (0=impossible, 1=difficult and 2=easy) when activities are done without help, irrespective of the limb(s) or strategies used. Scoring allows compensation, assistive equipment or the use of the unaffected limb. The ABILHAND was developed using the Rasch measurement model. Task scores are entered into the WINSTEPS computer program, where the ordinal raw score is converted to a linear measure expressed in logits (a linear unit that expresses the patient's odds of success on any given task). The center of the scale is set to 0 logit, whereby higher logit numbers indicate more perceived ability (Gustafsson et al., 2004).

Capabilities of Upper Extremity Instrument (CUE): CUE is a self-report measure assessing UL functional limitations in individuals with tetraplegia (Marino et al., 1998; Oleson & Marino, 2014). The revised version consists of 15 items scored separately for each arm and 2 bimanual tasks. Tasks focus on the ability to reach or lift, pull/push a light/heavy object, move and position the arm and wrist, use the hands and fingers, and press with the index finger. Perceived difficulty is rated by patients on 5-point scales from 0 (unable/complete difficulty) to 4 (no difficulty). The instructions ask respondents to think about the specific part of the arm or hand asked about in each question.

Motor-Activity Log (MAL): The MAL is a semi-structured interview assessing how much (Amount of Movement Scale) and how well (Quality of Movement scale) individuals use their more-affected arm outside of the clinical setting (Taub et al., 1993). Different versions include 14, 28 or 30 daily functional tasks (Uswatte et al., 2005; 2006). The Motor Activity Tasks include object manipulation and arm use during gross motor activities (e.g. transferring to a car or getting up from a chair). Each section is scored on 6-point scales ranging from 0='never use' to 5='same as pre-stroke'. Individuals may also select scores halfway between the anchors. The Quality of Movement scale rates how well the more affected arm contributes to the task and also captures if movements are slower, less accurate or require more effort.

5.5 Analysis of the degree to which clinical scales assess movement quality

Out of the 15 *Activity* level outcome measures identified, 9 assess how movement is performed by measuring either endpoint characteristics or movement quality: AMAT, ARAT, CAHAI, MAL, MESUPES, RPSS, Sollerman, TEMPA and WMFT. Among those measures, the RPSS is the only one that assesses both endpoint characteristics and movement quality, as well as the presence of compensatory movements. Unlike other measures, the RPSS quantifies how arm joints, trunk and hand are used during reaching tasks, and directly quantifies compensatory movements based on observational kinematics. The MESUPES also primarily assesses movement quality by considering how similar the movement is to premorbid movement patterns and the presence of compensatory movements, but does not assess endpoint characteristics. The seven other measures (AMAT, ARAT, CAHAI, MAL, Sollerman, TEMPA and WMFT) account to some extent for how movements are performed and attempt to capture the consequences of diminished endpoint characteristics and movement quality, but deficits are quantified only indirectly by giving a partial score if movements are slower or if difficulties are experienced. Specifically, AMAT and WMFT score tasks according to task accomplishment (time) while accounting for movement strategies. By rating performance in five categories (range of movement, strength, control of gross movement, prehension patterns and fine movement), TEMPA also identifies and quantifies difficulties encountered during the task. However, these measures use a summary task score or only rate global task performance, limiting their sensitivity to identify improvements in specific movement patterns (McCrea et al., 2002).

Six outcome measures do not assess parameters related to movement quality and do not distinguish between improvements due to motor strategies or those related to the presence of compensatory strategies. These include measures based on time (BBT, Jebsen and NHPT), two of the self-report measures (ABILHAND and CUE) and FAT. Outcome measures based on time assume that decreases in movement speed are due to UL impairments, but this assumption has not been kinematically validated (Rodrigues et al., 2017). While speed of execution is a good indicator of UL ability, it provides no information about movement quality, difficulties encountered or why more or less time may have been needed (Desrosiers et al., 1993). For example, an improvement in score may be based on the increased use of compensatory strategies rather than a decrease in UL impairments (Cirstea & Levin. 2000; Michaelsen et al., 2001). In particular, during a reaching movement, patients with stroke who used more trunk compensations made faster reaching movements than patients who used movement patterns more similar to those used by healthy individuals (Cirstea & Levin. 2000; Michaelsen et al., 2001). For self-report measures, an important barrier to movement quality assessment is the individual's subjective perception especially for patients with cognitive and/or communication difficulties that frequently occur after neurological injury (Ali et al., 2015; Douiri et al., 2010). Actual performance can be overestimated or underestimated, depending on motivation and cognitive ability (Penta et al., 2001). For example, Woodbury *et al.* (2008) noted some discrepancies between movement quality measured with kinematic analysis compared to the patients' self-perception. Patients who were asked to rate their performance did not perceive changes in movement quality despite significant objective improvements in arm movements, faster accomplishment of functional tasks, straighter hand trajectories and decreased trunk displacement.

5.6 Limitations

This review focuses only on ICF *Activity* level outcome measures specific to the UL. Therefore, common *Impairment* level outcome measures that arguably measure some elements of movement quality were excluded. Furthermore, the selection of outcome measures was based on national clinical practice guidelines from Canada and the United-States. There may have been relevant outcome measures recommended in guidelines from other countries that were not included. This review did not focus on the clinical utility of the outcome measures (e.g.: time of administration, availability), which may influence their selection in clinical practice.

5.7 Conclusion

We identified several UL outcome measures at the ICF *Activity* level that distinguish between motor recovery and compensation as defined in the motor skill acquisition and motor control literature (Levin et al., 2009). This is new information, as most previous reviews on UL outcome measures have primarily focused on psychometric properties and/or clinical feasibility (see Alt Murphy et al., 2015). While the systematic review by Lemmens et al. (2012) categorized outcome measures for individuals with stroke and cerebral palsy, the concept of movement quality was not defined and was rated subjectively on a yes/no basis, making the validity of the results questionable.

This review highlights an important problem with outcome measures used in neurological practice. Outcome measures that do not assess endpoint characteristics and movement quality are limited in their ability to track changes over time, distinguish compensation from recovery and identify specific motor impairments. Those that do assess these two levels of behaviour, such as the RPSS, can help clinicians by providing complementary information about functional performance measured on other UL activity scales. This review can help guide clinicians in the selection of outcome measures to better assess motor recovery and treatment effectiveness. As an alternative to using laboratory-based kinematic analysis, observational kinematics is an easy and low-cost approach to the assessment of UL movement in clinical practice. Observational kinematics consists of the assessment of body motions by an observer, in the absence of objective quantification using sophisticated technology (i.e., motion analysis systems). The evaluator can assess kinematics by observing the individual perform a task and rating the performance (e.g., movement speed, smoothness, hand path directness) and or movement quality (e.g., joint/segment movement) with a rating system (e.g., numerical or visual analogue scale). Bernhardt *et al*. (1998) found that physical therapists could make moderately to highly accurate judgments about the characteristics of endpoint and joint movements for a given task. Observation of kinematics may also allow clinicians to make inferences about UL impairments, such as joint contractures or spasticity, that may interfere with movement (Levin et al., 2004). Advances in low-cost markerless motion capture technology (Microsoft Kinect II, Washington, USA) also show promise for clinical assessment of UL movement quality during the accomplishment of everyday life tasks (Adams et al., 2015; Ozturk et al., 2016).

Future research should focus on developing better outcome measures with strong psychometric properties to assess UL endpoint characteristics and movement quality during varied and meaningful ADLs, preferably done in real-life settings or in the patient's own environment. It is anticipated that options for assessing UL movement quality will also expand with the development of new technology, making kinematic motion analysis more accessible to clinical practice. Incorporating more information about movement quality and use of compensatory strategies will allow clinicians to provide more individualized treatment by targeting key elements limiting motor recovery in individuals with neurological disorders.

Table 5.1: Definition of behavioural recovery and compensation according to the International Classification of Functioning model

(Adapted from Table 1 in Levin et al., 2009)

Levels	**Recovery**	**Compensation**
Body function/structure	Restoration in the ability to perform a movement in the same manner as it was performed before injury, which may occur through the reappearance of premorbid movement patterns during task accomplishment (voluntary joint range of motion, temporal and spatial interjoint coordination, etc.)	A new manner of performing an old movement, which may be seen as the appearance of alternative movement patterns (i.e., recruitment of additional or different degrees of freedom, changes in muscle activation patterns such as increased agonist/antagonist coactivation, delays in timing between movements of adjacent joints, etc.) during the accomplishment of a task
Activity	A successful task accomplishment using limbs or end effectors typically used by nondisabled individuals	A successful task accomplishment using alternate limbs or end effectors

Table 5.2: List of outcome measures excluded in this article

Excluded outcome measure	**Reasons for exclusions**
Ashworth Scale or Modified Ashworth Scale	Strictly evaluating Body function/structure
Chedoke McMaster Stroke Assessment	Strictly evaluating Body function/structure
Frenchay Activity Index	Evaluating participation
Fugl-Meyer Assessment	Strictly evaluating Body function/structure
Graded Redefined Assessment of Strength, Sensibility and Prehension	Strictly evaluating Body function/structure, recommended only in the chronic phase
Grasp and Release Test	Not recommended
Hand-Held Myometer	Strictly evaluating Body function/structure
Kinematics	Not commonly used in clinical practice due to high cost and expertise required[20,22]
Motor Assessment Scale	Global Assessment of Mobility
Motricity Index	Global Assessment of Mobility
Movement Ability Measure	Strictly evaluating Body function/structure; not recommended
Rivermaid Mobility Index	Global Assessment of Mobility
Stroke Rehabilitation Assessment Movement	Global Assessment of Mobility
Semmes Weinstein Monofilaments	Strictly evaluating Body function/structure
Tardieu Spasticity Scale	Strictly evaluating Body function/structure
Tetraplegia Hand Activity Questionnaire	Not recommended

Toronto Rehabilitation Institute Hand Function Test	Not recommended

Table 5.3: Outcome measures used to assess upper limb function at the activity level in neurological practice

Outcome measure	**Population**	**ICF level of the UL items**		**Assessed construct**	**Main Outcome**	**# of items**	**Assessment of movement quality**	**Examples of tasks**	**Psychometric properties***
		Body Function/ Structure	**Activity**						
Therapist rating of performance time									
BBT	Multiple Sclerosis, Traumatic Brain Injury, Stroke, Neuromuscular Disorders, Spinal Cord Injury, Fibromyalgia	x	x	Unimanual gross manual dexterity	Number of blocks transported in 60 sec.	1	No consideration of how movement is performed	Moving small blocks	Convergent validity: correlation with ARAT (r=0.95), FMA (r=0.92) and Hemispheric Stroke Scale (r=-0.67; Platz et al., 2005) Test-retest reliability: r=0.93-0.98 (Chen et al., 2009) Inter-rater reliability: ICC=0.99 for UL paresis (Platz et al., 2005)
Jebsen	Spinal Cord Injury, Stroke, Traumatic Brain Injury		x	Fine and gross motor hand function	Time	7	No consideration of how movement is performed	Writing a sentence, Card turning, Lifting small objects,	Concurrent validity: correlation with grip strength (r=0.79-0.81), pinch strength (r=0.60-0.79), ARAT (r=0.87-0.95), NHPT (r=0.84-0.97) and SIS-Hand function domain (r=0.61-0.83; Beebe & Lang, 2009)

								Simulated feeding, Stacking checkers, Picking up light and heavy cans	Internal consistency: Cronbach's alpha = 0.63-0.90 (Ferreiro et al., 2010) Test-retest reliability: r=0.92 (Beebe & Lang, 2009) Inter-rater reliability: ICC=0.82-1.00 (Hackle et al., 1992) Intra-rater reliability: r=0.84, 0.85 (Hackle et al., 1992)
NHPT	Brain Injury Stroke Parkinson's Disease	x	x	Fine manual dexterity	Time	1	No consideration of how movement is performed	Placing and removing wooden pegs into a board	Concurrent validity: correlation with SIS-Hand function domain (ρ=0.58-0.66), BBT and ARAT (ρ=-0.55 to -0.80), FMA and MAL (ρ=-0.16 to -0.33; Lin et al., 2010) Construct validity: correlation with Motricity Index (r=0.82; Parker et al., 1986) Test-retest reliability: ICC=0.64–0.86 (Chen et al., 2009) Interrater reliability: r=0.75-0.99 (Heller et al., 1987) Intrarater reliability: r=0.68-0.99 (Heller et al., 1987)
Therapist rating of performance quality									
AMAT	Stroke		x	UL function	Time 6-point ordinal scale	28 (13 ADLs)	Endpoint movement: speed, precision, smoothness; Movement in body space: muscle	Unimanual tasks: Eating with a spoon, Drinking from a mug Combing hair Bilateral tasks: Opening a jar,	Concurrent validity: correlation with the Motricity-Index-Arm (r=0.45-0.61; Kopp et al., 1997) and FMA (r=0.92-0.94; Chae et al., 2003) Construct validity: correlation with WMFT, FMA, and ARAT (r=0.78-0.79; O'Dell et al., 2013) Internal consistency: Cronbach's alpha: 0.93 (O'Dell et al., 2013)

							activation patterns	Tying a shoelace Putting on a cardigan	Test-retest reliability: ICC=0.93-0.99 (Kopp et al., 1997) Inter-rater reliability: ICC=0.95-0.99 (Kopp et al., 1997) Intra-rater reliability: ICC=0.94-0.97 (Kopp et al., 1997)
ARAT	Stroke Multiple Sclerosis Traumatic Brain Injury	x	x	UL activity limitations	4-point ordinal scale	19	Endpoint performance: speed	Grasp and lift items, Grip, Pinch, Gross arm movements	Concurrent validity: correlation with FMA (r=0.94; Yozbatian et al., 2008) Internal consistency: Cronbach's alpha=0.99 (Nijland et al., 2010) Test-retest reliability: ICC=0.89-0.97 (Platz et al., 2005) Inter-rater reliability: ICC=0.92-0.99 99 (Nijland et al., 2010; Van der Lee et al., 2001) Intra-rater reliability ICC=0.99 (Van der Lee et al., 2001)
CAHAI	Upper Extremity Paresis		x	Arm and hand recovery	7-point ordinal scale	7-13	Endpoint performance: speed	Open coffee jar, Call 911, Draw line with ruler, Pour glass of water, Wring out washcloth, Button short, Dry back with towel,	Construct validity: correlation with ARAT (r=0.94-0.95), and Chedoke-McMaster Stroke Assessment (r=0.84-0.85; Barreca et al., 2006) Internal consistency: Cronbach's alpha=0.97-0.98 (Barreca et al., 2004; 2006) Inter-rater reliability: ICC=0.98 (Barreca et al., 2005)

								Put toothpaste on toothbrush	
FAT	Neurological disorders		x	UL gross motor function	Pass-fail score (2-point scale)	5	No consideration of how movement is performed	Stabilize a ruler to draw a line, Grasp a cylinder, Drink from a glass, Place clothes pin on a dowel, Comb hair	Inter-rater reliability: r=0.75-0.99 (Heller et al., 1987) Intra-rater reliability: r=0.68-0.99 (Heller et al., 1987)
MESUPES	Stroke	x	x	UL quality of movement	Arm: 6-point ordinal scale Hand: 3-point ordinal scale	17	Endpoint performance: speed; Movement in body space: muscle activation patterns, range of motion	Reach for a plastic bottle, Grasp a bottle or a dice, Range of motion	Concurrent validity: correlation with Modified Motor Assessment Scale (ρ=0.80-87; Johansson & Häger, 2012) Internal consistency: person separation index =0.97-0.99 (Van der Winckel et al., 2006) Inter-rater reliability: ICC=0.95-0.97 (Van der Winckel et al., 2006)

RPSS	Stroke	x	x	Movement patterns and compensations during reach-to-grasp tasks	4-point ordinal scale	2	Endpoint performance: smoothness, straightness; Movement in body space: range of motion, interjoint coordination	Reaching to grasp an object located close to and far from the body	Content validity: correlation with FMA (r=0.87) and Composite Spasticity Index (r=0.75) Concurrent validity: correlation with FMA for close target (r=0.91-0.92) Test-retest reliability: ICC=0.98 Inter-rater reliability: ICC=0.58-0.95 (Levin et al., 2004; Subramanian et al., 2016)
Sollerman	Spinal Cord Injury Stroke		x	Hand function and handgrips	5-point ordinal scale	20	Endpoint performance: speed; Movement in body space: range of motion	Using a key, Picking up coins from a flat surface, Writing with a pen, Using a phone, Pouring water from a jug	Convergent validity: correlation with the International Classification for Surgery of the Hand in Tetraplegia (r=0.88) and the Motor Capacities Scale (r=0.96; Sollerman & Ejeskär, 1995; Fattal, 2004) Concurrent validity: correlation with visual analogue scale ratings of hand function (r=0.68; Sollerman & Ejeskär, 1995) Test-retest reliability: ICC=0.96-0.98 (Brogardh et al., 2007) Inter-rater reliability: ICC=0.92-0.98 (Sollerman & Ejeskär, 1995; Fattal, 2005; Brogardh et al., 2007) Intra-rater reliability: ICC=0.96-0.99 (Brogardh et al., 2007)

TEMPA	Geriatric Multiple sclerosis Stroke		x	UL function	Time Two 4-point scales Functional rating Task analysis	9	Movement in body space: range of motion, interjoint coordination	Pouring water from a pitcher into a glass, Shuffling and dealing card, Putting a scarf around one's neck	Construct validity: correlation with Functional Autonomy Measurement System (r=0.45-0.74), FIM (r=0.46-0.52), ADL self-questionnaire (r=-0.46 to -0.48; Feys et al.,2002) and FMA (r=-0.85 to -0.86; Michaelsen et al., 2008) Concurrent validity: correlation between TEMPA speed of execution and Jebsen (r=0.81-0.87), and NHPT (r=0.81-0.90; Feys et al., 2002) Test-retest reliability: ICC=0.70-0.98 (Desrosiers et al., 1993) Inter-rater reliability: ICC=0.94-0.97 (Michaelsen et al., 2008)
WMFT	Stroke Traumatic Brain Injury	x	x	UL function	Time 6-point ordinal scale Functional Ability Score	17	Endpoint movement: speed, precision, smoothness; Movement in body space: muscle activation patterns	Reach, Lift pencil, Stack checkers, Flip cards, Turn key in lock, Fold towel	Concurrent validity: correlation with FMA (r=-0.57 to -0.88; Wolf et al., 2001; Whitall et al. 2006), ARAT and WMFT Functional Ability Score (r=0.86; Njiland et al., 2010) Internal consistency: Cronbach's alpha=0.92-0.98 (Njiland et al., 2010; Morris et al., 2001) Test-retest reliability: ICC=0.90-0.99 (Whitall et al. 2006; Morris et al., 2001) Inter-rater reliability: ICC=0.93-0.99 (Wolf et al., 2001; Morris et al., 2001)
Patient self-report measures of performance quality									
ABIL HAND	Stroke, Adults with UL		x	UL function	3-point ordinal scale	23	No consideration of how	Peel potatoes with knife,	Concurrent validity: correlation with Jamar handgrip (r=0.38-0.56), BBT (r=0.48-0.60), Purdue pegboard (r=0.50) and NHPT (r=-0.37)

	impairments						movement is performed	Sharpen pencil, Spread butter on slice of bread, Pull up trouser zipper	Internal consistency: person separation reliability=0.90, item reliability index =0.94, Cronbach's alpha=0.99; All items of ABILHAND fit the Rasch model (Penta et al., 2001; Simone et al., 2011)
CUE	Spinal Cord Injury		x	UL function	5-point ordinal scale	32	No consideration of how movement is performed	Reach or lift, Pull/push a light/heavy object, Press with the tip of the index finger	Concurrent validity: correlation with FIM (ρ=0.80), Upper Extremity Motor score (ρ=0.80), Graded Redefined Assessment of Strength, Sensibility and Prehension (ρ=0.76-0.83; Marino et al., 1998; Kalsi-Ryan et al., 2012) Internal consistency: Cronbach's alpha=0.96 (Marino et al., 1998) Test-retest reliability: ICC=0.94 (Marino et al., 1998)
MAL	Stroke		x	Quality and amount of movement during daily functional tasks	6-point ordinal scale	14-30	Endpoint movement: speed, precision	Object manipulation (glass, cup, fork, comb), open a drawer, pick up phone, turn door knob, use TV remote, transfer to a car, steady oneself in standing, pull chair into table while sitting	Concurrent validity: MAL 28 and ARAT (r=0.63), MAL 28 Quality of Movement scale and SIS Hand Function scores (r=0.72; Uswatte et al, 2005), MAL 14, MAL 28 and accelerometry (r=0.52-0.91; Uswatte et al., 2005; Van der Lee et al., 2004) Internal consistency: MAL 14 Amount of use scale: Chronbach alpha=0.88-0.91, MAL 14 Quality of use scale: Chronbach alpha>0.81 (Uswatte et al., 2006; Van der Lee, 2004) Test-retest reliability: Amount of use scale: r=0.70-0.85, Quality of use scale: r=0.61-0.91 (Uswatte et al., 2006; Van der Lee, 2004)

Abbreviations: AMAT: Arm Motor Ability Test; ARAT: Action Research Arm Test; BBT: Box and Block; CAHAI: Chedoke Arm and Hand Activity Inventory; CUE: Capabilities of Upper Extremity Instrument; FAT: Frenchay Arm Test; FIM: Functional Independence Measure; FMA: Fugl-Meyer Assessment; ICC: Inter-correlation coefficient; Jebsen: Jebsen Hand Function Test; MAL: Motor-Activity Log; MESUPES: Motor Evaluation Scale for Upper Extremity in Stroke Patients; NHPT: Nine-Hole Peg Test; RPSS: Reaching Performance Scale for Stroke; SIS: Stroke Impact Scale; Sollerman: Sollerman Hand Function Test; TEMPA: Test d'Évaluation des Membres supérieurs des Personnes Âgées; WMFT: Wolf Motor Function Test; ρ: Spearman rank correlation coefficient

***Legend:** interpretation of the magnitude of the correlation coefficient: <0.25 indicate low, 0.25 to 0.5 indicate fair, 0.5 to 0.75 indicate moderate to good, and >0.75 indicate good to excellent.[70]

Chapter 6 - Kinematic validity of a low-cost 2D virtual environment for arm rehabilitation in stroke

6.1 Preface

The previous chapter identified the importance of incorporating movement quality measures in clinical assessment to identify underlying motor impairments. However, it also highlighted an important limitation of commonly used outcome measures: most outcome measures poorly capture how well a person moves or the compensatory strategies used. Therefore, most UL measures lack the sensitivity to assess small changes over time and discriminate compensation from recovery. Based on the results obtained in manuscript in Chapter 5, one outcome measure stands out as being able to describe movement at both the body space and the external space levels, while also considering the use of maladaptive compensatory movements, namely the Reaching Performance Scale for Stroke (RPSS). This review also emphasized the importance of using kinematic measures to objectively assess UL movements in functional tasks. Future intervention studies looking at the effectiveness of VR interventions for stroke rehabilitation should incorporate measures, such as the RPSS and/or kinematic analysis to capture significant changes in functional performance. Therefore, the structured review presented in Chapter 5 provided useful information for the selection of UL outcome measures used in the study presented in Chapter 6. It can also help guide the selection of outcome measures in future randomized control trials on the effectiveness of using VR intervention for stroke rehabilitation.

Towards the overall aim of the thesis to determine the feasibility of incorporating a VR-based intervention for stroke rehabilitation, the manuscript in Chapter 4 assessed the acceptability and safety of the intervention for individuals in the sub-acute phase of stroke recovery. Chapter 5 informed the selection of outcome measures for future intervention studies. The manuscript in Chapter 6 assesses the validity of movements performed in the

VR application. More specifically, the kinematics of natural, goal-oriented daily tasks performed in the VE and a similar PE are compared in healthy individuals and in individuals who have had a stroke with and without visual perceptual impairments. Deficits in visual perception may limit the ability to extract and process salient information or recover missing visual cues to produce appropriate motor actions in individuals who have had a stroke (Levin et al., 2014). Therefore, the impact of visual perceptual impairments on motor performance and movement quality is also assessed.

Kinematic validity of a low-cost 2D virtual environment for arm rehabilitation in stroke

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6.2 Abstract

Background: Increasing evidence supports the use of virtual reality for upper limb rehabilitation following a stroke. However, movement performance and quality may be altered by the different attributes of the virtual environments, which may be detrimental to motor relearning. The aim of this study was to determine whether upper limb movements made in a low-cost 2D virtual environment were kinematically similar to those made in a comparable physical environment. We compared upper limb movements made by healthy subjects and by stroke subjects with and without visual perceptual impairments.

Methods: Healthy participants (n=15) and individuals with mild-moderate arm paresis after a stroke (n=22) made unimanual and bilateral reach-to-grasp movements in a 2D virtual and a physical environment. The virtual environment represented a grocery store and arm and trunk movements were tracked using a Kinect II camera. Arm and trunk kinematics in both environments were recorded with an optoelectronic motion analysis system (23 markers; 120 Hz). Temporal and spatial characteristics of the endpoint trajectory and arm and trunk movement patterns were compared between environments and groups. How movements were altered due to visual perceptual impairments was investigated.

Results: In each group, movement speed, hand positioning at object contact time and trunk displacement were unaffected by the environment. Compared to the physical environment, in the virtual environment, unimanual reach-to-grasp movements were less smooth and time to peak velocity was prolonged. These differences were more pronounced in individuals with stroke. In the virtual environment, healthy individuals made straighter endpoint trajectories, whereas individuals with stroke used more shoulder flexion. Bilateral movements in healthy subjects were simultaneous and symmetrical in both environments. In contrast, movements in stroke subjects tended to be less simultaneous at time to peak velocity in the physical environment and were less symmetrical in the virtual environment at time of object grasping. Greater visual perceptual impairment in stroke subjects was related to longer movement times and times to peak velocity in the virtual but not in the physical environment, but did not affect any other aspects of unimanual or bilateral grasping.

Conclusions: Despite differences in the temporal structure of endpoint displacement for unimanual movement between environments, spatial endpoint variables and most movement quality variables in the 2D virtual environment were similar to those in a comparable physical environment in healthy participants and individuals post-stroke with and without visual perceptual impairments. The results suggest that using a low-cost 2D virtual environments may be a valid approach for sensorimotor rehabilitation following a stroke.

6.3 Introduction

Stroke is a complex and multifaceted medical condition, affecting approximately 2.7% of Canadians every year (Government of Canada, 2017). The prevalence of arm paresis, one of the most frequent impairments following a stroke, is estimated at 80% (Chen & Winstein, 2009; Hendricks et al., 2002). Visual perceptual impairments are also frequent with up to 76% of cases (Edmans & Lincoln, 1989). In recent years, continuing advances in virtual reality (VR) technology have supported its development for sensorimotor rehabilitation following stroke. When used as a therapeutic modality, VR can deliver high training intensity (repetitions, duration, level of difficulty), and can increase motivation and engagement of the learner, all factors that have been associated with experience-dependent neuroplasticity (Burridge & Hughes, 2010; Fluet & Deutsch, 2013; Kleim & Jones, 2008). VR can also provide a rich, multi-modal and stimulating environment shown to be important for motor learning in stroke rehabilitation. Task difficulty and feedback provision can also be tailored to offer individualized treatment (Burke et al., 2009; Holden, 2005; Weiss et al., 2009).

However, upper limb kinematics have been reported to be altered in some virtual compared to physical environments (Marathe et al., 2008; Subramanian & Levin, 2011; Thomas et al., 2016; Ustinova et al., 2010). This may be due to differences in the viewing environment or in the quality of motion tracking (Tao et al., 2013; Kenyon and Ellis 2014). Altered kinematics may be detrimental to motor retraining, as it may lead to maladaptive movements and limit functional recovery (Jones, 2017). In order for VR applications to be used for sensorimotor training in individuals with stroke, therefore, it is crucial to ensure that movements that are performed in a virtual environment (VE) are similar to those performed in real-life settings.

Motor planning and execution are guided by the perception of objects, the environment and the goal of the intended task (Gibson, 1954; Mark et al., 1997), a concept known as perception-action coupling. In VEs, perception-action coupling may be altered by differences in the viewing environment compared to the three-dimensional (3D) real-world. The different attributes of the VE, such as the resolution of the display medium, the viewer's perspective, and the co-existence of physical and virtual objects, can disrupt perception-action coupling (Kenyon & Ellis, 2014). This is especially true in low-cost two-dimensional (2D) VEs more commonly used in rehabilitation settings. To perceive the distance of an object in a 2D VE, a person needs to rely on the detection and the simultaneous use of multiple visual cues and the exploitation of predictive hypotheses about the possible ways to interact with an object (Gregory, 1980; Mon-Williams & Bingham, 2008). The viewing environment and the paucity of visual cues in the 2D VE can lead to difficulty with depth perception and uncertainty about object location. The differences between VE and PE may be exacerbated in individuals with visual perceptual impairments. This may limit their ability to extract and process salient information, to make visuo-motor transformations and make predictive hypotheses about object location in order to produce appropriate motor actions (Arbib, 1981; Bolognini et al., 2016). In addition, for bilateral symmetrical actions, perceptual and motor impairments may be enhanced in VEs and limit the ability to execute coordinated movements (Kantak et al., 2017).

To minimize problems in perception-action coupling in 2D environments, most game-like VR platforms offer an enriched 2D environment where depth perception is enhanced via cognitive and sensory cues mimicking stereovision (Ooi et al., 2001). Despite these efforts, the kinematic validity of movements performed in 2D VEs has been questioned. Another limitation of low-cost VR systems is the reduced accuracy of motion capture systems used for movement tracking movements. For example, Tao et al. (2013) found an average error of 6.3 cm in the accuracy of arm endpoint tracking using the Kinect II camera (Microsoft, Redmond, WA, USA). Inaccuracies have also been reported for tracking movements in the frontal and sagittal planes, and for other small movements (Chang et al., 2012; Huber et al., 2015; Li et al., 2015).

Most validity studies have compared motor performance and quality between 3D VEs and physical environments (PE; Chen et al., 2014; Knaut et al., 2009; Kuhlen et al., 2000; Levin et al., 2015; Lin & Woldegiorgis, 2018; Magdalon et al., 2011; Schafer & Ustinova, 2013;

Wang et al., 2011). For example, Knaut et al. (2009) compared kinematics of reaching to six targets in a 3D VE viewed through a head-mounted display and a similar PE, in healthy participants and in individuals with stroke. Reaching movements in VE made by healthy subjects were 35% slower than those made in PE to all targets, but ranges of motion were similar between environments. In individuals with stroke, movements performed in the VE were less accurate, more curved and less trunk displacement was used. In another study, reaching and grasping movements done while sitting in subjects with stroke were compared between a 3D VE providing haptic feedback and a physical environment. In the VE, reaches were more segmented and slower. However, arm and trunk kinematics were similar between environments (Levin et al., 2015). When reaching kinematics in a PE and in a 2D video-capture VE were compared, individuals with stroke made slower, shorter and less accurate movements in the VE. Moreover, overall movement quality was affected by the VE (Liebermann et al., 2012). These studies and others suggest that endpoint performance and joint kinematics are affected by the quality of the viewing environment (Marathe et al., 2008; Subramanian & Levin, 2011; Thomas et al., 2016; Ustinova et al., 2010). A limitation of current validity studies is that they focused only on unimanual reaching and grasping movements performed in sitting, mostly in 3D VEs, with multimodal sensory cues. Furthermore, the potential role of visual perceptual impairments is not well-understood. Understanding the limitations of VEs as training environments for upper limb sensorimotor recovery and who can benefit from using VEs for effective sensorimotor rehabilitation is crucial for deciding how and when to apply this technology (Kenyon & Ellis, 2014).

The first objective was to determine whether functional unimanual and bilateral reach-to-grasp movements made while standing are kinematically similar when performed in a low-cost 2D VE and a comparable PE, in individuals who have had a stroke and in healthy individuals. The second objective was to determine whether motor performance and movement quality variables in both environments are affected by visual perceptual deficits in individuals who have had a stroke. For unimanual reach-to-grasp movements, it was hypothesized that 1) Endpoint performance variables and hand orientation would be affected by the viewing environment in both groups; 2) Differences in endpoint and hand orientation variables would be greater in individuals with stroke than healthy individuals; 3) Endpoint and hand orientation variables would be correlated with visual perceptual impairments in the stroke group; 4) For bilateral reach-to-grasp, arm movement symmetry and synchronicity would be affected in VE in both groups. Preliminary results have appeared in abstract form (Demers & Levin, 2018).

6.4 Methods

6.4.1 Design

The study complied with STROBE reporting guidelines (Von Elm et al., 2014) and used a cross-sectional design.

6.4.2 Participants

Individuals with mild-moderate hemiparesis following a unilateral stroke (from 1 month to 5 years post-stroke) and healthy, right-handed individuals (control) participated in this study. Healthy participants were excluded if they had a previous neurological condition or visual perceptual impairments defined as a score <31 on the Motor-Free Visual Perception Test (MVPT; Colarusso & Hammill, 1972; Mazer at al., 1998, Korner-Bitensky et al., 2000). Participants with stroke were excluded if they were unable to stand for 1 minute, or if they had unilateral spatial neglect (positive test results on 2 of the 3 tests: Line Bisection Test, Apples test, Star Cancellation test), basic oculomotor deficits (determined by a chart review), severe cognitive impairments (<20/30 on the Montreal Cognitive Assessment; Waldron-Perrine & Axelrod, 2012), or pain in the upper limb (>4/10 on a visual analogue scale). Healthy participants were recruited from a list of volunteers and recruitment posters on social media, while participants with stroke were recruited from three rehabilitation centers affiliated with the Center for Interdisciplinary Research in Rehabilitation of greater Montreal (CRIR). Eligible participants with stroke were identified through an electronic database of discharged patients or by chart review. All participants were fully informed of the procedures involved and provided written consent on forms approved by the CRIR Ethics committee. The sample size was calculated *a priori* expected differences in movement times for reaches made in a 2D VE between healthy and stroke subjects (Viau et al. 2004).

6.4.3 Clinical assessment

Individuals with stroke participated in one clinical evaluation and one experimental session, whereas healthy individuals participated in a single session comprised of the application of the MVPT and the experimental session. The clinical assessment consisted of 6 outcome measures of motor and cognitive impairment (Composite Spasticity Index, CSI; Fugl-Meyer Assessment-Upper Extremity, FMA; MVPT; Nottingham Sensory Assessment: kinesthesia subscale) and function (Chedoke Arm and Hand Inventory 7, CAHAI-7; Reaching Performance Scale for Stroke; RPSS). The CSI (Levin & Hui-Chan, 1992) assesses elbow and wrist phasic (tendon jerk and clonus) and tonic (resistance to stretch) aspects of the stretch reflex and is expressed as a composite score ranging from 4 (no spasticity) to 16 (severe spasticity). The FMA (Fugl-Meyer et al., 1975) assesses motor impairment of the paretic UL. It includes finger, hand and arm movements, grasp, coordination, and reflex action. Each item is scored by direct observation using a 3-point ordinal-scale for a total score of 66 (normal UL motor performance). The MoCA (Nasreddine et al., 2005) assesses cognitive impairments and examines visuoconstructional skills, executive functions, language, memory, attention, conceptual thinking, and orientation on a scale of 1 to 30. A score of 26 and above is considered normal. The MVPT was used to assess five aspects of visual perception: visual discrimination, figure-ground discrimination, visual memory, constancy of form and visual synthesis. The test consists of 36 items, black-and-white line drawing stimulus, each with 4 multiple response options. Each correct answer is awarded 1 point, for a maximal score of 36. Time is also recorded for each question and averaged to obtain the visual procedural speed. The kinaesthetic subscale of the Nottingham Sensory Assessment simultaneously assesses movement position, direction and joint position space. For each joint (shoulder, elbow, wrist and finger), kinesthesia is scored on a 3-point scale (from 0= no proprioception to 2= normal proprioception) for a total score of 8 (Lincoln et al., 1998). The CAHAI-7 (Barreca et al., 2004) evaluates the functional ability of the hemiparetic arm and hand to perform 7 real-life tasks, such as pouring a glass of water or buttoning a shirt. Each task involves both ULs and is scored using 7-point ordinal scales

(7=task completed normally, 1=maximal assistance required), for a total score of 49 points. The RPSS (Levin et al., 2004) quantifies movement patterns and compensations during reaching-to-grasp for a cone located close to and far from the body. Movement components are evaluated on 4-point scales (0-3) for a total score of 18 for each target distance (normal movement patterns and quality).

6.4.4 Experimental session

During the experimental session, unimanual and bilateral reaching movements were made in each environments while standing. Unimanual movements were performed with the more affected limb in stroke and the non-dominant arm in healthy participants to allow a better comparison. Prior to data collection, each movement was demonstrated and a 5-minute familiarization period was allowed for each environment and task. Participants performed blocks of 20 repetitions for each movement and environment, in a randomized order. The initial position of the arm was alongside the body with the elbow slightly flexed to 10°. Participants were instructed to reach and grasp the object with one or both arms at their comfortable speed and transport the object towards their trunk, after hearing a go signal.

Kinematic data were recorded with a 2-Certus bar Optotrak motion analysis system (Northern Digital Corporation, Waterloo, Canada). A combination of 4 rigid bodies composed of 3 non-coaxial infrared emitting markers and 11 additional markers were used to record kinematic data. Rigid-bodies were placed on both mid-forearms and mid-arms. Additional markers were placed on both index fingertips, second metacarpophalangeal joints (endpoint), dorsomedial border of the wrist creases, lateral epicondyles, acromion processes and the mid-sternum. Data were recorded for 6 seconds at a sampling rate of 120 Hz.

6.4.5 Virtual and physical environment

The VE represented a grocery shopping task created with Unity Pro software and movements were tracked with a camera-based motion sensor (Kinect II, Microsoft, WA, USA). The motion tracking system allowed participants to interact with the objects in the virtual environment, without the need for a game controller or joystick. Hands and forearms were represented by avatars, which were viewed from a first-person perspective (Figure 6.1). The VE consisted of two scenes representing aisles filled with produce typically seen in a supermarket. The environment was displayed in 2D on a large screen (dimensions 2.1 x 1.6 m). The illusion of 3D was created by the size and shape of the objects, shadows and lighting, texture gradients and motion parallax (e.g. objects farther in space appeared smaller). The reaching distance between the participant and the target object was automatically calibrated to the subject's arm length using a distance calibration procedure at the beginning of the data collection. Participants interacted with the VE by placing their avatar hand over the target item for a minimum of 2 s. Collision detection occurred when the edge of the avatar arm or hand approximated the edge of the target item on the screen.

The unimanual movement consisted of reaching-to-grasp a small box (20.5 x 13.5cm; 0.28 kg) located in the subject's midline at shoulder height, while the bilateral movement consisted of reaching-to-grasp a large bag of rice (48.5 x 30 cm; 1.14 kg) located in the midline at mid-trunk level. Object sizes in the VE were matched those in the PE by changing the distance between the individual and the screen. Object locations in the PE were also calibrated to be identical to those in the VE for each participant. VE object height was measured as the distance between the object seen on the screen and the floor and then the physical object height was changed on an adjustable table. The distance between the subjects (mid-sternum) and the object on the screen in VE, was also reproduced in the PE by changing the distance of the table from the body. In the PE, grasping the physical object provided haptic feedback.

6.5.6 Data analysis

Positional (x, y and z) data were low-pass filtered at 10 Hz and linearly interpolated. Endpoint tangential velocity was calculated by the differentiation of positional (x, y and z) data of the endpoint marker. Upper limb kinematics were reconstructed from the four rigid-bodies in consideration of segment lengths and their positions with respect to single marker placements.

Movement performance variables related to the endpoint (i.e. movement time, peak velocity, time to peak velocity, trajectory straightness and smoothness) and movement quality variables (i.e. ranges of joint motion and interjoint coordination) were computed. For all movement performance and quality variables, only the outward reaching movement (i.e. from movement onset until the time of object grasping) was analyzed, even though the tasks involved a continuous movement of reaching, grasping and transporting. Movement onset and offset were defined as the time at which the endpoint tangential velocity exceeded above or fell below 10% of peak tangential velocity for a minimum of 50 ms. Onset/offset times were then verified by visual inspection. Movement time was determined from movement onset to offset. Endpoint movement smoothness was computed as the number of velocity peaks in the endpoint tangential velocity trace. 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). For bilateral movements, the difference between arms at time of movement onset and at the time to peak velocity was also computed. For movement synchrony, the cross-correlation between peak velocity times of each arm was computed from the endpoint tangential velocity, where a negative value indicated that the non-dominant/more-affected arm lagged the dominant/less-affected arm. For movement symmetry, the difference between the endpoint displacements between arms was computed, where negative values indicated that the dominant/less-affected arm moved further than the non-dominant/more-affected arm. Differences of more than 10% of the total movement time/distance were considered to be significant.

Hand positioning at the time of object contact was computed as the angle between the forearm (vector formed by the elbow and the wrist markers) and the horizontal plane, where the full horizontal projection = 180°). For movement quality variables, trunk rotations (pitch, yaw and roll) were computed from the rigid-body formed between the sternum and shoulders (initial position = 0°). Elbow flexion/extension range was calculated from segment lengths and the position of the rigid-bodies of the forearm and arm (full elbow extension = 0°). Shoulder flexion/extension range was computed from segment lengths and the arm and trunk rigid-bodies (arm alongside the body = 0°).

The primary outcome measures were movement time, time to peak velocity, index of curvature, number of velocity peaks and hand orientation for unimanual movements, while secondary outcomes were trunk and arm joint rotations. For bilateral movements, the primary outcomes were differences in movement onset times, times to peak velocity and the temporal coordination between both arms (index of cross-correlation of the endpoint velocity trace at time to peak velocity). Secondary outcome measures were joint and trunk angles.

6.4.7 Statistical analysis

Based on Shapiro-Wilk tests, non-parametric tests were used to test all hypotheses. The significance level was set to $p<0.05$. For hypothesis 1, Kruskal-Wallis tests compared endpoint performance variables between PE and VE for each group. Due to the high correlation between movement time and time to peak velocity, p-values were divided by 2 (Bonferroni correction) resulting in a significance level of $p< 0.025$. Effect-sizes for the primary outcome measures were computed using G-power software (v3.1.9.2, Düsseldorf, Germany). For hypothesis 2, Kruskal-Wallis tests were used with Bonferroni corrections to compare movement performance between groups ($p<0.025$). For hypothesis 3, correlations between MVPT scores and primary outcomes were analyzed using Spearman's correlations. For hypothesis 4, for healthy and stroke subjects, upper limb differences in movement onset, time to peak velocity, endpoint displacement and the index of cross-correlation between times to peak velocity of each arm were compared for the VE and the PE using Kruskal-Wallis tests. Spearman's correlations were also used to analyze the association between clinical tests and endpoint performance and movement quality variables. Data were analyzed using SPSS (v23, IBM, Armonk, NY).

6.5 Results

Twenty-two individuals with stroke (5 females; aged 62.4 ± 12.0 yr), and 15 healthy participants (9 females; aged 59.5 ± 17.7 yr) completed all sessions. Healthy participants scored between 33-36/36 on the MVPT. For the stroke group, participants had mild-moderate motor impairments with a mean FMA score of 50.6 ± 7.8 (range 34-64/66) and no to mild spasticity (CSI = 6.1 ± 1.8). The MVPT score ranged from 24-36 (mean: 32.2 ± 4.9), with 6 participants having mild-moderate visual perceptual impairments. All but 4 participants had normal arm or hand proprioception (Supplementary Table).

6.5.1 Endpoint performance and hand orientation differences for unimanual reaching between environments

For both groups, movement time, trunk displacement and hand orientation at the time of grasping was similar in both environments. Healthy participants had straighter endpoint paths (p=0.004) and used more wrist flexion (~4°) in VE than PE (p=0.007; Table 6.1). Stroke subjects had more temporally segmented movements (p=0.001) and used more shoulder flexion (~11°) in VE than PE (p=0.020). In VE, both groups made slower movements compared to PE. None of the primary or secondary outcome measures differed between the dominant and the non-dominant arm for healthy participants.

6.5.2 Endpoint performance and hand orientation differences for unimanual reaching between groups

Endpoint trajectory straightness (VE: p=0.107, PE: p=0.664) and hand positioning at the time of object contact (VE: p=0.536, PE: p=0.155) were similar between groups for both environments (Table 6.1). Joint rotation ranges were also similar (p>0.05), except for greater shoulder flexion in PE in individuals with stroke (p=0.013). Individuals with stroke had prolonged times to peak velocity (VE: p=0.001; PE: p=0.018) and more temporally segmented movements (VE: p=0.003, PE: p=0.023) than healthy individuals in both VE and PE. However, only in PE, this group made slower movements compared to the healthy group (VE: p=0.026, PE: p=0.007).

6.5.3 Differences in movement symmetry between environments for bilateral reaching-to-grasp

For bilateral movements, movement onset and time to peak velocity between the dominant/non-dominant arms for healthy and more/less affected arms for stroke were similar for both groups and environments (Table 6.2). In both environments, bilateral movements made by healthy subjects were symmetrical in terms of distance and were simultaneous. Specifically, in VE, all but 4 healthy subjects moved both arms symmetrically and simultaneously. In PE, arm movements were simultaneous, but 2 subjects moved the non-dominant arm further (>10°; Figure 6.2). For the stroke group, the timing between arms was similar in both environments, with 2 and 6 stroke subjects having a difference in timing between arms of > 10% in VE and PE, respectively. However, the difference in endpoint displacements between the more/less affected arms was greater in VE (~5.6 cm; p=0.008).

6.5.4 Impact of visual perceptual impairments on movement performance and quality

For the stroke group, greater visual perceptual impairments (greater MVPT scores) were moderately correlated with shorter movement time (VE: r_S=-0.474, p=0.026; PE: r_S =0.008, p=0.974) and shorter time to peak velocity (VE: r_S=-0.574, p=0.005; PE: r_S =-0.032, p=0.887) for unimanual movements made only in VE. However, visual perceptual impairments were not related to qualities of movement smoothness, trajectory curvature or hand orientation at the time of object contact in either environment. For bilateral movements, visual perceptual impairments were also not related to arm movement symmetry and synchronicity.

6.5.5 Clinical significance

For unimanual movements, there was a moderate negative correlation between FMA scores and movement time in the PE only (VE: r_S=-0.104, p=0.646; PE: r_S =-0.498, p=0.018), suggesting that individuals with greater upper limb motor impairments made slower movements in PE. However, motor impairment severity, spasticity severity or limitations in unimanual upper limb function were not related to the endpoint or movement quality variables in either environment. For bilateral movements, activity limitations for bimanual tasks, visual perceptual or motor impairment severities were not related to spatial or temporal characteristics of the bilateral movements.

6.6 Discussion

Upper limb kinematics of unimanual and bilateral reaching movements performed in VE were compared to those in a similar PE, in healthy individuals and in individuals who had a stroke with and without visual perceptual impairments. For unimanual reaching movements, the environment had an overall effect on temporal variables of movement performance. In VE, unimanual reaches were less smooth and times to peak velocity were longer. These differences were more pronounced in individuals with stroke. Movement speed was similar between environments, but in PE, individuals with stroke made slower movements than healthy participants. Hand orientation at the time of object contact and trunk kinematics were unaffected by the environment or group. Greater visual perceptual impairments resulted in longer movement duration and slower time to peak velocity in VE, but not in PE. Bilateral movements in healthy subjects were generally simultaneous and symmetrical in both environments. In contrast, movements in stroke subjects were less symmetrical in the VE, and tended to be less simultaneous in the physical environment. These results confirm hypotheses 1-3, but reject hypothesis 4, since only movement symmetry was affected by the environment in the stroke group. The differences between movements made by healthy and stroke in PE (i.e. slower and more temporally segmented movements) are similar to those obtained in other studies (Alt Murphy & Häger, 2015; Archambault et al., 1999; Cirstea & Levin, 2000; Levin, 1996).

Consistent with other studies (Levin et al., 2015; Liebermann et al., 2012; Magdalon et al., 2011; Schafer & Ustinova, 2013), our results suggest that temporal endpoint performance variables were altered by the 2D VE. However, as observed by Viau et al. (2004), spatial endpoint performance variables were not affected by the 2D VE. The slower time to peak velocity and the greater number of velocity peaks in 2D VE can be attributable to the lack of stereovision, the difficulties in depth perception and the poor motion tracking accuracy of the Kinect II camera. These difficulties could lead to uncertainty about the target or hand position resulting in longer time to reach peak velocity and more movement corrections as the hand approached the targets. Visual cues only appeared once the reaching movement was initiated, as the arm avatar was not displayed on the screen when the arm was in the initial position (alongside the body), which may have also contributed to the altered temporal parameters. The moderate correlation between scores on the MVPT and movement time, as well as time to peak velocity in VE also support the idea that the viewing environment influenced depth perception (Subramanian & Levin, 2011). Our results are also consistent with the work of Schafer and Ustinova (2013) in individuals with traumatic brain injury showing a moderate relationship between the MVPT scores and movement time in a 3D VE but not in a PE.

In addition to uncertainty about target position, the poor motion tracking accuracy of the Kinect II camera may have led to erroneous feedback about arm position, requiring participants to make a visuospatial transformation to ensure that their movements matched those projected in the VE. However, our findings that the movement quality was mainly preserved in the VE suggests that both healthy individuals and individuals with stroke were able to make the visuospatial transformation required to interact with the VE. Indeed, only the changes in wrist flexion for healthy participants and shoulder flexion for stroke participants differed between environments. However, while these ranges of motion were statistically significant, they were unlikely to lead to clinically important change. While we predicted that the lack of haptic feedback would impact hand positioning at the time of object contact, this was not supported by our results, even in individuals with visual perceptual impairments. The presence of enhanced visual cues in the VE may have compensated for the lack of haptic information. This highlights the importance of the quality of the viewing environment for reach-to-grasp movements (Kenyon & Ellis, 2014).

For bilateral reach-to-grasp movements, the viewing environment had an impact on arm movement symmetry for individuals with stroke only. The difference in endpoint displacements in VE may be explained by how the collision detection was set-up in our 2D VE, and not to sensorimotor impairment levels of patients, since none of the clinical tests were related to the spatial or temporal characteristics of bilateral movements. Specifically, in the VE, the virtual bag of rice could be grasped by each hand at different points along its sagittal axis. Thus, actual distance symmetry was not required for successful retrieval of the object in the VE.

Unlike other studies in which movement velocity was decreased in VE (Chen et al., 2014; Lin & Woldegiorgis, 2018; Magdalon et al., 2011; Robert & Levin, 2018; Schafer & Ustinova, 2013; Wang et al., 2011), movement time did not differ between the PE and VE. This may be due to the projection of the environment on a large screen, as opposed to viewing the VE through a head-mounted display. In studies comparing the effects of the viewing environment, healthy participants and individuals with mild motor impairments due to stroke made faster movements when the VE was viewed on a computer monitor or a screen, in comparison to a head-mounted display (Rand et al., 2005; Subramanian & Levin, 2011). While movement speed did not differ between environments, individuals with stroke had slower movement time in PE, which can possibly be explained by difficulty in grasping the object experienced by many of our participants with stroke. This is supported by the moderate correlation between the FMA scores and movement time, only in PE. The lack of correlation between three kinematic variables (i.e. index of curvature, number of velocity peaks and movement time) and two clinical tests (FMA and RPSS - far object) for reaching in VE were also consistent with the results obtained by Levin et al. (2015). Moreover, the poor correlation between the CSI and kinematics is not surprising, since our participants had mild or no spasticity.

Our results differed from those of Liebermann et al. (2013) who found differences in movement quality in another low-cost game-based 2D VE compared to reaching in a matched PE. In contrast to our study using a first-person perspective, the third-person perspective used in Liebermann et al. (2013) likely involving additional visuospatial transformations can explain the different results. The tasks also differed (reach-to-grasp performed standing vs. reaching to 3 targets from a sitting position), which directly impacts kinematics. Unlike reaching-only movements, reaching-to-grasp requires the individual to position and orient the upper limb according to object properties, location and affordance (Alt Murphy & Häger, 2015; Rosenbaum et al., 2012).

6.6.1 Limitations

The small number of individuals with visual perceptual impairments (n=6) may have limited our ability to detect differences between participants with and without visual perceptual impairments. Moreover, our sample was not large enough to allow us to stratify participants with stroke based on lesion location, side of lesion or hand dominance. Since individuals with unilateral spatial neglect were excluded from this study, the impact of unilateral spatial neglect on movement performance and quality in 2D VEs was not addressed. The exclusion of individuals with unilateral spatial neglect, severe cognitive impairments and the inability to stand limit results generalizability to the entire stroke population. However, our sample was constituted of individuals with a wide spectrum of sensorimotor, visual perceptual and cognitive impairments, reflecting the heterogeneity of stroke in the general population. The impact of lesion location, hand dominance, the side of hemispheric lesion and unilateral spatial neglect should be determined in future validation studies of VEs.

6.7 Conclusion

This study provides new information about the quality of unimanual and bilateral reach-to-grasp movements done while standing in a low-cost 2D VE. Only temporal parameters of movement performance for unimanual movements and symmetry for bilateral movements were altered by the 2D VE, suggesting that the movements were kinematically valid, even for individuals with mild-moderate visual perceptual impairments. This study helped to identify that, in the absence of haptic information, enhanced cognitive and sensory cues mimicking stereovision (e.g. objects size and shape, texture gradients, lighting, shadows, lighting and motion parallax) can help to ensure the kinematic validity of movements performed in a 2D VE. Future studies should focus on the ways upper limb movement performance and quality are impacted by the design of the VEs. For example, colors and target geometry have differential effects on depth perception (Powell & Powell, 2016). The impact of visual cues, visual representation and properties of target objects within the VE remains to be established to inform future design of VEs specifically designed for rehabilitation purposes.

With the increasing evidence supporting the use of VR intervention for stroke rehabilitation, these results contribute to supporting the use of low-cost 2D VE to supplement usual stroke care, while mimicking instrumental activities of daily living that could be impractical in clinical settings. The kinematic similarity of movements performed in 2D VE with the real-world could potentially facilitate the transfer of skills learned in therapy to real-life settings. However, while some studies have suggested that the changes made during VR interventions are transferred to real-life settings (e.g. greater perceived amount of arm use; Housman et al., 2009; Subramanian et al., 2013), more evidence is needed. The results can also guide rehabilitation professionals in the selection of VEs for sensorimotor rehabilitation.

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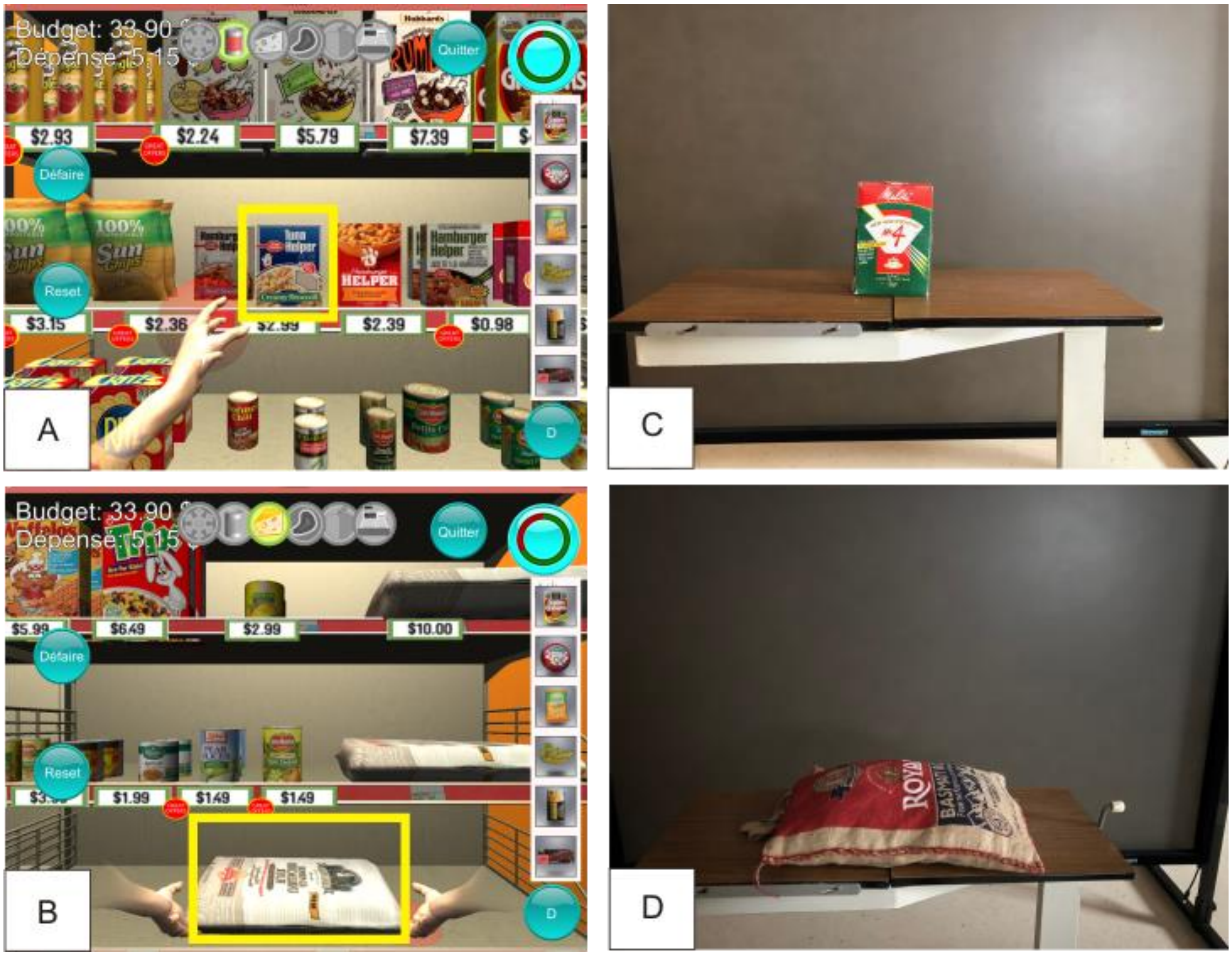
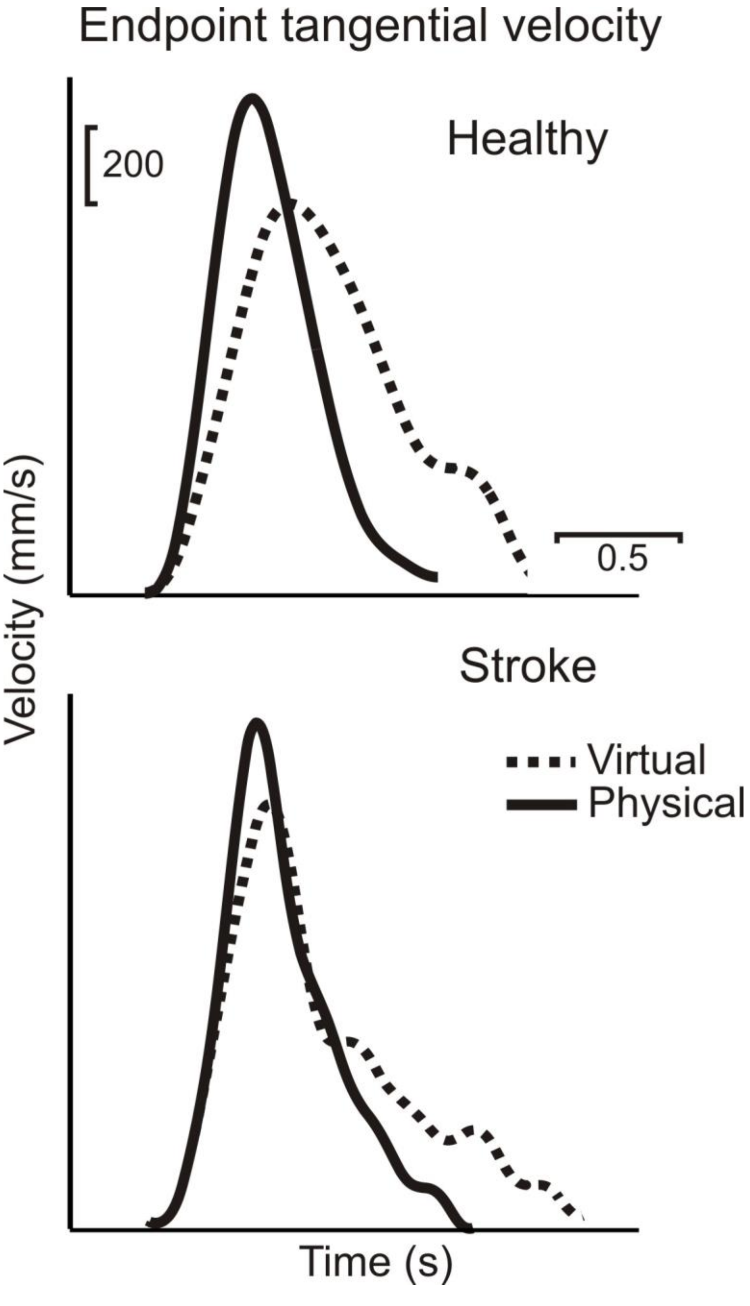
Figure 6.1 – Virtual and physical environments



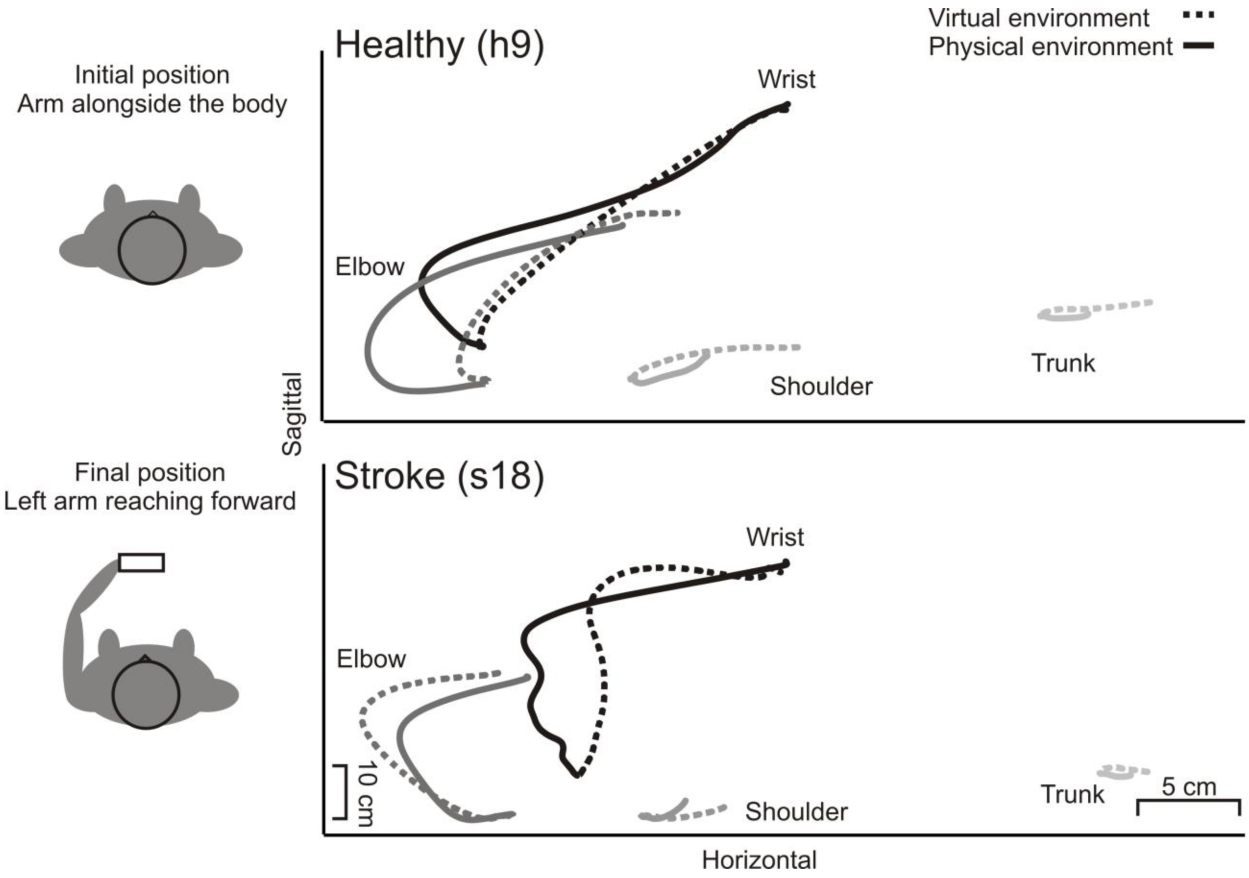
Legend: Objects to be grasped in the virtual environment (A, B) and in the matched physical environment (C, D) for unimanual (A, C) and bilateral (B, D) tasks. The objects to be grasped are outlined in A and B.

Figure 6.2 – Endpoint tangential velocities for unimanual reach-to-grasp task



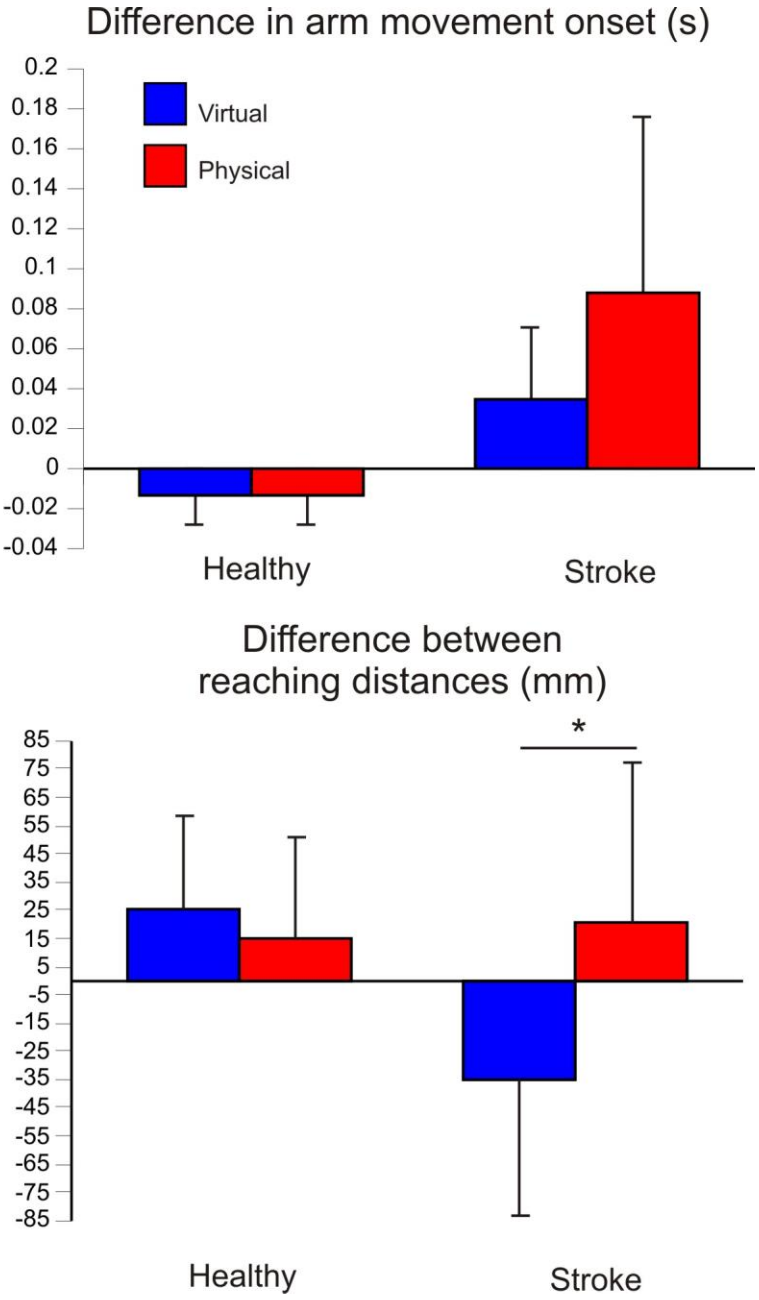
Legend: Representative traces of a single trial for unimanual reach-to-grasp task in a healthy subject (top graph) and a stroke subject without visual perceptual impairments (bottom graph). For both trials, in VE compared to PE, time to peak velocity was delayed, peak velocity was slower and movement duration was longer.

Figure 6.3 – Wrist, elbow, shoulder and trunk displacements for unimanual reach-to-grasp task



Legend: Representative trial for a unimanual reach-to-grasp task made in a virtual environment (VE) and a physical environment (PE) with the left upper limb in a healthy subject (top panel) and a stroke subject without visual perceptual impairments (bottom panel)

Figure 6.4 – Difference between arm reaching distances for bilateral reach-to-grasp task



Legend: *: p>0.025; Movement synchronicity is displayed in the top panel for healthy and stroke subjects, where positive values indicate that the dominant/less-affected arm lagged the non-dominant (healthy)/more-affected arm (stroke). Movement symmetry is displayed on the bottom panel for healthy and stroke subjects, where positive values indicate that the non-dominant (healthy)/more-affected arm (stroke) moved further.

Table 6.1 – Endpoint trajectory and movement quality variables for unimanual reach-to-grasp

	Healthy			**Stroke**		
Variables	VE (Mean ± SD)	PE (Mean ± SD)	Effect size	VE (Mean ± SD)	PE (Mean ± SD)	Effect size
Movement time (s)	1.61 ± 0.31	1.40 ± 0.36	0.625	1.93 ± 0.45	1.76 ± 0.52	0.350
Time to peak velocity (s)	0.55 ± 0.09	0.47 ± 0.14	0.680*	0.71 ± 0.17	0.56 ± 0.13	1.057**
Number of peaks	1.33 ± 0.32	1.14 ± 0.24	0.672	2.06 ± 0.90	1.58 ± 0.72	0.589*
Index of curvature	1.10 ± 0.08	1.15 ± 0.06	0.707	1.13 ± 0.07	1.19 ± 0.16	0.486
Hand orientation (°)	115.42 ± 13.46	111.51 ± 7.63	0.357	108.64 ± 15.23	117.84 ± 16.39	0.582
Shoulder flexion (°)	48.85 ± 15.87	45.85 ± 11.55	0.216	46.49 ± 15.50	35.51 ± 13.88	0.742*
Elbow extension (°)	35.42 ± 27.20	24.68 ± 13.80	0.500	31.33 ± 17.11	19.97 ± 16.47	0.676
Wrist flexion (°)	12.22 ± 9.57	8.36 ± 5.19	0.501*	12.61 ± 8.24	10.00 ± 6.62	0.349
Trunk pitch (°)	4.57 ± 3.45	4.95 ± 3.19	0.226	7.57 ± 6.26	8.40 ± 7.22	0.123

Legend: * $p<0.025$, ** $p<.0001$

Table 6.2 – Spatial and temporal movement symmetry for bilateral reach-to-grasp

	Healthy			**Stroke**		
Variables	VE (Mean ± SD)	PE (Mean ± SD)	Effect size	VE Mean ± SD	PE Mean ± SD	Effect size
Difference in movement onset (s)	-0.014 ± 0.061	-0.014 ± 0.035	0.00	0.035 ± 0.106	0.088 ± 0.126	0.455
Difference in time to peak velocity (s)	-0.005 ± 0.060	-0.001 ± 0.059	0.067	-0.043 ± 0.106	-0.033 ± 0.065	0.114
Cross-correlation	0.000 ± 0.019	0.002 ± 0.023	0.095	-0.013 ± 0.053	0.023 ± 0.126	0.372
Endpoint displacement (mm)	24.96 ± 33.00	14.48 ± 36.38	0.302	-35.38 ± 47.77	20.66 ± 56.54	1.953*

Legend: * $p<0.025$

Supplementary table - Socio-demographic and clinical characteristics of participants with stroke

ID	Age (yr)/ Gender	Time since stroke (mo)	Dominance	Stroke type and lesion site	FMA score (/66)	CSI score (/16)	RPSS far score (/18)	CAHAI-7 score (/49)	MVPT score (/36)
S1	47/M	7	Right	Right Isc cortical stroke (corona radiata)	34	5	15	37	35
S2	67/M	17	Right	Right Isc lacunar cortical stroke (internal capsule)	40	9	14	32	34
S3	75/M	3	Right	Right Isc cortical stroke (MCA)	43	4	16	43	26
S4	57/M	6	Right	Left Isc cortical (MCA) and subcortical (thalamus) stroke	43	9	7	39	36
S5	77/M	39	Right	Left Isc cortical (internal capsule) and subcortical (thalamus) stroke	44	8	14	17	35
S6	50/M	54	Left	Right Isc midbrain stroke (cerebellum)	44	5	16	39	35

S7	70/F	23	Right	Right Isc lacunar midbrain stroke (pons)	44	10	15	33	27
S8	56/F	9	Right	Right Isc cortical stroke (MCA)	48	6	14	42	35
S9	78/M	8	Right	Left Isc cortical stroke (MCA)	49	6	15	46	33
S10	68/M	64	Right	Right Isc cortical stroke (frontal)	49	9	14	40	24
S11	66/M	8	Right	Left hem cortical stroke (fronto-parietal)	50	6	18	47	36
S12	62/F	23	Right	Left Isc cortical stroke (frontal)	50	7	16	42	36
S13	32/F	46	Right	Left Isc cortical stroke (MCA) with hem transformation	52	5	16	47	36
S14	76/F	9	Right	Right Isc cortical stroke (MCA)	53	5	18	48	30
S15	64/M	5	Right	Left Isc cortical (MCA) and subcortical stroke	53	7	16	43	30
S16	61/M	21	Right	Righ Isc cortical stroke (MCA) with hem transformation	55	6	14	42	33

S17	56/M	3	Right	Right Isc pseudo-lacunar subcortical and mid-brain stroke	56	5	18	40	34
S18	58/M	35	Right	Right Isc cortical stroke (MCA)	57	5	15	42	35
S19	54/M	29	Left	Right hem subcortical stroke (thalamus)	60	4	16	39	30
S20	50/M	3	Right	Left hem cortical stroke	62	4	16	48	35
S21	82/M	10	Right	Left Isc cortical stroke (PCA)	62	6	18	42	17
S22	67/M	13	Right	Right Isc subcortical stroke (corona radiata)	64	4	16	48	36
Mean ± SD	**62.4 ± 12.0**	**19.8 ± 17.7**			**50.6 ± 7.8**	**6.1 ± 1.8**	**15.3 ± 2.3**	**40.7 ± 6.9**	**32.2 ± 4.9**

Abbreviations: CAHAI-7: Chedoke McMaster Arm and Hand Inventory – 7; FMA: Fugl-Meyer Assessment – Upper extremity; Hem: Hemorrhagic; Isc: Ischemic; MCA: middle cerebral artery; Mo: months; MVPT: Motor-Free Visual Perception Test; PCA: posterior cerebral artery; SD: Standard deviation; Yr: year

Chapter 7 – Discussion, implications, limitations and future directions

7.1 Summary of findings

The overall aim of the thesis was to determine the feasibility of using a low-cost VR intervention as a therapeutic option for improving UL function in individuals who have had a stroke. This overall aim was operationalized in three distinct manuscripts. In the first manuscript, feasibility was assessed by determining user satisfaction and safety of a low-cost VR intervention when delivered as a supplement to usual. Satisfaction, safety and usability were assessed from the point of view of clinicians and individuals with sub-acute stroke receiving rehabilitation. The second manuscript informed future planned VR-based intervention studies on the selection of outcome measures capturing UL motor performance and movement quality. The third manuscript determined the validity of the movements made in the low-cost 2D VR intervention compared to the real-world in healthy individuals and in individuals who had a stroke with and without visual perceptual impairments. To place this overarching discussion into context, the findings and conclusions from each manuscript are reiterated.

The first manuscript presented in Chapter 4 assessed the acceptability and safety of incorporating an adjunctive VR intervention as a therapeutic option for improving UL sensorimotor impairments in individuals who have had a stroke. More specifically, the occurrence of adverse events, the tolerance of the participants with stroke to the duration and intensity of a single intervention, and the level of satisfaction of clinicians and individuals with stroke were identified. The results provided insights on the perspectives of both clinicians and individuals in the sub-acute phase of stroke recovery about the VR intervention. The satisfaction with the VR intervention was high for both user groups. Clinicians perceived the usefulness of incorporating an adjunctive VR intervention to usual rehabilitation care to decrease UL motor impairment during functional tasks. In a single session, the VR intervention encouraged a high number of movement repetitions with a minimal level of exertion and individuals had no major adverse events using the VR platform. The results of this study also led to recommendations to improve the VR intervention and/or make it more suitable for stroke rehabilitation. Following this study, a technical programming expert was recruited to the team to implement changes to the VR intervention. A close working collaboration between researchers, clinicians and the programming expert was developed to implement the suggested modifications in order to facilitate the adoption of the VR intervention in clinical practice. Among the changes made, the feedback provision, the levels of difficulty and the navigation menu were modified. Specifically, the feedback provision given at the end of the Shopper's delight game, i.e. knowledge of performance and results, was enhanced by indicating the number of items placed in the shopping cart, the number of correct items purchased, the amount of money spent with respect to the allocated budget, and the occurrence of excessive trunk flexion during reaching, an unwanted compensatory movement. The location of the shopping list on the screen was also moved to avoid interference with the navigation menu and was displayed constantly. Finally, the size of the objects displayed was modified to decrease the level of difficulty of the Smash Blocks game.

The second manuscript presented in Chapter 5 determined the extent to which current outcome measures used in neurological practice capture how UL movements are performed at two levels of movement description (body space and external space levels). This review informed the selection of UL outcome measures at the *Activity* level of the ICF framework for future effectiveness studies. Our findings indicated that nine measures consider how movements are performed by measuring either endpoint characteristics or movement quality. However, only one measure, the Reaching Performance Scale for Stroke (RPSS), assesses both endpoint characteristics and movement quality by quantifying the presence of compensatory movements and how arm joints, the trunk and the hand are used during reaching tasks. From these findings, it was concluded that improvements measured strictly with self-report measures or timed-based measures should be interpreted with caution when the goal is to assess movement quality. An important limitation of time-based measures highlighted was that the time to accomplish a task may be influenced by the use of compensatory movements, which are not quantified by the measures rating only time for task accomplishment. For self-report measures, individuals with neurological disorders may not perceive changes in movement quality, and performance may be under- or overestimated based on motivation, language or cognitive ability. The review also emphasized the importance of using observational or laboratory-based kinematic measures to objectively quantify changes in UL movements and movement compensations to be able to assess the movement quality of the performance of functional tasks. Measures such as the RPSS and/or kinematic analysis could be incorporated into future intervention studies evaluating the effectiveness of VR interventions for stroke sensorimotor UL rehabilitation to objectively capture significant changes in UL functional performance.

The third manuscript presented in Chapter 6 assessed the kinematic validity of unimanual and bilateral reach-to-grasp movements performed in the 2D VR intervention and a comparable PE. This was done in healthy individuals and in individuals who have had a stroke with and without visual perceptual impairments. For unimanual movements, speed, hand orientation when grasping the object and trunk kinematics were unaffected by the environment or group. The results suggested that participants did not adopt greater maladaptive compensatory strategies in VE compared to PE. However, individuals with stroke and healthy individuals had altered temporal endpoint variables in VE. Specifically, in VE compared to PE, healthy individuals had longer time to peak velocity, whereas individuals with stroke made more segmented movements and the time to peak velocity was also prolonged. The impact of the 2D VE on temporal endpoint variables may likely be attributable to the reduced motion tracking accuracy of the Kinect II camera and the quality of the 2D viewing environment limiting depth perception. The severity of visual perceptual impairments was shown to be related to movement duration and the time to peak velocity in VE, but not PE. The similarity of movement quality variables between VE and PE suggests that participants were able to use the visual cues in the 2D VE to accurately judge object location and make the visuo-motor transformations required to interact in the VE. For bilateral movements, healthy individuals made generally simultaneous and symmetrical movements in both environments. In contrast, individuals with stroke had greater difficulty to make symmetrical movements in VE, but these difficulties were not related to the severity of visual perceptual or motor impairments. The decreased movement symmetry in VE may be related to the object collision detection in our 2D VE allowing participants to succeed in the task despite having asymmetrical movements at the time of object grasping.

The results indicated that the unimanual and bilateral reach-to-grasp movements performed in the low-cost 2D VE were generally similar to those performed in a real-life setting, hence supporting the use of the 2D VR intervention for stroke rehabilitation.

7.2 Discussion and clinical implications

The studies presented in Chapters 4-6 contributed to establishing the feasibility of using a low-cost VR intervention for supplementing stroke rehabilitation. The intervention was judged safe and useful in clinical practice to remediate UL motor impairments by clinicians and individuals receiving rehabilitation following a stroke. The level of satisfaction with the VR intervention was also high and the intervention was well-accepted by key stakeholders. The movements performed in VE were also considered valid for individuals with stroke, as they were made at the same speed, had similar spatial movement characteristics (except for movement symmetry in bilateral movements) and similar movement quality in the VE and a comparable PE. The collection of work presented in this thesis has implications for clinical practice.

7.2.1 Implications for individuals who have had a stroke

The developed VR intervention simulating an ecologically-valid functional task (grocery shopping) shows potential to safely supplement sub-acute stroke rehabilitation and to address common challenges of traditional rehabilitation. This VR intervention could target key elements of motor learning underlying experience-dependent neuroplasticity (Levac & Sveistrup, 2014), such as high engagement and motivation, enhanced feedback provision, active problem-solving, and high exercise intensity together with minimal fatigue. The strengths of the VR intervention identified by key stakeholders in Chapter 4 were the realism of the task, the game accessibility for individuals with motor and/or cognitive impairments, the high level of interactivity, engagement and motivation. The similarity of the movements made in the VE with those made in the real-world suggests that the incorporation of the VR intervention in stroke rehabilitation could help the transfer of skills learned early in the clinical setting to real-world situations. While UL motor recovery plays an important role in the incorporation of the paretic UL in everyday activities, other factors, such as higher order cognitive deficits, can potentially negatively impact UL behaviour in the natural environment. In a systematic review and meta-analysis on the relationship between motor and cognitive impairments, a moderate association was noted between cognition and arm motor improvement ($r = 0.43$; CI: 0.09–0.68; Mullick et al., 2015). Motor learning engages cognitive processes, such as attention, memory and executive functions (Cumming et al., 2013), hence the need to develop multi-faceted therapeutic interventions targeting both cognitive and motor impairments. The developed VR intervention could potentially target UL sensorimotor impairments and cognitive impairments simultaneously, which could result in greater motor learning and greater use in everyday activities. However, the effectiveness of the VR intervention must first be established (see Future directions).

Our results suggested that the VR intervention could be used for individuals with a large spectrum of motor, cognitive or language impairments, with various levels of familiarity with VR interventions and at different stages in their rehabilitation process (in/outpatient). Individuals with visual perceptual impairments could also benefit from using the VR-based intervention for sensorimotor UL rehabilitation, as endpoint spatial parameters and movement quality were similar to those used by individuals without perceptual impairments. However, the VR intervention might not be suited for all individuals who have had a stroke. Certain characteristics, such as a fair amount of exposure to commercial video games, may limit the patients' engagement with the VR intervention, since low-cost VEs do not replicate the production values of commercial video games. More research is needed to determine the characteristics of participants who might benefit the most from using VR interventions for stroke rehabilitation.

7.2.2. Implications for clinicians working in stroke rehabilitation and rehabilitation services

Grocery shopping tasks, like other instrumental activities of daily living, are often difficult or impractical in clinical settings due to the lack of time for transportation to a real grocery stroke, or the technical complexity of reproducing the visual and auditory cues present in a grocery store (Rand & Katz, 2009). From the point of view of clinicians working in stroke rehabilitation, it was perceived that VR could be practical and beneficial to simulate grocery shopping, without the inconveniences associated with performing the task in the real-world. The VR system interface was perceived as simple, user-friendly, requiring minimal set-up, and the cost was low, thereby addressing common organizational and technological barriers to knowledge translation about the adoption of VR in rehabilitation (Glegg et al., 2013; Hughes et al., 2014; Levac et al., 2012; Nguyen et al., 2018). The usability and usefulness of the VR intervention, crucial factors for the adoption of technology for UL stroke rehabilitation (Hochstenbach-Waelen & Seelen, 2012), could facilitate the implementation and sustainability of the VR intervention in clinical practice. However, the literature on knowledge translation for VR emphasizes the importance to establish the effectiveness of the VR intervention, obtain the buy-in from decision-makers and provide ongoing educational training to clinicians to facilitate implementation of the VR intervention in clinical practice (Levac et al., 2012; Nguyen et al., 2018).

Aside from the potential benefits of using the VR intervention for stroke rehabilitation, the results gained from this thesis will help guide occupational and physical therapists in the selection of valid and reliable outcome measures to assess UL activity limitations on which to base their clinical decisions. The review in Chapter 5 also underlined the importance of incorporating movement quality assessment into clinical practice to identify the underlying motor impairments in movement production, evaluate treatment effectiveness, and measure motor recovery. In clinical practice, occupational and physical therapists often use their observational skills during functional activities to develop individualized therapeutic plans, progress the level of difficulty of a task and make inference about underlying impaired body function/structure. As an alternative to using kinematic movement analysis, the use of observational movement analysis in clinical practice can be an easy and low-cost approach to improve the assessment of UL movement quality during functional activities. Technological advancements, such as wearable miniaturized sensors or markerless motion capture technology, may make monitoring of UL kinematics more feasible to objectively measure UL improvements in clinical practice and in future stroke recovery trials (Kwakkel et al., 2017).

Regarding the contribution of this work to the existing literature about the kinematic validity of the movements performed in VEs, the results support the use of enhanced-2D VE and 3D VE, as valid approaches for the rehabilitation of the paretic UL. However, therapists should be aware that the viewing environment may influence motor behaviour. The study in Chapter 6 highlighted that some kinematics differed between VE and PE, especially temporal endpoint parameters, due to effects on depth perception and the uncertainty about target location of the VE. Moreover, as demonstrated by Liebermann et al. (2013) in different VR system, 2D VE using a third-person perspective may lead to altered movement quality and may promote the use of maladaptive compensatory strategies. The results presented in Chapter 6 along with other studies using low-cost 2D VE (Liebermann et al., 2013; Robert & Levin, 2018; Viau et al., 2004) stresses the importance of having a qualified therapist supervising treatment delivery using VR, since endpoint performance and joint kinematics may be affected by the quality of the viewing environment. As opposed to delivering VR therapy without supervision, the presence of a training therapist when delivering VR interventions can help to provide meaningful feedback about movement performance and quality, and detect if individuals with stroke are adopting maladaptive compensatory strategies in VE, which could ultimately result in decreased possibilities for motor recovery. The current work along with the body of literature comparing UL kinematics when movements are made in different viewing environments will help guide rehabilitation professionals on the selection of a VR application to enhance UL function after a stroke.

7.3 Limitations

There are a few limitations that should be acknowledged. The work presented in this thesis refers to the feasibility of incorporating the VR intervention developed by our research team (a custom-based VR intervention using the motion capture system Kinect II camera). While some of the findings may be translated to other VR applications using low-cost game-based systems or VR interventions using the Kinect II camera, our results are mostly applicable to our specific VR intervention. Feasibility was determined for both clinicians and individuals who have had a stroke. However, the adoption of VR in clinical practice also depends on other stakeholders such as decision-makers. The exclusion of managers and policy-makers may limit the eventual implementation of low-cost VR interventions to supplement usual care, as many organizational barriers to implementing VR interventions have been identified in the literature (Glegg et al., 2013; Hughes et al., 2014; Levac et al., 2012; Nguyen et al., 2018). Moreover, the feasibility of using the VR intervention for sub-acute stroke rehabilitation was only evaluated in a single session with potential users, limiting our ability to estimate whether a supplemental VR interventions delivered multiple times a week could be tolerated and the enjoyment maintained over time.

The validity study presented in Chapter 6 has also limitations that should be acknowledged. Only two functional movements, unimanual and bilateral reaching-to-grasp, were compared. While these two functional movements are often used in everyday activities, they only represent a small sample of all possible UL movements performed daily. Moreover, participants were not stratified by the lesion location, side of lesion or hand dominance. The stroke group included 9 participants with dominant-side hemispheric lesions and 13 with non-dominant side lesions. Due to our small sample size, analyses between the right and left hand dominant participants with stroke separately or between those with dominant and non-dominant hemispheric lesions were not performed. The impact of lesion location, hand dominance and the side of hemispheric lesions should be explored in future validation studies of VEs. Since participants with unilateral spatial neglect were excluded from this study, it was not possible to conclude about the impact of unilateral spatial neglect on movement performance and quality in VEs. Thus, VR interventions, when used as therapeutic modalities, may not be applicable to participants with visual field impairments.

Finally, when the VR intervention was developed, the Kinect II camera was recently launched and was the latest available low-cost technology. A few years later, technological advancements have progressed, as the field of virtual rehabilitation in general. Furthermore, the Kinect II camera is not produced anymore, despite still being used in clinical practice. The rapid evolution of the VR technology is a challenge with any research done in this field, as the technology progresses faster than the evidence.

7.4 Directions for future studies

This thesis fits into a larger context of VR for stroke rehabilitation research by laying the groundwork for future planned intervention studies to evaluate the effectiveness of adjunctive VR interventions for stroke rehabilitation. While the quantity of randomized control trials investigating VR for stroke rehabilitation is growing, most studies published have small groups, are done with participants in the chronic phase of stroke recovery, or do not involve an active comparison group (Fluet & Deutsch, 2013; Laver et al., 2017). To address the current gap in the literature, high quality evidence from large randomized control trials comparing adjunctive VR-based interventions to active treatment are needed to support the effectiveness of supplementary VR-based intervention in the sub-acute phase of stroke rehabilitation. Future randomized control trials would benefit from using valid and reliable outcome measures, such as laboratory-based kinematic analysis, observational kinematics or the Reaching Performance Scale for Stroke (RPSS), to objectively measure UL movement performance and quality during functional tasks. The development of guidelines for the use of kinematic and kinetic metrics to identify motor deficits, such as the current work by the Stroke Rehabilitation and Recovery Roundtable, will help to standardize the assessment of UL motor recovery in future effectiveness trials (Bernhardt et al., 2016; Kwakkel et al., 2017). With the limitations of current outcome measures used in neurological practice to assess movement quality and performance, the use of VR combined with markerless motion capture systems is promising for the assessment of the UL during functional activities. One recent study compared the scorings of the RPSS by trained clinicians with an automated algorithm analyzing movements collected by the Kinect II movement tracking system (Scano et al., 2018). The correlation between the trained clinician and the algorithm was high. While the results are very promising, this study has important limitations that were not acknowledged by the authors (i.e. the RPSS was not administered properly and the task did not involve grasping), limiting the applicability of the results. However, the potential for using VR for enhancing UL assessment in clinical practice is high and should be more carefully investigated in future studies.

Another question of interest for future trials of VR-based interventions is whether the incorporation of VR interventions using ecologically-valid environments can lead to better transfer of skills to real-world situations. To date, only a few studies have investigated the effectiveness of VR intervention on UL function in everyday activities, using the Motor Activity Log as an outcome measure (Housman et al., 2009; Subramanian et al., 2013). Therefore, the transfer of skills from VR interventions to real-life settings remains to be better established with outcome measures that can track UL behaviour in natural settings. While higher doses of VR interventions (e.g. more than 15 hours of intervention in total) could be preferable to lower doses (e.g. less than 10 hours in total; Laver et al., 2017), a dose-response relationship also remains to be established. A cost-analysis would also be beneficial to inform whether VR interventions (commercial VR applications or customized VR applications) are more efficient than other supplementary interventions. A cost-analysis would allow clinicians to make informed decisions on the cost vs. the potential benefits and the number of clients who may benefit from use. Finally, to inform the design of future VEs for rehabilitation purposes, understanding how UL movement performance and quality are impacted by the visual features of the VE such as visual cues, visual representation and properties of target objects could help to progress the field of virtual rehabilitation.

Ultimately, the development and implementation of VR applications for stroke rehabilitation should be done in close collaboration between individuals receiving rehabilitation care, clinicians, researchers and industry at all the stages of the developmental process. With the growing field of patient oriented research in healthcare (Sacristán, 2013), the active participation of end-users is imperative to ensure the development of accessible and sustainable VR interventions based on the preferences and objectives of the targeted users. Industry experts have the technical knowledge and the ability to develop creative and motivating VR applications for users. This close collaboration between all stakeholders will ensure that VR applications are accessible for individuals with disabilities, easy-to-use for key stakeholders and specifically targeting rehabilitation goals to capitalize on the potential of VR interventions for rehabilitation.

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Appendix 1 – Interview guides

Focus Group Discussion Guide

Introduction:

This focus group discussion is designed to assess your current thoughts and feelings about a newly developed video game program designed for the rehabilitation of individuals who have had a stroke. The video game program targets motor impairments in the upper limb and aims at simulating a grocery shopping task. Your feedback will serve to improve this program to obtain a final version that can be used in the rehabilitation of individuals who have had a stroke. The focus group discussion will take no more than one hour. May I tape the discussion to facilitate its recollection? (if yes, switch on the recorder)

Anonymity:

Despite being taped, I would like to assure you that the discussion will be anonymous. The tapes will be kept safely in a locked facility until they are transcribed word for word, then they will be destroyed. The transcribed notes of the focus group will contain no information that would allow individual subjects to be linked to specific statements. You should try to answer and comment as accurately and truthfully as possible. We will appreciate it if you would refrain from discussing the comments of other group members outside the focus group.

Ground rules:

The most important rule is that only one person speaks at a time. There may be have the temptation to jump in when someone is talking but please wait until they have finished.
There are no wrong answers but rather differing points of view.
You do not have to speak in any particular order
When you do have something to say, please do so. It is very important that we hear all your opinions.

Please feel free to be frank and to share your point of view, regardless of whether you agree or disagree with what you hear.

My name is Marika. My role consists in asking you questions and listen. I will not take part in your discussion. Daniel is here to take notes on the discussion and to make sure the recording device is working well.

I'll ask a dozen questions, prompting you to jump from one subject to another. During focus groups, some participants tend to talk more than others. Because we want to hear everyone's opinion, it is possible that I interrupt people or I invite others to speak more.

Warm up

First, I'd like everyone to introduce themselves. Can you tell us your name, if you are working with in- or out-patients?

Guiding questions

Topic 1 - Familiarity of clinicians with virtual reality

- Have you used any forms of virtual reality, including video games, in the past, as part of your treatment modalities?
- Describe the context in which you used virtual reality.
- What is your perception of the effectiveness of using virtual reality intervention to target upper limb motor impairments?
- To target activities of daily living, such as grocery shopping?
- Describe your level of awareness of the evidence supporting virtual reality in rehabilitation following a stroke?

Topic 2 – Satisfaction with the virtual reality games

- What is your perception of the virtual reality program?
    - More specifically "Smash Blocks" game?
    - More specifically "Shopper's delight" game?

- What was your level of satisfaction with the virtual environment in which the games take place?
- How do you find the realism of games?
- What is your perception of the level of difficulty of the Smash Block for individuals who have had a stroke? … the level of difficulty for Shopper's delight?
- Is it appropriate for in-patients, as well as out-patients?

Topic 3 – Usefulness of the virtual reality program

- What is your perception of the usefulness of this program in clinical practice?
- Would you use this intervention in your clinical practice? Why?
- What elements of this program are appealing to you in your clinical practice?
- What are the strengths of this virtual reality program?
- What are the weaknesses of this virtual reality program?

Topic 4 - Ease of use of the virtual reality program in rehabilitation

- What is your perception of the ease of use in rehabilitation?
- What is your perception of the accessibility of the program for individuals who have had a stroke?

Concluding question

Of all the things we've discussed today, do you have any other comments or concerns about the virtual reality intervention?

Summary of the discussion

Let's summarize some of the key points from our discussion. Is there anything else?
Do you have any questions?

Conclusion

Thank you for participating in this focus group. This has been a very successful discussion Your opinions will be a valuable asset to this study. We hope you have found the discussion interesting.

Interview Guide

Introduction:

We want to thank you again for agreeing to participate in this study. Now that you had the chance to interact with the videogames, we want to obtain your impressions and your satisfactions towards the games. We will first ask you to complete a short questionnaire. Then, I will ask you additional questions to obtain your feedback about your experience of using the video games.

This discussion is designed to assess your current thoughts and feelings about a newly developed video game program designed for individuals who have had a stroke, like you. You should try to answer and comment as accurately and truthfully as possible. Your feedback will serve to improve this video game to obtain a final version that can be used in the rehabilitation of individuals who have had a stroke. The discussion will take no more than 30 minutes. May I record the discussion to facilitate its recollection? (if yes, switch on the recorder)

Anonymity:

Despite being taped, I would like to assure you that the discussion will be anonymous. The tapes will be kept safely in a locked facility until they are transcribed word for word, then they will be destroyed. Daniel will assist me in taking notes about our discussion.

Introduction:

Previous experience

- Do you have experience using video games in the past?
- If yes, could you describe the type of games you tried?
- How frequently were you playing video games before your stroke?
- Have you used video games as part of your treatment following your stroke (in occupational therapy, physical therapy or in the Games room)?

Topic 1 – Enjoyment

- How was your experience of playing both video games?
- How would you describe your level of enjoyment with the video games?

Or

- *Probe question* - You mentioned you enjoyed _____ the video games. Could you elaborate?
- *Probe question* - What did you enjoy about the games?
- *Probe question* - What did you not enjoy about the intervention?
- *Probe question* - Why did you (or not) enjoy ___ ?

Topic 2 – Immersion/Realism

- *Probe question if participant answered it was not realistic* – Why did you perceive that the environment was not realistic?

Topic 3 – Control

- Why did you feel (or not) in control of the situation?

Topic 4 – Tolerability

- How did you feel during the interaction with the video games?
- How are you feeling now?
- Did you perceive the level of difficulty was adequate for someone with arm impairments after a stroke?
- *Probe question* - Why did you perceive the intervention was ___ difficult?

Topic 5 –Safety

- *Probe question* - Could you describe the type of discomfort you experienced?
- Have you experienced any of the following symptoms? Nausea, headaches, dizziness, eyestrains, blurred vision, pain?
- If yes, how would you rate/describe these symptoms?

Topic 6 - Type of intervention

- How did you like the feedback given by the computer?
- *Probe question if the participant perceived the feedback was not clear* – What was not clear about the feedback?
- How could the feedback provided be improved?
- Did the feedback help you to perform/guide your arm movements?

Summary of the discussion

Let’s summarize some of the key points from our discussion. Is there anything else?

Do you have any questions?

Conclusion

Thank you for participating in this study. This has been a very successful discussion

Your opinions will be a valuable asset to this study.

Appendix 2 – Consent forms

Clinician's consent form (Manuscript 1)

TITLE OF PROJECT: Feasibility of a virtual reality training environment for upper limb rehabilitation in sub-acute stroke

PERSONS IN CHARGE OF PROJECT

Mindy F. Levin, PhD, PT, Principal Investigator, School of Physical and Occupational Therapy, McGill University – tel.: (450) 688–9550, local: 3834

Marika Demers, OT, PhD candidate, School of Physical and Occupational Therapy, McGill University

Rhona Guberek, pht, research assistant, *CRIR-HJR*

INTRODUCTION

We are asking you to participate in a research project aimed at evaluating the feasibility of using virtual reality to retrain the arm in people who have had a stroke. Before agreeing to participate, please take the time to understand and consider carefully the following information.

This consent form explains the goal of the study, the procedures, the advantages, the risks and inconveniences, as well as the contact information for persons you might want to contact if the need arises.

This consent form may include words that you do not understand. We invite you to ask all the questions that you judge necessary to the researchers or other members of the research team and to ask them to explain any word or information that is not clear.

DESCRIPTION AND GOAL OF THE STUDY

Following a stroke, impairments of the arm, hand and fingers are common. It can impact on the ability to use the arm in everyday life activities, such as washing, dressing, cooking and shopping. The objective of this project is to develop and evaluate the feasibility of using a virtual reality intervention for the rehabilitation of the paretic arm for people who have had a stroke. The virtual reality program consists of two games: Block Smash, where users have to hit virtual objects as quickly and accurately as possible, and Shopper's delight, where users have to retrieve common items from a grocery store. Both games are designed to encourage functional upper limb movements, such as reaching. The virtual environment is interactive, as the user can manipulate objects with their arms and hands. The arm, hand, and trunk movements are tracked using the video motion sensor Kinect II (Microsoft, USA). No joystick, mouse or controller is needed to play the games. Both games provide feedback about movement performance (success scores and speed) and quality (use of compensations) necessary for maximal motor recovery. Each game has three levels of difficulty to ensure individualized training. The virtual environment can be projected on a large television or a projector screen. The results of this study will allow finalizing of the virtual reality intervention to develop a final version that will be appropriate for the rehabilitation of people who have had a stroke.

NATURE AND DURATION OF PARTICIPATION

Your participation in this project consists in participating in a discussion group for a period of 1 hour. This discussion will take place in a closed room at the Jewish Rehabilitation Hospital. The discussion group will include 4 to 8 participants. The research team will present the newly developed virtual reality intervention designed for individuals who are undergoing rehabilitation following a stroke. You will be invited to discuss your perception of the virtual reality intervention to target motor impairments in the upper limb, the game accessibility, your satisfaction with the virtual environment and the feedback given, the level of difficulty for individuals who have had a stroke, the ease of use in rehabilitation and the usefulness in clinical practice. The discussion group will be audiotaped.

ADVANTAGES THAT MAY RESULT FROM YOUR PARTICIPATION

As a participant in a research study, you will not benefit directly from the study. However, information gathered in this study may contribute to the development of better rehabilitation approaches for people who have sustained a stroke.

RISKS AND INCONVENIENCES RESULTING FROM YOUR PARTICIPATION

There are no underlying medical risks deriving from this project. The only inconvenience will be the time that you will devote to this project, since the project will take place over the lunch hour.

AUTHORIZATION TO USE RESULTS

You agree that the information gathered during this project can be used for scientific, professional and teaching communications. It is understood that your anonymity will be respected.

CONFIDENTIAL NATURE OF THIS STUDY

Focus group participants will be required to respect the confidentiality of each participant by not disclosing any information about the focus group. All personal data about you during the course of the study will be coded in order to sure confidentiality. Only members of the research team will have access to them. However, you should be aware that a person mandated by the Research Ethics Board of the CRIR establishments or of the Quebec Ministry of Health and Social Services may access study data and that these persons adhere to a policy of strict confidentiality.

Records that identify you as a participant will be stored under lock and key by the investigators for a period of 5 years after the end of the project. After this period, the data will be destroyed.

COMPENSATION

There is no monetary compensation offered for your participation in the research project.

WITHDRAWAL FROM THE STUDY

Your participation in the research project described above is completely free and voluntary. You understand that I have the right to withdraw from the study at any moment without giving reason.

RESPONSIBILITY CLAUSE

By accepting to participate in this study, you do not surrender any of your rights and you do not liberate the researchers, their sponsors or the institutions involved from their legal and professional obligations.

INFORMATION CONCERNING THE PROJECT AND RESOURCE PERSONS

For information or questions concerning your participation, please contact the persons in charge of this project: Rhona Guberek, pht, at 450-688-9550 extension 4824 or Mindy Levin at 450-688-9550 extension 3834.

If you have any questions regarding your rights as a research subject and you wish to discuss them with someone not conducting the study, please contact Anik Nolet, research ethics coordinator for CRIR at (514) 527-4527 extension 2643 or by email: anolet.crir@ssss.gouv.qc.ca. You can also contact the office of the Commissioner of Complaints and Quality of Services of the CISSS Laval at 450 - 668-1010 ext. 23628.

DECLARATION OF CONSENT

I declare having read and understood the present project, the nature and extent of my participation they are presented in this consent form. I have had the opportunity to ask questions concerning the different aspects of the study and they have been answered to my satisfaction.

I, undersigned, freely and voluntarily consent to participate in this study. I can withdraw at any time without any effect or penalty.

I certify that I have been given enough time to make my decision.

I accept to be contacted by the same researchers to participate in other scientific study done in a similar area of research.

Yes, for one year ☐ Yes, for two years ☐ Yes, for three years ☐ No ☐

I accept that the data collected in this study can be used for other scientific studies related to the present project, by the same researchers.

Yes ☐ No ☐

A signed copy of this information and consent form must be given to me.

__________________________ __________________________

Name of participant Signature of participant

Done in ________________, date__________________, 20_____.

COMMITMENT OF THE RESEARCHER

I, the undersigned, ____, certify

(a) having explained to the signer the terms of the present form ;
(b) having answered their questions regarding the project;
(c) having clearly indicated that (s)he remains free of withdrawing their participation to this research project described above; and
(d) that I will give them a signed and dated copy of this consent form.

____

Signature of the person responsible for project or their representative

Done in __________________, date ______________ 20__.

Consent form for individuals who have had a stroke (Manuscript 1)

TITLE OF PROJECT: Feasibility of a virtual reality training environment for upper limb rehabilitation in sub-acute stroke

PERSONS IN CHARGE OF PROJECT

Mindy F. Levin, Ph.D, PT, Principal Investigator, School of Physical and Occupational Therapy, McGill University – tel.: (450) 688–9550, local: 3834

Marika Demers, OT, PhD candidate, School of Physical and Occupational Therapy, McGill University
Rhona Guberek, pht, research collaborator, CRIR-HJR

INTRODUCTION

We are asking you to participate in a research project aimed at evaluating the feasibility of using virtual reality to retrain the arm in people who have had a stroke. Before agreeing to participate, please take the time to understand and consider carefully the following information.

This consent form explains the goal of the study, the procedures, the advantages, the risks and inconveniences, as well as the contact information for persons you might want to contact if the need arises.

This consent form may include words that you do not understand. We invite you to ask all the questions that you judge necessary to the researchers or other members of the research team and to ask them to explain any word or information that is not clear.

DESCRIPTION AND GOAL OF THE STUDY

Following a stroke, impairments of the arm, hand and fingers are common. It can impact on the ability to use the arm in everyday life activities, such as washing, dressing, cooking and shopping. The objective of this project is to develop and evaluate the feasibility of using a virtual reality tool for the rehabilitation of the arm for people who have had a stroke. The virtual reality tool aims to simulate a task of everyday life: shopping in a grocery store. The results of this study will allow finalizing the virtual reality tool to develop a final version that will be appropriate for people who have had a stroke.

NATURE AND DURATION OF PARTICIPATION

Your participation in this project consists in a 1½ hr session. This study will take place at the Sensorimotor Control & Rehabilitation Laboratory of the Jewish Rehabilitation Hospital. During the session, you will interact with a virtual reality tool and provide your feedback and impression of this tool. The virtual reality tool was developed by the research team, specifically for the rehabilitation of the arm following a stroke. It consists of 2 video games: Block Smash, where you will have to hit virtual objects as quickly and accurately as possible, and F(V)AST, where you will retrieve common items from a grocery store. During 1 hour, you will interact with the video games display on a large screen. The games will require you to use both arms. A camera will capture your movements and a cartoon of your arms will be displayed on the screen. You do not have to use a joystick or a controller. The games will be performed in the standing position, but you can sit down at anytime if needed. The session will also be video recorded to allow the research team to count the number of arm movements performed during the session. Following the 1-hour session with the virtual reality tool, you will be asked for your feedback about the games, by filling a questionnaire and answering a few questions. The questionnaire contains 8 questions used to rate the realism, perceived usefulness, level of difficulty and satisfaction with the tool. Then, a researcher will also ask you additional questions to obtain your feedback about your experience of using the virtual reality tool. Your answer to the questions will be audio recorded. This portion will last approximately 30 minutes.

ADVANTAGES THAT MAY RESULT FROM YOUR PARTICIPATION

As a participant in a research study, you will not benefit directly from the study. However, information gathered in this study may contribute to the development of better rehabilitation approaches for people who have sustained a stroke.

INCONVENIENCES RESULTING FROM YOUR PARTICIPATION

It is possible that you will experience the following inconveniences: additional fatigue, nausea, headaches, dizziness, vomiting, eyestrains, blurred vision or pain. A physical or occupational therapist will be present at all times when you will interact with the virtual reality tool. If you experience any inconvenience, the activity will be stopped and the research team will make sure that an appropriate health professional will be available to help you. If you feel tired during the evaluation sessions, you will be able to rest at any time before continuing. Also, having to come to the research laboratory and the time to participate in the evaluation sessions may represent an inconvenience for you.

AUTHORIZATION TO USE RESULTS

You agree that the information gathered during this project can be used for scientific, professional and teaching communications. It is understood that your anonymity will be respected.

ACCESS TO YOUR MEDICAL CHART

You agree that the people responsible for this project may access your medical records at the rehabilitation hospital to gather relevant information about your stroke, such as the date on which the injury occurred, its location and the results to the evaluations performed in physical and occupational therapy for your arm (test of strength, dexterity, sensation and ability to manipulate objects). Information related to the projects goals will be accessed.

CONFIDENTIAL NATURE OF THIS STUDY

All personal data about you during the course of the study will be coded in order to ensure confidentiality. Only members of the research team will have access to them. However, you should be aware that a person mandated by the Research Ethics Board of the CRIR establishments or of the Quebec Ministry of Health and Social Services may access study data and that these persons adhere to a policy of strict confidentiality.

Records that identify you as a participant will be stored under lock and key by the investigators for a period of 5 years after the end of the project. After this period, the data will be destroyed.

COMPENSATION

There is no monetary compensation offered for your participation in the research project.

WITHDRAWAL FROM THE STUDY

Your participation in the research project described above is completely free and voluntary. You understand that I have the right to withdraw from the study at any moment without giving reason. This will not affect the health care and services you receive. Should you withdraw from the study, if you agree, your data will be used in the study.

RESPONSIBILITY CLAUSE

By accepting to participate in this study, you do not surrender any of your rights and you do not liberate the researchers, their sponsors or the institutions involved from their legal and professional obligations.

INFORMATION CONCERNING THE PROJECT AND RESOURCE PERSONS

For information or questions concerning your participation, please contact the persons in charge of this project: Rhona Guberek, pht, at 450-688-9550 extension 4824 or Mindy Levin at 450-688-9550 extension 3834.

If you have any questions regarding your rights as a research subject and you wish to discuss them with someone not conducting the study, please contact Anik Nolet, research ethics coordinator for CRIR at (514) 527-4527 extension 2643 or by email: anolet.crir@ssss.gouv.qc.ca. You can also contact the office of the Commissioner of Complaints and Quality of Services of the CISSS Laval at 450 - 668-1010 ext. 23628.

DECLARATION OF CONSENT

I declare having read and understood the present project, the nature and extent of my participation as they are presented in this consent form. I have had the opportunity to ask questions concerning the different aspects of the study and they have been answered to my satisfaction.

I, undersigned, freely and voluntarily consent to participate in this study. I can withdraw at any time without any effect or penalty.

I certify that I have been given enough time to make my decision.

I accept to be contacted by the same researchers to participate in other scientific study done in a similar area of research.

Yes, for one year ☐ Yes, for two years ☐ Yes, for three years ☐ No ☐

I accept that the data collected in this study can be used for other scientific studies related to the present project, by the same researchers.

Yes ☐ No ☐

A signed copy of this information and consent form must be given to me.

______________________________ ______________________________

Name of participant Signature of participant

Done in ________________, date__________________, 20_____.

COMMITMENT OF THE RESEARCHER

I, the undersigned, ____, certify

(a) having explained to the signer the terms of the present form ;

(b) having answered their questions regarding the project;

(c) having clearly indicated that (s)he remains free of withdrawing their participation to this research project described above; and

(d) that I will give them a signed and dated copy of this consent form.

____

Signature of the person responsible for project or their representative

Information and consent form (healthy individuals and individuals who have had a stroke; Manuscript 3)

1. TITLE OF PROJECT

Reaching, thinking, moving: virtual reality for upper limb rehabilitation

2. PERSON IN CHARGE OF PROJECT

Mindy F. Levin, PhD, PT
Professor, McGill University
Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal
Telephone: (450) 688-9550, extension 3834
E-mail: mindy.levin@mcgill.ca

3. COLLABORATORS

Marika Demers, MSc, OT
PhD candidate, McGill University
Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal
Telephone: (450) 688-9550, extension 4824
E-mail: marika.demers@mail.mcgill.ca

Réjean Prévost, OT
Research assistant
Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal
Telephone: (450) 688-9550, extension 4824
E-mail: rejeanprevost.jrh@gmail.com

4. SPONSORING ORGANIZATION

Marika Demers received a scolarship from the Fonds de la Recherche du Québec en Santé.

5. PREAMBLE

We are asking you to participate in a research project comparing the way arm movements used to accomplish everyday activities are performed in a virtual environment, as well as in the real world, in individuals who have had a stroke and in healthy individuals. Before agreeing to participate in this research project, please take the time to read and carefully consider the following information.

This consent form explains the aim of this study, the procedures, advantages, risks and inconvenience as well as the persons to contact, if necessary.

This consent form may contain words that you do not understand. We invite you to ask any question that you may have to the researcher and the other members of the research team and ask them to explain any word or information that is not clear.

6. DESCRIPTION OF THE STUDY AND ITS PURPOSE

Virtual reality and videogames are increasingly used in the rehabilitation of individuals who have had a stroke. To ensure that the movements that are practiced when playing videogames/virtual reality 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 project aims to compare if 3 functional arm movements performed in a virtual environment are similar to the same movements performed in the real world, in individuals who have had a stroke and in healthy individuals. Three movements will be studied: reaching for a box with one arm, reaching for a large bag of rice with both arms, and opening a refrigerator door and reaching to grasp a can.

7. NATURE AND DURATION OF PARTICIPATION

If you agree to participate, your participation in this project consists in 2 sessions of approximately 2 hr per session. This study will take place at the Sensorimotor Control & Rehabilitation Laboratory of the Jewish Rehabilitation Hospital.

During the first session, an experienced clinician will use clinical tests to assess your arm movements, your balance, your visual perception and your cognition (memory, attention, etc.) For example, you will have to make different movements of the arms (lift your arms in the air, flex the wrist, etc.), open a container, button 5 buttons and identify images placed in different directions. During these tests, it is possible that the research team will discover some impairment that has not been identified before (e.g., perceptual impairments). Based on the results of the tests, it is possible that some participants will be excluded from this study.

During the second session, you will be asked to make 3 different arm movements in 2 environments: a virtual environment that replicates a grocery store and a mock-up version of the grocery stroke (physical environment). Your movements will be recorded by two cameras (motion capture system) by way of markers attached to the skin of your arms, trunk, hips and big toe with hypoallergenic tape. In each environment, each movement will be repeated 20 times while standing, for a total of 120 movement repetitions. Rest will be offered after each block of 20 movement repetitions. Participants will be asked to wear a tank top or a t-shirt for the experimental session.

8. BENEFITS THAT MAY ARISE FROM YOUR PARTICIPATION

As a participant in a research study, you will not benefit directly from participating in this research project study. However, from a scientific point of view, you would have participated in the advancement of scientific knowledge about the use if virtual reality to address arm motor impairments in individuals who have had a stroke**.**

9. INCONVENIENCES THAT MAY RESULT FROM YOUR PARTICIPATION

There is no risk to your participation in this study. While the virtual reality program has already been tested regarding its feasibility for individuals who have had a stroke, there is a slight possibility that you may experience the following inconveniences: nausea, headaches, dizziness, vomiting, eyestrains, or blurred vision. A physical or occupational therapist will be present at all times to monitor your status. If you experience any inconvenience, the activity will be stopped and the research team will make sure that an appropriate health professional will be available to help you. It is possible that the effort required during the experiment may cause some fatigue or muscle/joint pain, but this will be temporary. It is understood that if you feel tired during the session, you can rest before continuing at any time. The tape used to attach the markers on your skin may cause a skin reaction. If redness is observed, a calming lotion will be applied on the area. If the skin reaction continues for more than 24 hours, you should notify the researchers and consult a doctor. Also, having to come to the research laboratory and the duration of evaluation and the experimental sessions of about 2 hours may represent an inconvenience for you. It is understood that your participation in this project does not affect your present or future medical care or services. If the research team discover, during the screening, some impairment that has not been identified before (e.g., perceptual impairments), you will be directed to your treating physician or to an appropriate health professional.

10. ACCESS TO RESULTS AT THE END OF RESEARCH

At the end of the study, you will be able to access the general results from this research project.

Yes ☐ No ☐

Email address: ____

11. ACCESS TO YOUR MEDICAL CHART (PARTICIPANTS WITH STROKE ONLY)

You agree that the people responsible for this project may access your medical records at the rehabilitation hospital to gather relevant information about your stroke (e.g. lesion type/location, medical history, medications, upper limb motor ability, perception and/or cognitive ability). Only information related to the project objectives will be accessed.

12. CONFIDENTIALITY

All personal information collected about you during the study will be coded to ensure your confidentiality. Only members of the research team will have access to them. However, for purposes of research monitoring, your research chart could be consulted by a person authorized by the REB of CRIR institutions or by the Directorate of Ethics and Quality of the Department of Health and Human Social Services of Quebec, which adheres to a strict privacy policy. Research data (paper or recordings) will be kept under lock and key at the Sensorimotor Control & Rehabilitation Laboratory by the head of the study for a period of 10 years following the end of the project, after which they will be destroyed. In case of presentation of results of the research or publications, nothing can identify you.

13. VIDEO RECORDING AND/OR TAKING PHOTOGRAPHS

It is possible that some sessions will be recorded on videotape, and that photographs will be taken. We would like to use these, with your permission, for the purpose of training and/or scientific presentations. It is however not required to consent to this section in order to participate in this project. If you refuse, recordings and photographs received will be destroyed at the end of the project to respect your confidentiality.

May we use your photographs or recordings for training or scientific presentations and keep them with your research data?

Yes ☐ No ☐

14. VOLUNTARY PARTICIPATION AND RIGHT TO WITHDRAW

You are free to accept or refuse to participate in this research project. You can withdraw from the study at any time, without giving any reason, and will not experience any kind of prejudice. You simply have to notify the contact person of the research team and give verbal notice. In case of your withdrawal, with your permission, your data will be retained in the study.

15. FURTHER STUDIES

It is possible that the results obtained following this study may lead to another research project. In this case, do you authorize the members of this project to contact you again to ask you if you want to participate in this new research?

☐ no
☐ yes for one year *
☐ yes for two years *
☐ yes for three years *

* Note that if you select one of these three cases, your personal details will be kept by the principal investigator for the period to which you consent.

16. RESPONSIBILITY CLAUSE

By agreeing to participate in this study, you are not waiving any of your rights nor release the researchers or the establishment of their civil and professional responsibilities.

17. COMPENSATION

For your participation in this research project and the related constraints (e.g. travel costs), an indemnity of $30 CAD will be paid by the person in charge of the research project. If you withdraw after the first session, you will be compensated for only one session ($15).

18. RESOURCE PERSONNEL

If you have questions about the research project, if you wish to withdraw from the study or if you want to inform the research team of an incident, you can contact the Project Director, **Mindy Levin** at the following address:

Jewish Rehabilitation Hospital
Research Department
3205 Place Alton Goldbloom, Laval, QC, H7V 1R2
tel: (450) 688-9550, extension 3834
fax: (450) 688-3673 attn.: Vira Rose

If you have any question about your rights, recourse or participation in this research project, you may contact **Mrs. Anik Nolet**, Coordinator of Research Ethics for CRIR at: **(514) 527-9565, extension 3795** or by email anolet.crir@ssss.gouv.qc.ca. You can also contact the office of the Commissioner of Complaints and Quality of Services of the CISSS de Laval: **Hélène Bousquet**, **(450) 668-1010, ext. 23628** or by email plaintes.csssl@ssss.gouv.qc.ca
or the ombudsman of the CIUSSS Centre-Ouest de l'Ile de Montréal: **Rosemary Steinberg, 514-340-8222, ext 25833** or by email ombudsman@jgh.mcgill.ca

19. CONSENT

I have read and understood this project, the nature and extent of my participation, as well as the risks to which I expose myself as presented in this consent form. I have had the opportunity to ask any questions about the various aspects of the study and receive satisfactory answers.

I, the undersigned (e) voluntarily agree to participate in this study as a subject. I may withdraw at any time without prejudice of any kind. I certify that I was given the time to make my decision.

A signed copy of this information and consent form will be given to me.

NAME OF PARTICIPANT (print)	SIGNATURE OF PARTICIPANT
______________________________	______________________________

Signed in ______________, on the __________________, 20____

20. RESEARCHER'S COMMITMENT (OR THEIR REPRESENTATIVE)

I, the undersigned, ____certify that I:

a) have explained to the signatory all the conditions related to the present form;
b) have answered all the questions that have been asked in this respect;
c) have clearly indicated that (s)he remains free to withdraw their participation to this research project described above;
d) will give him/her a signed and dated copy of the present form.

____

Signature of Principal investigator or representative

Signed in _________________, on the _____________ 20___