Design and Implementation of a Haptic-Based Robotic System with Virtual Assistance for Children with Disabilities

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

In

Rehabilitation Science

Faculty of Rehabilitation Medicine
University of Alberta

ABSTRACT

BACKGROUND: Limited opportunities for haptic manipulation and motor experience in children with disabilities is linked to developmental delays including cognitive, perceptual, and social impairments. Assistive robots (e.g. Lego robots) have been used as alternative means to remotely act on the environment. Yet, there are critical limitations in provision of direct assisted manipulation. Firstly, typical assistive robot interfaces (e.g. head mounted switches) remotely control the robot in the environment, and thus, fail to simulate the critical aspect of haptic manipulation in transferring the objects' touch-related information. Second, a human helper oftentimes mediates the child's interaction with the environment, obstructing direct interaction with the environment and reducing the child's sense of independence and task control. The functionality of assistive technologies in delivering a haptic-based direct (unmediated human) manipulation experience, particularly in the context of play, has remained unexplored. This suggests the need for research on development of a robotic-based medium capable of simulating direct haptic manipulation and provision of unmediated human assistance.

OBJECTIVE: This thesis work is the result of a literature review, a feasibility study and two usability studies in order to address the following objectives: 1) Determine the researched application areas of haptic-based assistive technology for people with disabilities, and determine their implications for children with disabilities. 2) Develop the initial technical requirements for simulation of direct haptic-based manipulation and critically analyze the appropriate choice of candidate robot interfaces for the requirements for the user and task. 3) Identify the technical feasibility to develop and implement a robotic system with virtual (unmediated human) assistance in a manipulative play task. 4) Clinically validate the effectiveness of the developed technology in accommodating manual skills of individuals with disabilities and compare the outcomes of the robot augmented performance with a typical assistive technology computer interface approach.

METHODS: The objectives were addressed as follows: 1) A literature review was undertaken to establish a retrospective insight into research on assistive robotics for people with disabilities with the focus on manual performance. The potential ideas and challenges for implications of the technology for children with disabilities were identified. 2) Simulation of haptic-based direct manipulation was performed through development of a teleoperation system (dual-robot configuration) featured with haptic feedback. Haptic feedback was tested through a teleoperated drawing task. Technical feasibility was established to determine the choice of robots appropriate for requirements of the user and task. 3) Robotic-based virtual assistance was developed and integrated into a single-robot configuration system. Two protocols were designed to validate the system through a usability study with 15 abled-bodied adults. First, an exploration task was performed to evaluate the safety, stability and perceptibility of the virtual assistance. Next, adults performed a set of functional play tasks, i.e. coloring, with and without virtual assistance in order to validate the effectiveness of assistance. Data derived from the robotic system, survey questions and robot usability questionnaires were collected and analyzed. 4) Clinical validation of the system occurred through a single-subject case study with an individual living with cerebral palsy. The individual participated in the same set of coloring tasks using the robotic system as well as her typical computer interface. A comparison of the approaches was performed.

RESULTS: The most researched application areas of haptic robotic systems and their implications for use by children were identified and represented through the retrospective review of the literature The technical feasibility testing provided the initial set up for the haptic-based manipulation and technical requirements for the user-side and task-side robots in the teleoperation system configuration. Through the usability study with abled-bodied adults, the validity of the technical implementation was confirmed in terms of the system's safety and stability, and performance. Participants performed significantly better in the coloring tasks when virtual assistance was provided. Both medium and maximum levels of assistance significantly outperformed the unassisted condition and led to relatively the same performance improvements. The study with the individual with cerebral palsy confirmed the effectiveness of the system in leveraging her manual capabilities in a functional

manipulative task requiring coordination and fine motor skills. Her typical approach using the computer interface showed considerably less effectiveness compared to the robotic-based approach with assistance in performing the tasks.

PREFACE

This thesis is an original work by Nooshin Jafari, under the supervision of Dr. Kim Adams. The two research projects that form part of this thesis received research ethics approval from the University of Alberta Research Ethics Board:

"Robotic Interface - Guidance for Children with disabilities to explore play objects and color pictures", Pro00060395, December 13, 2015

"Robotic interface with Haptic Guidance and Artificial Intelligence for People with Disabilities", Pro00049751, November 23, 2015

Chapter 2 of this thesis has been published as:

1) Nooshin Jafari, Kim Adams, and Mahdi Tavakoli, "Haptics to improve task performance in people with disabilities: A review of previous studies and a guide to future research with children with disabilities", Journal of Rehabilitation and Assistive Technologies Engineering, 2016, 3:1-13

Chapter 3 has been published as an extended abstract in the following conference, but also includes additional text in the materials section:

2) Nooshin Jafari, Kim Adams, and Mahdi Tavakoli, "Haptic telerobotics: application to assistive technology for children with disabilities", Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) Conference, Poster presentation, June 12-14, 2015

Chapter 4 of this thesis has been accepted for publication as:

3) Nooshin Jafari, Kim Adams, Mahdi Tavakoli, and Sandra Wiebe, “Development of an Assistive Robotic System with Virtual Assistance to Enhance Interactive Play with the Environment for Children with Disabilities - Preliminary Study”, Journal of Medical and Biological Engineering, 2016 (in press).

The student was responsible for the design of the study, ethics application, data collection and analysis as well as the manuscript composition. Dr. Kim Adams was the supervisory author and was involved in the concept formation, data collection, manuscript composition and edits, and data analysis. Dr. Mahdi Tavakoli was involved with the concept formation, data analysis and manuscript edits. Dr. Sandra Wiebe was involved with the data analysis and manuscript edits.

Acknowledgment

I would like to express my sincerest thanks to my supervisor Dr. Kim Adams for her continuous support, patient guidance, thoughtful advice and encouragements throughout my research at the University of Alberta, and for providing me with the great opportunity to engage in a rewarding research project. I would also like to thank Dr. Mahdi Tavakoli for his inspiring guidance, knowledge, advice, and time throughout my research. Thank you to Dr. Sandra Wiebe for her critical and helpful feedback and advice.

I would like to thank my lab mates Elizabeth Guevara, Isabela Sebastian Vieira, Lina Maria Becerra, Paola Rocio Esquivel, Maria Gomez Medina, Javier Leonardo Castellanos and Isao Sakamaki who made my time in the Assistive Technology lab an always memorable and pleasant experience. Finally, I would like to thank my beloved family for their unconditional love, support, and patience throughout my studies in Canada and my entire life.

Last but not the least, I would like to acknowledge the financial support for this research, the Collaborative Health Research Project (CHRP), a joint initiative of the National Sciences and Engineering Research Council (NSERC) and Canadian Institutes of Health Research (CIHR), and the Glenrose Rehabilitation Hospital Foundation.

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Chapter 1

INTRODUCTION AND OVERVIEW

Manipulation and environmental interaction

Developmental theories suggest a strong tie between early exposure to environmental exploration and manipulation, and development of perceptual, cognitive, linguistic and social skills (Power, 2000). Exploratory actions can provide unique and simultaneous exchange of information between a human and his/her surrounding environment (Taylor, Lederman, & Gibson, 1973). Gibson's ecological perceptual theory of development describes exploratory behavior in children as an ongoing cycle between action, perception, and cognition (Gibson, 1988b). Perception involves the process of gathering information from different sensory modalities including visual, hearing and haptic systems. Infants experience haptic perception through simple and spontaneous exploratory behaviors from birth (Gibson, 1988a) and later, through more developed behaviors throughout their childhood (Power, 2000). They are intrinsically motivated to explore and discover the world (Gibson, 1988b). Their simple motor and sensory activities lead to construction of primary knowledge about the surrounding environment, which is critical in evolution of more complex motor and perceptual behaviors (Gibson, 1988b). As the musculoskeletal and sensory system develops (around 5-9 months old), new action systems emerge and children engage in more advanced exploratory behaviors (Gibson, 1988b).

According to Gibson, children build foundation of knowledge (i.e. the cognition aspect) about what the world around them affords and what they can do with it by acting on the environment and realizing its perceptual consequences (Gibson, 1988b). The knowledge obtained from the action and perception of objects brings about the ability to predict a tool's use, resulting in increased dexterity and accuracy of exploratory movements. This view suggests that exploratory behavior in children is based on some prediction about the outcomes and is not just a random act. Consistent with Gibson, Flanagan et al. (2006) also suggest that the mechanism of object manipulation relies on the fast predictions made by the central nervous system (CNS) about the object (Flanagan, Bowman, & Johansson, 2006). Before the action happens, the CNS predicts the required movements and forces needed to manipulate an object and predicts the sensory events as a consequence of the action. After the action takes place, the sensorimotor process gets involved by transferring the signals, generated by the cutaneous and proprioceptive receptors, to the CNS where the predicted and actual sensory events will be compared. In the event of a mismatch, the CNS triggers a "corrective" signal that modifies the action, for instance, by increasing or decreasing the forces at the fingertips, and subsequently, updating the representation of the object properties in memory.

Children usually experience manipulation and environmental interaction through play. Play contributes to children's development in terms of social competence, focused attention, and self-esteem (Blanche, 2008). It begins with exploring the physical properties of objects through mouthing and then evolves to more complex actions by inclusion of other sensory inputs (vision, sound, and touch) (Fazio & Parham, 2008). Jean Piaget introduced one of the most influential theories of play in accordance with his theory of cognitive development (Piaget & Cook, 1952). He stated that sensorimotor play begins from birth and develops during the first two years of life and involves actions such as motor reflexes, simple motor movements, imitation of behaviors, and exploration of objects through novel motor actions. The sensorimotor stage of play has a crucial role in construction of an infant's advanced levels of thinking (Piaget & Cook, 1952).

Play is not only a means of pleasure and fun but also promotes development of cognitive and motor skills (Sutton-Smith, 2001).

Scribbling and coloring

Coloring is a *manual play activity* that involves interaction with the environment (i.e. a coloring surface) as well as manipulation of objects (i.e. a coloring/writing tool), which are critical stimuli to various aspects of development (Gibson, 1988b; Piaget & Cook, 1952). Children are usually introduced to coloring before school though coloring books and coloring tools (Mayesky, 2009). Gruber et al. (1994) studied self-interpretation of coloring activities in primary-aged children (Gruber & McNinch, 1994). Children were asked about their feelings and memories of coloring and findings showed that children viewed coloring as a favorite and positive activity by reporting it as a happy, fun, good experience, and desired more involvement with it. Similarly, the parents saw coloring as a "positive tool for expression and imaginations" (Gruber & McNinch, 1994).

Coloring can generally contribute to fine motor skills, eye-hand coordination, artistic thoughts, focused attention and imagination (Gruber & McNinch, 1994; Mayesky, 2009). It begins with initial scribbling and later, the obtained skills evolve into the meaningful symbols and drawings (Gruber & McNinch, 1994), and use of writing tools through a rewarding and pleasurable experience (McGee & Richgels, 2011). Early use of writing tools can enhance "in-hand manipulation" skills such as how to grasp the tool and adjust the applied pressure and direction of movements, or how to rotate tools between the palm and the fingers (Feder & Majnemer, 2007).

The circle and oval, and later, the square and rectangle are generally the first four basic forms children draw (Mayesky, 2009), and are related to the next stages of writing and art. They initially develop when the child recognizes them in his scribbles and then, tries to repeat them. In the same way, writing is believed to usually start with imitating simple geometric shapes such as the circle and square (Feder & Majnemer, 2007).

Based on Takata's taxonomy of play development, children develop the required skills to use coloring tools and begin scribbling during the sensorimotor stage (Takata, 1974). At this stage, scribbling and coloring is not well controlled and is more of a sensory experience with the materials (e.g. rolling the crayons in hands and over the paper, or feeling the crayon on the paper) (Lowenfeld, 1957; Mayesky, 2009). They may first scribble the whole page but the scribbling (and coloring) becomes more elaborate and purposeful as they gain physical control and eye hand coordination and through the repetition (Lowenfeld, 1957; Mayesky, 2009). This gradual gaining of muscle and visual control gives the child a great deal of enjoyment since they notice coordination between what they are doing and seeing (Mayesky, 2009). This process can be different or delayed for children with disabilities due to their fine motor deficits.

Manipulation and play in children with disabilities

In children with disabilities, the cycle of action, perception and cognition may be broken due to restrictions in body functions that limit children in acting on the environment, even if their perception and cognition are intact (Gibson, 1988b). Not being able to act, will limit opportunities for manipulation and exploration, which in turn can affect learning, and lead to delayed perceptual and cognitive skills (Gibson, 1988b). Lack of physical or cognitive demands of a play activity can result in "primary deprivations" (Missiuna & Pollock, 1991), referred to as "organic impairments" (Gindis, 1995), which are a result of a medical condition. "Secondary deprivations" might arise due to the limited play opportunities or exclusion from social, educational, and environmental interactions (Vygotsky, 1978). Failing to provide alternative manipulation and play opportunities for children with impairments can produce secondary deprivations. .

Primary deprivations such as neurological damage in children with disabilities may generate *perceptual deficits* affecting the child's tactile and proprioceptive discrimination (Fazio & Parham, 2008). For example, in an experimental study, children with cerebral palsy showed significant preference for certain play materials that provided more intense sensory input such as hard toys over soft ones (Curry J, 1988). The authors explained this by impaired tactile sensitivity in children with cerebral palsy and the need for stronger proprioceptive feedback. Similarly, multiply handicapped children preferred an object with more distinct tactile stimuli such as vibration as opposed to texture (e.g. yarn or fur) (Danella, 1973).

Affolter et al. (2004) studied the underlying cause of *perceptual* deficits in children with disabilities and supported the idea that action and interaction with the environment is a fundamental element of perceptual development (Affolter, 2004). They demonstrated that children with visual and hearing impairments, whose tactile perception was intact, could eventually reach the ceiling performance, but with a delay compared to their typically developing peers, in a series of perceptual tasks. However, children with disabilities, whose perceptual functioning was atypical, were scored lower in the tasks. Therefore, the authors concluded that seeing and hearing do not underlie exploratory and perceptual performance (but their absence can reduce motivation) whereas perceptual deficits, as a result of limited environmental interaction, can impair performance.

A reduced sense of *self-efficacy* is another secondary disability that could arise due to impaired manual functioning. Perceived self-efficacy[1] is defined as “beliefs in one's capabilities to mobilize the motivation, cognitive resources, and courses of action needed to meet given situational demands” (Bandura, 1994, p 408). In other words, self-efficacy describes how one believes in his/her abilities to succeed in a task, and this in turn can influence future performance in achieving goals and facing challenges. “Theoretically, enhanced feelings of self-efficacy will in turn result in improved perception of performance and satisfaction with performance” (Reid & Campbell, 2006, p. 257). Dweck (2002) reviewed studies on developmental changes in children’s self-perception of ability, especially in the event of failure, and how they can affect their beliefs, motivation and performance (Dweck, 2002). Young children (preschoolers and kindergarteners) are described as “hardy” children who are generally highly optimistic about their abilities and are less “vulnerable” to fail. If they fail, they will try more as they believe in the positive effect of “effort”. They view a fail as a lack of effort rather than ability. But as children age (around 7 years old), they become less optimistic about their abilities. They tend to show a strong loss of motivation in the event of failure as they see less benefit in effort to improve ability. Thus, their present failure is more likely to affect their future performance. If they fail in doing a certain task, they might avoid trying it again. Considering children with disabilities who may experience more failures or performance dissatisfaction due to physical challenges, they may be more susceptible to develop a reduced sense of self-efficacy and performance satisfaction. For example, children with cerebral palsy may fail to perform playful activities requiring fine motor movements such as coloring or drawing. It can be challenging to coordinate hand movements due to sensorimotor impairments such as hand tremor or spasm. This may result in coloring large areas outside the borders or scribbling all over the sheet.

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[1] The terms “self-efficacy” and “self-esteem” have been interchangeably used in the literature.

Provision of robotic-based assistance could increase the chance of success in performing the task and thus, lead to an enhanced sense of self-efficacy and satisfaction.

The people around a child with disabilities, such as playmates or caregivers, can also be the source of a secondary disability called '*learned helplessness*'. Learned helplessness is when a child comes to believe that he/she is not able to perform a task without help, even if he/she has the required skills (Harkness & Bundy, 2001). Caregivers and playmates of children with disabilities often mediate the interaction of the child with the environment during his/her play activity. This can reduce opportunities for independent interactive play with the environment, leading the child to experience more adult interaction than play itself. In addition, the caregivers and playmates often dominate the child's play that can again affect the sense of independence and mastery over the play (Blanche, 2008), All these behaviors can make the child with disabilities passive in play activities, making him/her feel unable to accomplish the task. An *alternative play opportunity* to overcome this deprivation could be achieved through an assistive system that provides *virtual assistance* so the child receives the assistance required to accomplish the task more successfully and satisfactorily while feeling more sense of independence with the least mediation from people around him/her.

Assistive Technologies

Assistive technologies (AT) have been used to connect individuals with disabilities with the environment, and to provide them alternative means to play and reveal their skills. They include a broad range of devices from low tech AT (e.g. mechanical pointers, and paper-based communication boards) to high tech AT (e.g. computers, alternative and augmentative communication devices, power mobility devices, and robot). According to the International Classification of Functioning, Disability, and Health (ICF) model (Organization, 2001), enhancing environmental factors can deliver individuals with disabilities with alternative means to reach levels of performance of typically developing people. An example is switch-controlled assistive robots used for remotely manipulating objects, controlled by head or hand switches, to facilitate task performance in individuals with disabilities, mostly in the area of play for children with disabilities (Cook, Hoseit, Liu, Lee, & Zenteno-Sanchez, 1988; Cook, Howery, Gu, & Meng, 2000; Kronreif & Prazak-Aram, 2008; Rios-Rincon, Adams, Magill-Evans, & Cook, 2015; Rios-Rincon, Adams, Magill-evans, Cook, & Maria, 2016; Robins et al., 2012; Smith & Topping, 1996; Tsotsos et al., 1998). A robot called "PlayROB" assisted children with severe physical disabilities to interact with standard toys such as Lego Bricks and thus, enabled autonomous play (Kronreif, Prazak, Kornfeld, Hochgatterer, & Furst, 2007). Children with significant physical and cognitive impairments used a Rhino XR robotic arm to engage in a series of play and exploration activities (Cook et al., 2000). The robotic arm allowed children to experience independent object play. In free-play scenarios, children with severe cerebral palsy experienced an increased level of playfulness and intrinsic motivation when using a Lego robot (Rios-Rincon et al., 2015, 2016). The general theme of these robots is provision of manipulation and exploration in the context of play.

Purpose

A limitation of the currently used AT systems is that they remotely perform the task in the environment, and thus, fail to simulate the physical sensation of objects. As a result, the child will miss the critical aspect of haptic manipulation involving objects' touch-related information. In addition, the child's interaction with the play environment is usually mediated by a human helper, obstructing direct interaction with the environment and reducing the child's sense of independence and task control. This research introduces an AT robotic-based medium capable of simulating direct haptic manipulation and provision of virtual (unmediated human) assistance implemented in a play activity (i.e. coloring). Coloring introduces children to the use of writing tools and also can reinforce their learning of geometric shapes, which can be used towards their drawings, creative arts and writing letters. Children with disabilities may lack the required manual skills for purposeful coloring due to fine motor deficits, hand spasm, or coordination difficulties). They may cross the borders, color a large area outside the picture, and scribble all over the sheet instead of the desired picture. As a result, the child may experience frustration, disappointment and reduced sense self-efficacy. Virtual assistance is aimed to provide the required physical support.

Research Objectives

This thesis is the result of a review of the literature and the collection of data in order to answer the following objectives.

1) Determine the researched application areas and implications of haptic-based AT for individuals with disabilities that aim at enhancing manual performance and identify their implications for children with disabilities
2) Develop the initial technical requirements for simulation of direct haptic-based manipulation and critically analyze the appropriate choice of candidate robot interfaces for the requirements of the user and haptic manipulation task simulated through a teleoperation system
3) Identify the technical feasibility to develop and implement the robotic system with virtual (unmediated human) assistance, in terms of safety considerations and effectiveness of the technology, in a play activity involving direct interaction with the play environment
4) Clinically validate the effectiveness of the developed technology in accommodating manual skills of individuals with disabilities, and determine the performance differences between the typical AT approach and robot-assisted approach, given different levels of assistance

The papers

The current thesis is composed of four papers that together address the abovementioned research objectives.

Chapter 2. Paper 1: Haptics to Improve Task Performance in People with Disabilities: A Review of Previous Studies and a Guide to Future Research with Children with Disabilities

This retrospective literature review examines the research on the applications of haptic-based assistive robotics using haptic interfaces, exclusively focusing on attributes affecting manual task performance. The paper covers background on the developmental advantages of haptic-based manipulation and exploration for children, and thus, the need for provision of alternative means to typical manipulation for children with disabilities. The research on the use of haptic-based assistive robotics to augment manipulative capabilities of children is scarce and thus, the paper reports the utility of the technology for various disability populations. The limitations, challenges and ideas with respect to research for children with disabilities are outlined.

Chapter 3, Paper 2: Haptic Telerobotics: Application to Assistive Technology for Children with Disabilities

The requirements for technology and task development to simulate teleoperated haptic-based manipulation are provided. A haptic teleoperation system in a master-slave configuration consisting of two haptic robots is developed, the master robot being operated by the human user, and the slave to manipulate the objects in the environment. Teleoperation systems vary with the choice of master and slave robots with respect to certain specifications adequate for certain tasks and target population. Commercially available haptic interfaces are evaluated to determine the best choice for the slave and master robots. Haptic manipulation is implemented through a drawing task.

Chapter 4. Paper 3: Development of an Assistive Robotic System with Virtual Assistance to Enhance Play for Children with Disabilities: A Preliminary Study

Limited exposure to manipulation and unmediated-human interaction with the environment significantly affects various aspects of development in children with disabilities. Motivated by this fact, this paper presents development and implementation of a robotic system with virtual (or unmediated-human) assistance as an alternative tool to typical manual performance to provide access to functional manipulative play and environmental interaction. The preliminary validation of the system is carried out with 15 abled-bodied adults to inform the safety considerations of the robotic system. Potential limitations and obstacles for studies with children with and without disabilities are identified.

Chapter 5. Paper 4: Clinical Validation of a Developed Assistive Robotic System with Virtual Assistance for Individuals with Cerebral Palsy

Cerebral palsy (CP) is a neurological condition that gives rise to clinical symptoms such as tremor, spasm, and involuntary muscle movements. As a result, it can be difficult for an individual with CP to perform manual activities that require fine motor movement and coordination. This paper evaluates the usability of the system in enhancing manual capabilities through empirical testing by an individual with CP. Testing includes user performance in coloring tasks when using the robotic system as well as a customized computer interface. A comparison of the two approaches is presented. Potential implications and limitations to be addressed are discussed in order to improve the system for studies with children.

Chapter 2

PAPER 1: HAPTICS TO IMPROVE TASK PERFORMANCE IN PEOPLE WITH DISABILITIES: A REVIEW OF PREVIOUS STUDIES AND A GUIDE TO FUTURE RESEARCH WITH CHILDREN WITH DISABILITIES

This review examines the studies most pertinent to the potential of haptics on the functionality of assistive robots in manipulation tasks for use by children with disabilities. Haptics is the fast emerging science that studies the sense of touch concerning the interaction of a human and his/her environment; this paper particularly studies the human-machine interaction that happens through a haptic interface to enable kinesthetic feedback. Haptics-enabled user interfaces for assistive robots can potentially benefit children whose haptic exploration is impaired due to a disability in their infancy and throughout their childhood. A haptic interface can provide touch feedback and potentially contribute to an enhancement in perception of objects and overall ability to perform manipulation tasks. The intention of this paper is to review the research on the applications of haptics, exclusively focusing on attributes affecting task performance. A review of studies will give a retrospective insight into previous research with various disability populations, and inform potential limitations/challenges in research regarding haptic interfaces for assistive robots for use by children with disabilities.

Keywords

Haptics, people with disabilities, task performance, object manipulation, haptic interface, and haptic feedback.

Introduction

The word haptics originates from the Greek words *haptesthai* and *haptikos* (meaning “to touch”) and it pertains to both perceptions of touch (or tactile feedback) and force (kinesthetic feedback) (“BS EN ISO 9241-910-,” 2011). Haptics is a bidirectional sensory modality involving the simultaneous exchange of information between a human and his/her environment. It can provide a considerable amount of information to the individual about his or her surrounding environment. Haptic perception relates to the sense of touch through which one can distinguish and recognize objects, even without seeing them (Bushnell & J. Paul Boudreau, 1993). Haptic perception in children develops through environmental exploration and object manipulation in their infancy and throughout their childhood (Power, 2000; Warren, 1982), particularly in the context of play (Gibson, 1988a) and education (Minogue & Joncs, 2006). Piaget’s research in haptic exploratory activities had a significant contribution to the theories of development of haptic perception through manipulative and exploratory activities in early years of life and its importance on cognitive development (Piaget, 1954; Piaget & Cook, 1952; Piaget & Warden, 1926). As children grow, they intuitively learn more sophisticated manual activities as a result of advanced hand functions (Rochat, 1987), such as using a stick to reach a toy. In children with disabilities who cannot reach, grasp and directly manipulate objects due to their physical limitations, perceptual development can be delayed compared to typically developing children of the same age (Harkness & Bundy, 2001). The perceptual cost of constraining haptic manipulation and exploration on object recognition has been studied with non-disabled participants (R. L. Klatzky, Loomis, Lederman, Wake, & Fujita, 1993; Lederman & Klatzky, 2004). By constraining exploration between the hand and object (e.g. wearing thick gloves, plastic finger sheaths or hand-held probes), the authors observed that manual exploration and object identification was impaired as a result of the reduced touch and kinesthetic feedback to the user (Lederman & Klatzky, 2004, 1993).

Direct object manipulation provides information about the properties of an object (e.g., roughness and compliance) that cannot be obtained via seeing and hearing (Taylor et al., 1973). While touching the objects provides cutaneous, thermal and kinesthetic sensory inputs, motor capabilities in terms of reaching and grasping objects enhance the perceptual functions of the hand during exploratory movements for object recognition (Lederman & Klatzky, 1987). Different hand movement patterns that are used to recognize objects during manipulation and exploration have been defined in previous literature (Appelle, 1991; Lederman & Klatzky, 1987; Révész, 1950; Zinchenko & Lomov, 1960). In a series of studies, Lederman and Klatzky outlined the association of haptic perception of each object property (such as hardness and texture) with the employed movement patterns when these researchers observed adults' hand movements during exploratory tasks (Klatzky, Roberta L and Lederman, 1993; R. L. Klatzky, Lederman, & Metzger, 1985; R. Klatzky, Lederman, & Reed, 1987; Lederman & Klatzky, 1987). The researchers categorized the movement patterns into different "exploratory procedures" for exploring different object properties through which the maximum sensory input could be achieved. For instance, exploratory procedure to identify hardness of an object is pushing a finger against the surface of the object.

Assistive robots have been used for people with disabilities (Cook et al., 1988; Kronreif et al., 2005; Kronreif, Kornfeld, Prazak, Mina, & Furst, 2007; Kronreif & Prazak-Aram, 2008), and children with disabilities in the context of education (Kwee, Quaedackers, van de Bool, Theeuwen, & Speth, 2002; Smith & Topping, 1996; Wavering, 1999) and play (Rios-Rincon et al., 2015; Tsotsos et al., 1998) to compensate for their physical limitations and facilitate their object manipulation. However, typical assistive robot interfaces do not transfer the objects' touch-related properties to the user, and as a result, children miss some environmental information. Children do not feel through the interface the physical sensation of knocking over a stack of blocks, hitting a rigid or deformable toy or holding a heavy ball, for example. There needs to be a built-in intermediate link that interfaces children with their environment through the simulated sense of touch. To this aim, mechanized rigid links, referred to as *haptic interfaces*, have been employed to provide haptic feedback, enabling the integral component of physical sensation in robot-mediated object manipulation for children with disabilities.

Haptic interfaces have been defined as "being concerned with the association of gesture to touch and kinesthesia to provide for communication between the humans and machines" (Hayward, R. Astley, Cruz-Hernandez, Grant, & Robles-De-La-Torre, 2004, p16). In other words, a haptic interface generates touch, weight and rigidity sensation to the muscles and skin (Grunwald, 2008). The early haptic interfaces were costly and sophisticated (F P Brooks Jr., Ming, & Batter, 1990; Frederick P Brooks Jr, 1987; Iwata, 1990). Thus far, within the history of haptic interfaces (Grunwald, 2008), most research-based interfaces have been application-specific (Rahman, Hua, Yap, Yeong, & Su, 2012).

A considerable amount of research has been done to address haptic perception of remote environments or virtual environments (VEs). Haptic interfaces have been designed to transfer the interaction forces sensed at the remote environment or VE to the human user through a teleoperation system. In teleoperation applications, the basic haptic system consists of two robots: the user-side haptic interface (master robot) being operated by the human user, and the environment-side robot (slave robot) following the positions (movements) of the user interface and manipulating the objects in the environment. If the environment robot touches an object, the user interface will simulate the touch sensation by generating force feedback (or haptic feedback) to the user hand. This way, the human user gets a feeling of virtually touching the remote object while actually manipulating it through the teleoperation system. In virtual applications, the user moves the user interface, sees the environment on a screen and perceives properties of virtually simulated objects (e.g., shape and texture) through software calculated forces.

Haptic interfaces are being applied in the assistive technology domain. In *rehabilitative* assistive technologies, the primary purpose of intervention is recovery or improvement of impairment (Cook & Polgar, 2008); a typical application is using haptic exotendons for hand rehabilitation therapy (e.g., Rozario, Housman, Kovic, Kenyon, & Patton, 2009). On the other hand, *compensative* assistive technologies are being used to simply compensate for a deficit or an impairment. Common applications are customized haptic interfaces for blind people to aid with computer interaction (e.g., Xiaolong, 2010), or customized haptic joysticks for people with motor and cognitive impairments to better control power wheelchairs (e.g., R. H. Wang, Mihailidis, Dutta, & Fernie, 2011). Similarly, another area of research in compensative assistive robots aims at using haptic interfaces to enable robot-mediated access to object play and manipulation, which may ultimately lead to overall task performance improvement (F. Atashzar et al., 2016). With increased opportunities for manipulative activities, it is possible that children with disabilities will experience improved haptic perception development, potentially leading to improved overall cognitive and social interaction in the long term.

The purpose of this review is to examine the studies most pertinent to the potential of haptics for the functionality of assistive robots in manipulation tasks for children with disabilities. To this end, a literature review was undertaken to reveal trends for the use of haptic interfaces, and to identify potential ideas and challenges for future research in using haptic interfaces for children with disabilities. It should be noted that this review only pertains to the kinesthetic (also called force) perception as a subset of haptic sensation. Kinesthetic perception relates to the sense of position and movement of body limbs and muscular contractions (Gandevia, McCloskey, & Burke, 1992), which contributes to recognition of object properties such as hardness, size, weight and shape. Studies on haptics exclusively pertaining to tactile perception such as vibration, temperature, texture or pressure were not included in this review.

Search Strategy

The search for studies was performed through the electronic databases MEDLINE and PubMed via OVID and EBSCOhost. Informal resources such as citation lists from articles, publication lists of leading authors in the field, and grey literature (e.g. conference proceedings, theses, etc.) were also searched for relevant studies. The search strategy was limited to English articles.

Initial search: The initial keywords searched included: ('haptic' OR 'haptic guidance' OR 'haptic interface') AND 'disability' AND ('task performance' OR 'object manipulation' OR 'environmental exploration'). Boolean operators were utilized to query all relevant concepts in the abstract, title, text and bibliographic fields. Other search strategies to improve the final search were inclusion of alternate spellings, alternate endings, synonyms and acronyms of the keywords and correspondingly, excluding their antonyms and homonyms (word combinations which have different applications/meanings).

Final search: The next step was to narrow down the search to the most researched application areas of haptics concerned with *the use of haptics to improve task performance of people with disabilities.* A perusal of the studies resulting from the initial search showed that three application areas were most common, namely *computer access*, *powered wheelchair (or mobile robot) control*, and *rehabilitation*. Each of these categories were combined with the initial search using an AND operator to extract the final papers. Finally, the retrieved articles were screened by the title and abstract to ensure they met the main purpose of the literature review.

Results of the review studies on the use of haptic interfaces in the three aforementioned areas are presented next. *Haptic guidance* is described as a standalone section as it is an overarching assistive feature integrated not only into the abovementioned applications of haptic systems but also other application areas (e.g. handwriting training) to enhance the performance of people with disabilities. Finally, the salient points from this review that are relevant to research with children with disabilities are discussed.

Haptics Applications

To the best of our knowledge, very few studies to date have exploited the functional implications of haptics on task performance for children. Studies have looked at the performance of *non-impaired adult computer users* (Dennerlein, Martin, & Hasser, 2000; Dennerlein & Yang, 2001), *motion-impaired adult computer users* (Asque, Day, & Laycock, 2012; Hwang, Keates, Langdon, Clarkson, & Robinson, 2001; Langdon, Keates, Clarkson, & Robinson, 2000), *adult computer users with visual impairments* (Memeo, Campus, Lucagrossi, & Brayda, 2014; C Sjostrom, Danielsson, Magnusson, & Rassmus-Grohn, 2003) and *adult power wheelchair users* (Protho, LoPresti, Brienza, & Ph, 2000; M. Wang & Reid, 2011). Studies on children with disabilities involved only *toddler wheelchair users* (specifically, a child with severe motor impairment (L. Marchal-Crespo, Furumasu, & Reinkensmeyer, 2010) and a child with spina bifida (Chen, Ragonesi, Galloway, & Agrawal, 2011)). The functionality of haptic-enabled assistive technologies in manipulative and exploratory tasks for children with disabilities is unexplored.

Computer Access

Integrating haptics along with the sound and graphics components of computer interfaces has created a new experience of computer interaction, especially for gaming. Haptic interfaces give the user a sense of action (e.g., shooting) and properties of on-screen objects as the user moves the cursor around the screen. Besides the entertainment aspect, haptic interfaces have been used to facilitate computer access for people with disabilities. Haptic interaction in computer access only involves VE-based manipulation. Therefore, the user exchanges kinesthetic information through a haptic interface with a computer simulated environment.

Computer Users with Visual Impairments

The majority of research on haptics for computer access for people with disabilities is devoted to customizing interfaces for people with vision impairments. The idea is, for example, as a person moves the cursor, he or she can manipulate virtual objects on the screen and perceive their position or shape. Haptic interfaces (e.g. a 6-degrees of freedom (DOF) PHANToM, a force feedback joystick, and a 2-DOF force feedback FEElit Mouse) to access computers have been used for exploring and manipulating on-screen objects (e.g., mathematical curves), and to ascertain the potential of haptics to access a Windows-like operating system (C. Sjostrom, 2001; Sjöström, 2001; C Sjostrom et al., 2003; Calle Sjostrom, 2001; C Sjostrom & Rassmus-Grohn, 1999).

Research using haptic interfaces for people with visual impairments primarily aims at building a *cognitive map* of haptically simulated environments. Building a cognitive map is the process of manipulating and correctly perceiving the surrounding environment based on the acquired information through the available sensory channels (i.e. seeing, hearing and touching) (Downs & Stea, 1973). In a similar study, a graphical exploration of a geographical map (a subset of a cognitive map) was evaluated with two blind users using a Wingman force feedback Mouse (Baptiste-Jessel, Tornil, & Encelle, 2004). Users reported that the system helped to perceive a mental representation of the map. Brayda et al. (2013) evaluated a haptic mouse for representation of a cognitive map of virtual objects with blindfolded sighted users (Brayda, Campus, & Gori, 2013). The results indicated that information acquisition (reflected by the touch information acquired by the user) and cognitive load (reflected by perceived difficulty in map construction) were jointly significant predictors of task performance in correctly manipulating and perceiving the cognitive mapping. In those participants who correctly constructed the objects, higher information acquisition was associated with higher cognitive load while in incorrect mappers, no indicative link was observed. In a similar approach, the effect of map complexity was qualitatively evaluated in mental map construction of 3D virtual maps with 15 blind users and 15 blindfolded, sighted users (Memeo et al., 2014). A TActile MOuse (TAMO) provided 3D tactile maps of the virtual objects. The measures of performance were amount of acquired information and cognitive load. The results showed that mental map perception was affected by the level of map complexity but was independent of whether the person had visual impairments. Park et al. (2015) employed cognitive mapping to enable mobile navigation, and remote object exploration and manipulation in virtually simulated public places (such as art galleries and museums) for individuals with visual impairments (Park, Ryu, & Howard, 2015). A telerobotic system using a PHANToM Omni device and a VE with 3D haptic feedback was used. Additionally, color and distance (from the target) information were captured through a 3D-depth Kinect camera and were translated to the user through sound feedback (as a brief verbal description). The experiments were carried out with visually impaired and blindfolded, sighted participants. There was a significant effect navigating and distinguishing objects with respect to completion time when using haptic feedback, but not with respect to success rate as subjects without impairments only relied on the color information to make decisions. Authors suggest further analysis with a larger group of participants to analyze the real effect of haptic feedback. Overall, the participants reported that the system provided a “fairly realistic” feeling of the remote VE.

Computer Users with Physical Impairments

For physically impaired computer users, hand symptoms such as spasm, tremor, and muscle weakness make it difficult, or impossible, to use standard computer interfaces (S Keates, Robinson, Karshmer, Blattner, & Berns, 1999). Major difficulties occur during point-and-click computer activities (S Keates et al., 1999) when the user wants to click on the target (Langdon, Hwang, Keates, Clarkson, & Robinson, 2002). Involuntary clicks and sliding over the target are also a major cause of errors (Trewin, Keats, & Moffatt, 2006). Haptic interfaces for physically impaired computer users mainly aim at either resisting or assisting the user’s movements, depending on the type of impairment. Haptic feedback (forces) can be applied in a manner to reinforce or improve the user inputs in the case of muscle weakness or poor coordination, or to restrict or filter motions in the case of spasm or tremor (Simeon Keates, Langdon, Clarkson, & Robinson, 2000).

The effect of haptic forces on the operator’s perceived comfort has been studied. Dennerlein et al. investigated the effect of haptic feedback on musculoskeletal loading (Dennerlein & Yang, 2001). Participants performed a point-and-click task 540 times using a prototype FeelIt

Mouse with and without force feedback. The metrics were task difficulty, pain and discomfort. Forces were implemented along the user's intended movements, called "attractive basin forces" (attractive force fields around the target) and against them, called "distracting forces". The distracting forces increased exposure to musculoskeletal loading, user fatigue and discomfort, although the user performance greatly improved. Later studies investigated novel techniques for haptic assistance which constrained the user less and applied less force. For example, Asque et al. (2012) developed haptic effects referred to as haptic cones and V-shaped walls to assist users with motion impairments in point-and-click tasks using a 3-DOF PHANToM Omni to control the cursor (Asque et al., 2012). Haptic cones were implemented around the targets and created a gravity hole, which pulled the cursor inside when trying to reach the target. Haptic walls, on the other hand, created a V-shape effect on the centre of the target that oriented towards the cursor. When the cursor came close to a wall, it was drawn to the centre of the target. Measures of travelled distance between a click down and a click release, and the absolute displacement between the click and release showed haptic cones outperformed previous techniques as well as haptic walls in improving clicking performance. Both assistance approaches were claimed to be less "intrusive on interaction" and not impose any distracting forces to the user when exiting a target, unlike previous techniques.

The effectiveness of haptic forces can vary with the level of impairment. Keates et al. (Hwang et al., 2001; S Keates, Hwang, Langdon, Clarkson, & Robinson, 2002; Simeon Keates et al., 2000) and Langdon et al. (Langdon et al., 2002, 2000) performed a series of point-and-click experiments with both motion-impaired and able-bodied participants using a Logitech force-feedback mouse. There were greater improvements in completion time for physically impaired users when using haptic feedback; the more the severity of impairment, the greater the improvement.

Another factor influencing the effectiveness of haptic forces is the number of DOF of the interface, including both positional and rotational movements. An increased number of DOFs results in improved interactions due to increased information transfer (Langdon et al., 2000). Inclusion of fingers in manipulation, as opposed to only wrist and elbow as in typical computer mice, also results in a higher number of DOFs and accordingly, improves computer interactions (Milgram, Buxton, Zhai, Milgram, & Buxton, 1996). This was observed by including fingers in manipulation (using a 6-DOF FingerBall to be rolled and moved by fingers), and excluding them (by having the ball under the palm). However, an increased number of DOFs has shown to increase cognitive demands of a task as well (S Keates et al., 1999).

Power Wheelchair and Mobile-Robot Control

Maneuvering power wheelchairs can be difficult if a user with severe physical or cognitive impairments is autonomously controlling it using a control interface. Fehr et al. (2000) highlight the “inadequacy” of wheelchair control interfaces for users with severe impairments (Fehr, Langbein, & Skaar, 2000). The most commonly used control interfaces are joysticks (Fehr et al., 2000), which apply low cognitive load on the user due to their obvious mapping to the environment (Nilsson & Nyberg, 1999); for example, if the joystick is moved to the left, the wheelchair will turn to the left. Yet, some wheelchair maneuvers such as passing through narrow spaces require a high demand on cognitive and motor skills (Vander Poorten et al., 2012), and can be challenging for novice riders, children, and severely impaired individuals. In 1996, a focus group of wheelchair users brainstormed priorities for power wheelchair control interfaces (Brienza & Angelo, 1996). The most highlighted priority was alternatives for feedback modalities to the user, highlighting the need for "*smart*" power wheelchairs. There has been relatively a large body of research on smart wheelchairs (see e.g., Baumgartner & Skaar, 1994; Nisbet & Craig, 1994; Simpson et al., 1998). The sensors on the smart wheelchair's control unit provide feedback allowing the robot to take over some of the control during operation, augmenting the individual's capabilities (Craig & Nisbet, 1993). Additionally, haptic feedback has been integrated into wheelchair control interfaces to potentially increase safety, independence, and maneuvering skills (Vander Poorten et al., 2012). Haptic interfaces can assist in power wheelchair maneuvering skills by helping to avoid collisions (e.g., not hitting obstacles or getting through narrow spaces), or by haptic navigation assistance.

Force feedback joysticks have primarily been used on mobile robots (movable robotic systems with an attached electric wheelchair or a seat) and later on power wheelchairs particularly for collision avoidance. Early studies on mobile robots reported a reduced number of collisions but not considerable improvement with speed and minimizing deviations from the intended path (Barnes & Counsell, 1999; Borenstein & Koren, 1991; S. Lee, Sukhatme, Kim, & Park, 2002). In a study with power wheelchairs, Fattouh et al. (2004) used a Microsoft SidewinderTM Force Feedback joystick with adults with severe motor disabilities (Fattouh, A. ; Sahnoun, M. ; Bourhis, 2004). Researchers adjusted the compliance of the force feedback joystick proportional to the wheelchair distance to the closest obstacle; thus the closer to the obstacle, the higher the force feedback. Improved performance was reported based on the completion time, travelled distance and number of obstacle collisions. This approach provided the user with complete control authority, except for the compliance of the joystick. Similar collision avoidance approaches were investigated in other studies (Brienza & Angelo, 1996; Cooper et al., 2002; Protho et al., 2000). The usability (satisfaction, efficiency, and effectiveness) of a collision-avoidance power wheelchair a was also studied with adults who were in long-term care and had mild or moderate cognitive impairments (R. H. Wang et al., 2011). Auditory, visual, and haptic feedback were added to the wheelchair and guided the user in driving away from obstacles. The results indicated that the multisensory feedback improved driving performance. Haptic feedback alone ensured the correct directions of movements, however one participant found the other sources of feedback more useful and one found haptic feedback too controlling. Other studies with adults with disabilities were performed with a haptic navigation assistance system in the form of collision-free circular paths (Craig & Nisbet, 1993), and obstacle avoidance (Brewer, Fagan, Klatzky, & Matsuoka, 2005), providing information about the surrounding environment. The results indicated increased navigation accuracy due to the supplementary information. There are very few studies with children. A child with cerebral palsy (L. Marchal-Crespo et al., 2010), and a child with spina bifida (Chen et al., 2011) steered a power wheelchair faster and more accurately along target lines while avoiding obstacles with the use of a haptic joystick.

Rehabilitation

Robotic rehabilitation augments movement therapy of body limbs by the use of control interfaces. It can provide a more intensive and effective therapy that requires less mediation of a therapist compared to one-onto-one therapies (Brewer et al., 2005). Robotic rehabilitation has been shown to foster recovery based on several clinical studies and assessments (see review in Scott & Dukelow, 2011), for instance, in increased strength and range of motion (Lum, Burgar, Shor, Majmundar, & Van der Loos, 2002; Volpe, Krebs, & Hogan, 2001). Haptic feedback has been augmented into robotic rehabilitation in order to generate haptic sensation (including tactile and kinesthetic) during motor tasks and to better simulate real therapy situations. Demain et al. (Demain, Metcalf, Merrett, Zheng, & Cunningham, 2013) reviewed the rationale of integrating haptics into the rehabilitation of hand, the “haptic exploratory organ” (Gibson, 1988b). Authors point to previous studies in which the loss of haptic information has resulted in poor recovery rates in the hand after stroke (Sunderland et al., 1992; Wade, Langton-Hewer, Wood, Skilbeck, & Ismail, 1983). Haptic robotic rehabilitation can stimulate the kinesthetic system by providing force feedback about physical properties of objects, resulting in increased potential of motor recovery (Demain et al., 2013). Further advantages are provision of task-specific properties in order to practice activities of daily living (e.g., Olivier Lambercy et al., 2009), and improved range-of-motion in repetitive tasks (e.g., Rozario et al., 2009). VE-based haptic robotic rehabilitation is another area with potential advantages over physical implementation, such as safety, flexibility, convenience, automatically grading the level of difficulty, and creating various interactive environments (L. Marchal-Crespo & Reinkensmeyer, 2009).

There have been a number of studies in rehabilitation of the hand in *post-stroke* (Demain et al., 2013). Few studies have looked into haptics-enabled hand rehabilitation aiming at functional daily living activities. In one study, a 2-DOF haptic knob with varying force feedback was designed to improve hand function for activities such as opening door knobs, jar lids, etc. (Dovat et al., 2006; O Lambercy et al., 2007). The device was tested with nine people who had a stroke in two virtual reality games with augmented assistive forces as well as resistive forces to add complexity and challenge to the exercise (Olivier Lambercy et al., 2009). The results showed promising improvements in hand function (assessed by the Fugl-

Meyer assessment scale). In a later stroke study, hand rehabilitation of low-functioning patients was accommodated through a Haptic TheraDrive robot (S. F. Atashzar, Shahbazi, Tavakoli, & Patel, 2015; Theriault, Nagurka, & Johnson, 2014). The system included a position-dependent adaptive controller with resistive/assistive forces to tune rehabilitation therapies (and change the task challenge) by attracting or repelling the hand from the target position. The experimental studies showed decreased root-mean-square (RMS) error in a tracking and positioning exercise. Researchers proposed that the developed system could help to improve hand motor function and spasticity in patients who had a stroke. However, the effectiveness of various types of haptic assistance (determined by the control algorithm) needs to be determined with regards to the patient characteristics (different control algorithms are reviewed in (L. Marchal-Crespo & Reinkensmeyer, 2009)). Kang Xiang et al. (2014) proposed a haptic interface, Haptic Sense, to explore the effect of assistance based on different haptic sensations including the sensation of weight, a wall and a spring (Khor et al., 2014). The authors proposed to validate the effectiveness of each haptic sensation with patients who had a stroke using a set of virtual reality games with simulated functional tasks with graded difficulty.

Commercial haptic devices have been commonly employed in post-stroke studies. They can replace custom-made interfaces if they are simple, affordable and small, and can be easily learned by patients and easily implemented by system operators (Demain et al., 2013). The 6-DOF *PHANToM* haptic devices (Geomagic, Cary, NC) have commonly been used for rehabilitation purposes. In a therapist-mediated therapy trial, Rozario et al. used a PHANToM Premium and an exotendon glove to extend range of motion of the hand by provision of augmented forces in patients who had a stroke (Rozario et al., 2009). The repetitive therapy movements were substituted with haptic/visual error augmentation[2] treatment with the same amount of practice. Researchers reported improved range of motion but recommended longer training to avoid task ambiguity and to obtain significant results. Inexpensive commercial haptic interfaces have also been used in other rehabilitation areas besides hand rehabilitation. A PHANToM Omni was used to deliver balance cues provided by kinesthetic haptic feedback to non-disabled adults and adults who had a stroke and body sway (Raheel Afzal et al., 2015). Healthy subjects' vision was covered by eye masks to make them rely on haptic cues, and their body sway was disturbed by changing their postural condition (e.g. standing on one foot or heel-to-toe), or ground condition (e.g., using an unstable foam). Haptic feedback assisted the users in body sway reduction and balance control by generating "intuitive balance cues" via light touch. Experimental trials showed promising reduction in body sway in both participants with and without stroke and body sway.

In rehabilitation applications, there has been an increasing interest in VEs. Some studies showed that VE-based rehabilitation was more effective than conventional rehabilitation in restoring hand motor functions in patients who had a stroke (Turolla et al., 2013) and in robot-supported training during upper limb related activities of daily life in persons with multiple sclerosis (Feys et al., 2015). The intensive and long-term motor training exercises can be motivated by developing rehabilitation exercises in VEs (Lewis GN & Rosie JA., 2012; McPherson, 2011). Acquired skills from training in VEs can eventually be transferred to a real environment (e.g., in a "steadiness tester" task (Rose et al., 2000)). However, according to Burdea (2003) some challenges with VEs are "lack of natural interfaces, lack of child-size

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[2] Error augmentation is claimed to be a promising robotic-training paradigm in which the user movements get disturbed by distracting forces instead of assisting forces (Wei, Patton, Bajaj, & Scheidt, 2005)

equipment, technical expertise, clinic and clinical acceptance, and cognitive load” (Burdea, 2003, p10).

VE-based arm rehabilitation and training has been facilitated through different haptic robot-assisted media such as a system called HapticMaster. Vanmullken et al. (2015) studied the feasibility of the HapticMaster in improving the arm-hand performance in five individuals with different levels of cervical spinal cord injury (Vanmulken, Spooren, Bongers, & Seelen, 2015). In a pre-defined VE-based movement trajectory task, the patient’s hand was assisted passively (the therapist or the device moved the hand), partially (movements were aided by the therapist/device) or was moderately resisted in the active mode (the patients moved themselves against the resistance). The system was found to be easy to use, easy to learn, motivating and feasible, yet further improvements on the usability of the HapticMaster system were needed to make more complex and larger hand movements possible. In a similar approach, Feys et al. (2015) investigated the effectiveness of a HapticMaster in arm training with seventeen individuals with multiple sclerosis (Feys et al., 2015). A series of games were developed in a custom-built VE with augmented haptic, visual and auditory stimuli. The VE games provided learning and training of a series of arm functions required for daily activities (e.g., lifting, pushing, pulling, reaching and etc.). The system was evaluated based on motor control function, activity level, range of motion, and duration, velocity and quality of movement. Improved motor control function was reported for highly disabled participants. However, no significant clinical improvement was observed at the group level.

Haptic Guidance Systems

Haptic guidance refers to forces generated by a haptic robotic interface to physically guide a user through a desired pattern of movement (Feygin, Keehner, & Tendick, 2002). It is an overarching assistive feature between all application areas of haptics augmenting the user's capabilities in different haptic-based tasks. There is, however, a controversy about the benefit of haptic guidance as it may impair the "natural patterns of kinematics" required to accomplish a task (L. M. Marchal-Crespo & Reinkensmeyer, 2008). This is caused by different "dynamics of movement" during training with haptic guidance compared to a situation in which the person independently does the movements. Similarly, Gurari et al. (2014) highlighted the need for further investigation on whether applied forces will hamper or improve learning performance in sensorimotor tasks (Gurari & Baud-Bovy, 2014). They describe the technical development of a joystick kinematically constrained by a mechanical damper (to adjust the magnitude of forces) to study whether children learn to efficiently interact with the applied forces; at the time of writing, no trials of this system with children were located in the literature. Despite the potential drawback, the following studies describe the two common application areas, including *motor training* and *multimodal haptic guidance systems*, in which haptic guidance has been beneficial and resulted in performance improvements.

Motor training

Haptic guidance systems have been commonly used is in motor-training tasks. In medical applications, for instance, guidance is used for palpatory training by following the recorded position trajectories of an expert physician (Williams, Srivastava, Conaster, & Howell, 2004) or training practitioners to learn how much force to apply during a surgical procedure (e.g., Yem et al., 2012). In wheelchair driving training, the trainee learns motor training strategies through guidance from an experienced person (physical guidance) or forces generated by software (virtual guidance) (L. Marchal-Crespo et al., 2010; L. M. Marchal-Crespo & Reinkensmeyer, 2008), or it allows training novice users or children with disabilities on how to use the wheelchair controls (L. M. Marchal-Crespo & Reinkensmeyer, 2008). Guidance has also been used to replicate an expert's motor skills in order to facilitate hand movements for training handwriting (e.g., for novice learners (Srimathveeravalli & Thenkurussi, 2005), or Chinese language learners (Teo, Burdet, & Lim, 2002)). Kindergarten children with poor handwriting, dysgraphia (Hennion, Gentaz, Gouagout, & Bara, 2005; Palluel-Germain, 2007), as well as adult participants (Bluteau, Coquillart, Payan, & Gentaz, 2008) have also been haptically guided to train handwriting by following the outlines of letters using a haptic interface. The letters were computer generated and participants were asked to stay on the outline of the letter while holding the haptic interface. In the event of passing over the line, the haptic guidance feature of the system pulled the interface towards the correct trajectory.

Multimodal haptic guidance systems

In multimodal haptic guidance systems, haptic guidance interfaces have been accompanied by visual and/or auditory sensory information to enhance the perception and task performance of people with disabilities. Morris et al. (2007) investigated the overall effectiveness of a visuohaptic training paradigm on performing a trajectory following task to learn an abstract motor skill (Morris et al., 2007). The haptic guidance, implemented via an Omega 3-DOF haptic device (Force Dimension, Lausanne, Switzerland), pulled the user's hand along the trajectories while visual feedback indicated the desired trajectory. The results from different training modes (visual only, haptic only, and combined vision and haptic) were compared. The highest improvement in memorizing the trajectories was achieved when haptic feedback was combined with vision. A prototype of a multimodal guidance system using a PHANToM interface was proposed and tested through studies with persons with *Down syndrome and* *developmental disabilities* (Covarrubias et al., 2011; Covarrubias, Bordegoni, & Cugini, 2015; Covarrubias, Gatti, Mansutti, Bordegoni, & Cugini, 2012; Covarrubias, Bordegoni, & Cugini, 2014; Covarrubias, Gatti, Bordegoni, Cugini, & Mansutti, 2014). The researchers designed a system to perform a set of trajectory following tasks such as sketching and foam-cutting operations, which required high movement precision and coordination. First, haptic guidance was provided to assist the user's hand movements in sketching a template shape by tracing its contours in a VE. The sketched shape was then printed on a piece of foam and haptic guidance assisted to cut it out using a hot wire tool connected to the PHANToM device. Audio feedback provided feedback related to the hand's velocity and position. Participants' accuracy of operation was evaluated before and after being guided by sound and haptic feedback. Overall, the results supported the effectiveness of haptic guidance in augmenting cognitive and motor abilities in tasks demanding coordination such as sketching. However, audio feedback did not show statistical significance on the subject performance and authors attributed that to the easiness of the tasks and incorrect implementation of audio feedback. The authors suggested further experiments involving more complex tasks, more effective implementation of audio feedback and a higher number of trials to obtain statistical significance.

It should be noted that adding haptics to vision (HV) is taken as a different approach than adding vision to haptics (VH). Van Polanen et al. (2014) observed that adding touch cues to the visual representation of an object (HV) led to significant improvements in task performance (memory retrieval for object identity and location) while adding visual representation to touch cues (VH) was not as beneficial as the HV case (Van Polanen, Tiest, Creemers, Verbeek, & Kappers, 2014). Additionally, it has been observed that vision alone can be more beneficial in extracting object properties compared to haptics alone (Liu, Cramer, & Reinkensmeyer, 2006).

Yet, visuohaptic feedback has overall contributed to greater improvements in task performance as opposed to visual or haptic modalities alone (e.g., Huang, Gillespie, & Kuo, 2004). Sound feedback has been added to visual and haptic information but its effectiveness on improvement of performance was not always conclusive (e.g., Covarrubias, Gatti, et al., 2014). In studies with blind people, the addition of sound was reported to be complementary to the haptic modality (Park et al., 2015; Calle Sjostrom, 2001). Overall, integrating haptics along with sound and vision has also contributed to enhancement of human-machine interactions and to improvements in manual task performance (e.g., R. H. Wang et al., 2011).

Discussion and Conclusion

This review indicated the tendencies for use of haptic interfaces for people with disabilities in three major application areas of haptics including computer access, wheelchair (or mobile robot) control and rehabilitation. Among the reviewed literature, only a few had explored the functionality of haptic systems for use by children with disabilities, most corresponded to adults with visual impairments, adults who had a stroke, or adult power wheelchair users. In the following, a number of salient points from the reviewed literature are described, which raised potential ideas or challenges for future work with children with disabilities.

As seen in the literature, haptic guidance typically improves performance and reduces the number of errors in motor learning tasks (Srimathveeravalli & Thenkurussi, 2005; Teo et al., 2002; Williams et al., 2004). However, it can degrade or hamper performance improvement when guidance is removed (L. M. Marchal-Crespo & Reinkensmeyer, 2008). This concern is a factor when haptics is used for the goal of training and improving motor abilities to eventually perform tasks independently later. With regards to robots for children with permanent impairments, the primary purpose of the robot is to compensate for a function that is not expected to improve enough to perform tasks independently. Thus, the robot acts as a compensative assistive technology enabling access to object play and manipulation which should lead to overall functional task performance improvement.

Increased musculoskeletal loading is another uncertainty about the use of haptic interfaces. Haptic feedback can take some load off the user if the applied forces are towards the intended movements (Dennerlein & Yang, 2001). This is usually the case in goal-oriented tasks such as point-and-click in which there is a specified target. In unstructured tasks, however, haptic feedback can have adverse effects on loading if it resists the user's movements to keep them between the borders or force them towards pre-planned paths. Thus, the user will experience extra forces from the interface if being forced against their intended movements. In computer access, the effect of haptic feedback on musculoskeletal loading might be negligible since computer access usually requires fine motor movements such as point-and-click or mouse dragging actions. However, in applications with more elaborate hand movements (e.g., involving wrist and arm movements), it could add extra load. In children's studies, the existence of extra forces needs to be taken into account with regards to the required range of motion in the proposed tasks. Extra loading may happen to children who have involuntary hand movements. However, children with fine range of motions may not experience as much loading because of the small range of motion. It will be important to assess loading with qualitative measures such as user's fatigue and discomfort. In the case of children who cannot reliably respond to questionnaires due to their disability or cognitive age, discomfort can be assessed by observing behavioural expressions (e.g., smiling or frowning). The frequency of an expression (e.g., frowning) or cause-and-effect behavior (e.g., releasing the robot and frowning) could be potential measures. Additionally, quantitative measures such as the amount of exerted forces from the interface to the user can be obtained from the software to infer the expected level of discomfort.

According to the reviewed literature, another valid point for children's studies is the evidence that while increasing the DOFs of the task or the control interface can enhance human-machine interactions (Milgram et al., 1996), it may result in increased cognitive demands of the task or the control interface (S Keates et al., 1999). For children's studies, it should be assured that children's cognitive level is no less than the cognitive demands of the proposed task, and that they have the required cognitive skills to understand the system and the tasks. Studies have shown that children as young as 8-months old can control robots in a simple cause and effect task (Cook et al., 1988) but only 5-year olds are expected to have the required cognitive demands to understand a switch-controlled robot with lateral movements and sequences (Poletz, Encarnação, Adams, & Cook, 2010). In tasks with higher cognitive or motor skill demands, different levels of haptic guidance (e.g., "fixed guidance" or "guidance as needed") (e.g., L. M. Marchal-Crespo & Reinkensmeyer, 2008) can be applied to compensate for a child's cognitive limitations. An alternative approach is applying an adaptive shared control paradigm (Carlson, Monnard, Leeb, & Millan, 2011), which allocates the control authority of task execution between the software and the user proportional to the user's performance. Thus, the software will take over a higher share of the control if the child's skills do not satisfy the task's and the system's demands.

VE has shown advantages over the use of direct physical therapies in rehabilitation applications (Feys et al., 2015; Lewis GN & Rosie JA., 2012; L. Marchal-Crespo & Reinkensmeyer, 2009; McPherson, 2011; Turolla et al., 2013). Some wheelchair studies have also shown the advantage of training maneuvering skills in VEs (e.g., L. M. Marchal-Crespo &

Reinkensmeyer, 2008). However, in manipulative and explorational activities for children with disabilities, the significance of direct physical manipulation of objects on development of perceptual, cognitive and social skills has been highlighted in the literature (Gibson, 1988b; Taylor et al., 1973; Warren, 1982). Manipulation of real objects provides unique information about an object that cannot be obtained via other modes of manipulation (Taylor et al., 1973). Accordingly, VE interactions transfer less information about the physical properties of environment and objects to a user compared to physical interactions. Consequently, in studies concerning development of children with disabilities, addressing direct physical interaction, which is essential for a child's perceptual development, should be taken into consideration as a requirement of the tasks and the haptic system.

Overall, the literature indicated the effectiveness of adding haptics to the existing information channels of user interfaces with the intention of enhancing task performance for people with disabilities. Still, a more pragmatic approach is required to measure the effect of haptic-based assistive technologies on performance improvement. The literature indicated a lack of clarification on whether the acquired improvement was exclusively as a result of haptics or other contributing factors. A general framework can be developed for each application of haptic interfaces to systematically measure the interaction of various contributing factors. More theoretical outcome measures could also help to increase the validity and robustness of the results. For instance, as reviewed, haptic-based wheelchair studies have generally looked at measures such as completion time, travelled trajectory, or accuracy to assess the user's performance. The individual's physical and cognitive profile is not usually taken into account to exclusively assess the intervention of haptics on performance specific to the individual's characteristics. A standardized assessment tool such as Quebec User Evaluation of Satisfaction with Assistive Technology (Demers L, Weiss-Lambrou R, 1996) could also be utilized to assess general factors concerning the use of an assistive technology (e.g. safety, simplicity of use, comfort and etc.) in order to explicitly study their effect.

Another area that requires a greater deal of attention is involving the clinical perspectives in the initial stages of design and development of haptic interfaces for individuals with disabilities. In most studies presented in this review, the considerations for design and development were typically focused on the engineering aspects of the technology. Future studies should reflect viewpoint of health professionals who directly work with individuals with disabilities. For instance, in rehabilitation applications, the haptic-based therapies need to be designed based on each individual's diagnosis, therapeutic goals and requirements. This would be achieved by provision of a more dynamic interaction between the engineers and health providers to merge benefits of both professionals in the relatively young but fast growing field of haptic technology for individuals with disabilities. Further research needs to be done to investigate child-technology interactions, which is particularly essential for children with disabilities who interact with interfaces on various assistive technologies (computer, wheelchair, robotic arms, etc.), and to reveal the potential of haptics in empowering children's ability to perform every day activities such as play and education.

The salient points from this review as well as the reviewed applications of haptics for people with disabilities can inform future research in better understanding some of the potential ideas, challenges or necessary considerations towards developing a haptic system for children with special needs. This can ultimately contribute to a rational basis for clinical and home-based implementation of this category.

Chapter 3

PAPER 2: HAPTIC TELEROBOTICS: APPLICATION TO ASSISTIVE TECHNOLOGY FOR CHILDREN WITH DISABILITIES

Robotic systems for master-slave teleoperation with haptic feedback capability have been used in diverse areas such as surgical simulation and telerehabilitation. Such systems have not yet been used by children with disabilities who can potentially control the master human-machine interface to sense and manipulate objects using the slave robot. This paper presents a comparison of candidate robots for the roles of the master robot as the child's human-machine interface and the slave robot for object manipulation in the environment. After establishing the appropriate robot choice, the control parameters for the stable system are determined. The system will subsequently be used for studies with children with disabilities doing manipulation tasks such as haptically guided drawing and painting in virtual and physical environments.

Note: this chapter has been published as an extended abstract (cited in the Preface), but also includes additional text in the materials section.

Introduction

The word haptics has its roots in the Greek words “haptesthai and haptikos” meaning “to touch” (“BS EN ISO 9241-910-,” 2011), and comprises touch (tactile/cutaneous) and kinesthetic (force) perceptions. A haptic interface has been defined as being concerned with the “association of gesture to touch and kinesthesia to provide for communication between the humans and machines” (Hayward, Astley, Cruz-Hernandez, Grant, & Robles-De-La-Torre, 2004, p. 16). Haptic interfaces have been used in different areas including robot-assisted surgery and surgical training (Tavakoli, Patel, & Moallem, 2006) and telerehabilitation (S. F. Atashzar, Polushin, & Patel, 2012).

To date, few studies have exploited the functional benefits of haptic teleoperation systems for children with disabilities. Studies have investigated the performance of non-impaired adults on maneuvering a virtually simulated wheelchair (e.g., L. M. Marchal-Crespo & Reinkensmeyer, 2008), motion impaired adults on human-computer interaction (e.g., Langdon et al., 2000), adults with Down syndrome performing cutting and painting (e.g., Covarrubias, Gatti, et al., 2014), and adults with visual impairments controlling computer cursors (e.g., Sjöström, 2001). Studies with children with disabilities involve only toddler power wheelchair users to help their maneuvering skills (a child with severe motor impairment (L. Marchal-Crespo et al., 2010) and a child with spina bifida (Chen et al., 2011)).

Our research aims primarily at using haptic assistive technology for enabling access to object play and manipulation (e.g., playing with objects, drawing and painting) which hypothetically will lead to overall task performance improvement and higher percentage of successfully finishing the task. With increased opportunities for such activities, it is possible that children with disabilities experience improved cognitive development thanks to object manipulation.

The feasibility of haptic assistive technology systems has remained unexplored in manipulation and exploratory tasks for children with disabilities.

Purpose

We propose to develop a haptic telerobotic system featuring position error based (PEB) control in a master-slave configuration. The child's interface will be the master robot, which sends position commands to the slave robot and receives forces if the slave robot is in contact with an object in the environment. The force feedback will be proportional to the difference between the position of the master and slave robots, which serves as the commanded position for the slave robot. This paper initially represents a comparison of candidates for the roles of master robot for the child interface and slave robot for manipulating or exploring objects in the environment. After establishing appropriate robot choice, the control parameters for a stable system are determined.

Materials

Master and Slave Robots

The two potential systems for the master and slave robots are two commercial haptic devices. A brief review on their specifications is presented in the following:

1) The Novint Falcon (Novint Technologies Inc., Rockville Centre, NY) is a low-cost 3 degrees-of- freedom (DOF) desktop controller with haptic feedback (Figure 3-1-a). The Falcon was first released by in 2007 and is mainly designed for gaming and entertainment. Martin and Hillier (2009) characterized the Falcon and realized non-uniformity in its workspace. The effective workspace of the Falcon can roughly be considered a cube 10 cm on each side. Its limited workspace is a drawback of its delta

configuration (originally designed by (Clavel, 1990)). Yet, a delta design makes it stiff and robust. The Falcon's software development kit (SDK) is developed on Microsoft Visual Studio C++ but is compatible with MATLAB. It connects to a PC via a USB port.

2) The PHANToM Premium 1.5A (Geomagic Inc., Cary, NC) has 6-DOF (3-DOF rotational and 3-DOF translational) with 3-DOF haptic feedback (in translational directions only) (Figure 3-1-b). The Premium evolved through the research by Massie (1993) and is a desktop haptic device. The Premium's SDK, OpenHaptics, is developed in C++ and is compatible with MATLAB. It requires some hardware to interface to a PC via a parallel port including "a Phantom Communication Converter (PCC - sold separately) and FireWire Card (requires IEEE-1394a-2000 compliant FireWire Port)"[3].

Figure 3-1 a)3-DOF Novint Falcon, and b) 6-DOF PHANToM Premium 1.5A a)

Quark software (Quanser Inc., ON, Canada) was used for interfacing the robots. Quark is a real-time control software toolbox developed in MATLAB. It is integrated into the Simulink toolboxes in Matlab and provides Simulink blocks that support some haptic devices including the Falcon and Premium.

The robots' technical specifications (partially presented in Table 3-1[4&5]) were reviewed to

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[3] http://dl.geomagic.com/binaries/support/downloads/Sensable/3DS/Premium1.0_1.5_HF_Device_guide.pdf

[4] http://www.novint.com/index.php/novintfalcon

establish which robots are appropriate for the role of master and slave. The Falcon is a parallel robot, and though the Premium has a parallel linkage designed to reduce its inertia (L. F. Lee, Zhou, & Krovi, 2011), the robot can be approximated as a serial-chain robot. Table 3-2 presents a comparison of serial and parallel robots specifications (investigated by (Briot & Bonev, 2007)). A detailed comparison, final selection and justification for Falcon as master and Premium as slave are presented in the Feature Comparison section.

Table 3-1 Robots technical specification

Spec.	**Novint Falcon**	**PHANToM Premium 1.5**
Input DOF	3-DOF	6-DOF
Workspace (mm)	101.6x101.6x101.6	381x267x191 (translational)
Force Max (N)	> 8.9	8.5
Weight (kg)	2.72	9
Position resolution (dpi) -*translational* (vs. rotational)	400	860
Joint-link configuration	Revolute	Revolute
Cost ($)	~300	~10,000

Table 3-2 Comparison of serial and parallel robots specifications (Briot & Bonev, 2007)

Feature	**Parallel robot**	**Serial robot**
Workspace	Small and complex	Large
Position error	Averages	Accumulates
Force error	Accumulates	Averages
Maximum force	Summation of all actuator forces	Limited by minimum actuator force
Stiffness	High	Low
Dynamics characteristics	Very high	Poor, especially with increasing size

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[5] http://www.dentsable.com/documents/documents/STI_Jan2009_1.5%206DOF_print.pdf

Payload/ weight ratio	High	Low
Speed and acceleration	High	Low
Accuracy	High	Low
Uniformity of components	High	Low
Calibration	Complicated	Relatively simple
Workspace/ robot size ratio	Low	High

The Falcon's default interface is a removable spherical grip. The other commercially available grips are a pistol grip designed for gaming, a needle insertion for simulated surgery (e.g., Coles & John, 2010), or a pen-shaped stylus for computer interaction (e.g., Kim, Collins, Bulmer, Sharma, & Mayrose, 2013) (as depicted in Figure 3-2). If a child can hold and drag the default or another commercial interface, it can be used. If not, interfaces can be adapted. A joystick-type interface might be a suitable option for participants with grasping and dragging capabilities. In case of the need for joystick adaptation, Pellegrini et al. (2004) investigated alternative options for conventional joysticks for people with restricted ability. They identified alternatives such as mini joystick and isometric-mini joystick (Pellegrini et al., 2004).

Figure 3-2 The Falcon alternative user interfaces: pistol grip (left), needle insertion (middle), and a pen-shaped stylus (right)

The Premium comes with a removable pen-shaped stylus, and a counterbalance weight. Other commercial end-effectors are scissors and thumb-pad for surgical training (shown in Figure 3-3). The default or commercial interface can be adapted for children to be able to hold and for tasks.

Figure 3-3 The Premium alternative stylus: scissors (left) and thumb-pad (right)

Teleoperation System

A basic teleoperation set-up is a *position-error-based* (PEB) control architecture known as a *unilateral* (no haptic feedback) approach. The schematic and block diagram are shown in Figure 3-4 and Figure 3-5, respectively. In this approach, the positions of the master's end-effector, X_m, are reflected at the slave side. A positional displacement error, ΔX_s, is generated as a difference between X_{md} (i.e, delayed X_m) and the current position of the slave, X_s. Accordingly, as the user pushes or moves the user interface, the slave replicates the same motions in the environment. The controller forces at the slave, F_s, are generated as a product of $K.\Delta X_s$ where K corresponds to the controller gains. Eventually, a summation of F_s and the interaction forces of the slave with the environment, F_{Env}, are applied to the slave.

In unilateral mode, the position commands of the slave are not sent to the user interface (one-way information flow). Therefore, the user does not feel the properties of the objects being manipulated by the robot. The user interaction forces with the master, F_{User}, exclusively controls the master. F_{User} cannot be manipulated or scaled by the software (controller) as the user forces are *directly* applied to the master robot's actuators. The unilateral approach helps to ensure the technical requirements for accurately teleoperating the two robots are met and that the slave robot exactly follows the position of the master side.

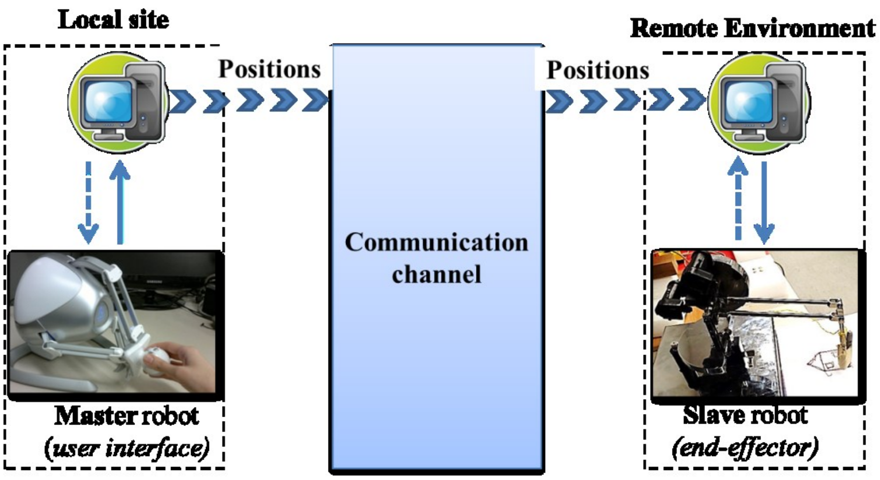

Figure 3-4 Schematic of a PEB unilateral teleoperation control: flow of information (positions) is only from the master to the slave

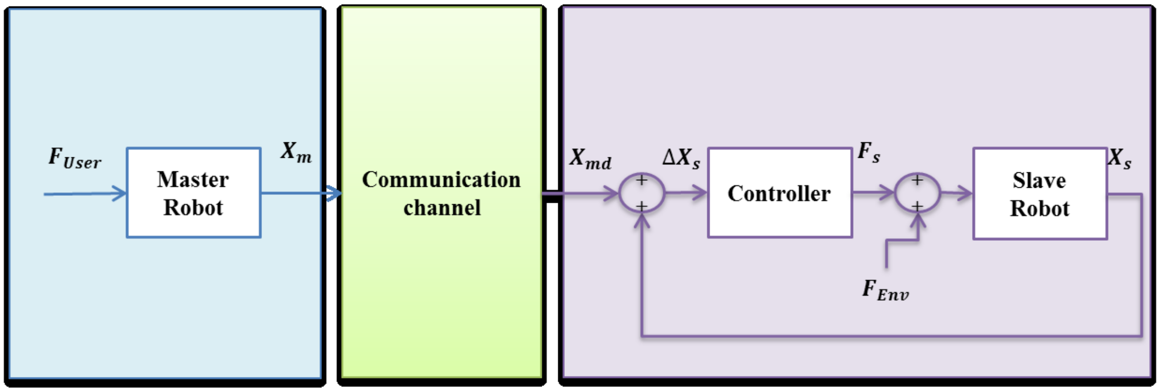

Figure 3-5 Control schematic of the unilateral teleoperation system

In order to provide force feedback to the user, *bilateral* (or haptic) teleoperation is necessary (demonstrated in Figure 3-6 and Figure 3-7). In this mode, in addition to the position of the master's end-effector being reflected at the slave side, the slave's position commands are fed back to the master (bidirectional information flow). Therefore, a summation of controller forces at the master, F_m, and F_{User}, are applied to the master robot. This way, the user gets a sensation of the remote object being manipulated by the slave. So, if the object is heavy, for instance, a stronger force is felt at the master's interface as a result of a larger positional displacement whilst if the object is light, less force is felt at the master's interface.

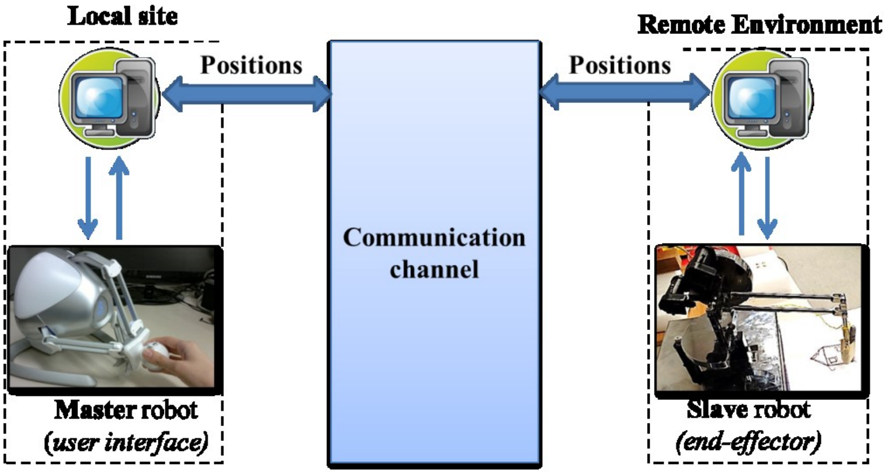

Figure 3-6 Schematic of a PEB bilateral (haptic) teleoperation control: there is a bidirectional flow of the information (positions) between master and slave

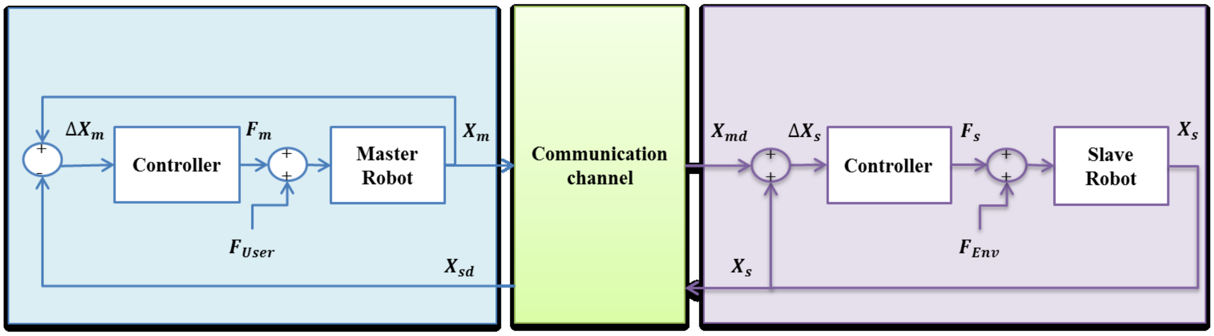

Figure 3-7 Control schematic of the bilateral teleoperation system

Transparency is a fundamental requirement of teleoperation systems. It is defined as a match of the perceived information commands (positions and forces) between the master and slave robots (Salcudean, Zhu, Zhu, & Hashtrudi-Zaad, 2000). If the master positions and forces are followed by the slave faithfully, transparency is achieved (Hashtrudi-Zaad, Salcudean, & Hashtrudi-Zaad, 2001). To ensure transparency, the system control gains are tuned such that the transmitted interaction forces, sent from the slave's end-effector to the master, are adequate to operate the desired tasks.

Stability ensures the operator's safety and system robustness in the presence of unwanted noises or oscillations (Hashtrudi-Zaad & Salcudean, 2002). It can be disturbed by factors such as "hard contact and a relaxed grasp of the user" (Pacchierotti, Tirmizi, & Prattichizzo, 2014). *Hard contact* can be interpreted as sudden forces exerted by the user or by the robot interacting with a hard object. Small noises or oscillations can get amplified in the control loop by a *relaxed grasp of the user* which otherwise would get dampened. There is a trade-off between transparency and stability. Higher control gains enhance transparency but, in return, degrade stability. For the current system, the control gains were manipulated and determined to achieve a reasonable balance between transparency and stability.

It should be noted that in real-world teleoperation systems, the slave and master sides are meant to be *remotely* connected from distant locations. This feature is useful in applications such as telerehabilitation where the patient (slave side) and the therapist (master side) are at a distance. In that case, the internet is the communication channel to transfer information between the master and slave. In our application, both slave and master were locally connected via a cross cable (instead of the internet channel). Besides set-up being simplified, local connection can avoid time delays. Time delay is a common issue in teleoperation systems, especially in the presence of long distances, which can result in transparency and stability degradation (Lawrence, 1993). However, small delays will be inevitable (indicated as X_{md} in Figure 3-7).

Feature Comparison

We established our comparison criteria based on several features of serial and parallel robots. Candidate features were positional accuracy (the robot's positional deflection from its desired location), kinematic design (related to the possibility to easily map DOF of the master and the slave), workspace, and inertia. In theory, parallel robots are recognized with higher positional accuracy and smaller inertia while serial robots are recognized with simpler kinematic design and larger workspace (Pandilov & Dukovski, 2014; Wavering, 1999). However, these generalizations may not apply to all robots taking into account each robot's individual structure. Some of these exceptions are discussed later.

In master-slave teleoperations, the choice of the master and slave robots is very much application-dependent. Our first step is to develop a telerobotic system for children with disabilities who have a small range of motion, but want to do manipulation tasks such as drawing and painting. This implies features including safety, ease of use, and smaller apparent inertia for the master and operational workspace, and positional accuracy for the slave.

Our intention is to have the master held by the child. This necessitates the master being very safe. The Falcon robot has a smaller workspace than the Premium, so it has less chance of harming the child if it goes unstable. Moreover, despite parallel robots generally having small inertia, the Falcon has a higher apparent inertia compared to the Premium. If the user releases the master while it is applying a force on the user's hand, it will accelerate in free space. This acceleration will be higher for low-inertia master devices (e.g. Premium). High-acceleration impacts of the master on the user's body can be unsafe. These features point to the Falcon being a better choice for the master.

We are interested in a slave robot with simpler kinematic design letting us better manipulate the objects in the environment. Also, a bigger workspace provides a wider reachable area in the environment; this ensures more flexibility in task development. These imply having a serial robot (i.e., the Premium) as slave. It should be noted that although positional accuracy is generally an advantage of parallel robots, translational position resolution of the Premium (860 dpi) compared to the Falcon's (400 dpi) indicates the Premium's higher positional accuracy.

This is largely a factor of the difference in cost of the systems. Having fine resolution in the environment could be beneficial in future applications if fine detailed tasks are selected. Machine vision and intelligence can help to guide the slave interface to the correct position.

The Falcon's default interface is a removable spherical grip that can be replaced with a pistol grip designed for gaming, a pen-shaped stylus for virtual computer interaction, or a needle insertion for simulated surgery. The Premium comes with a removable pen-shaped stylus. Other end-effectors are thumb-pad and scissors for surgical training. These interfaces will be used or adapted, or custom ones will be built to replace the commercial ones.

Tuning Control Parameters

To determine the ideal control parameters for each robot, a proportional-derivative (PD) controller for the master and one for the slave were applied. The parameters were experimentally adjusted and trialed to determine the system's stability threshold (where the system goes instable) while still ensuring the highest possible transparency (while using the master robot, the user feels as if he/she is directly manipulating the object in the environment) by varying control gains, K_p (proportional gain, N/m) and K_d (derivative gain, N/m).

We first stabilized the Premium (due to its lower apparent inertia and higher risk of instability). To this aim, its movements were observed under different K_p and K_d parameters to tune its controller using a trajectory following method, with a sine-wave as desired trajectory. The Premium's trajectory best resembled the sine wave with $K_p = 70$ and $K_d = 10$. The Premium's trajectory under untuned and tuned controllers is shown in Figure 3-8 and Figure 3-9.

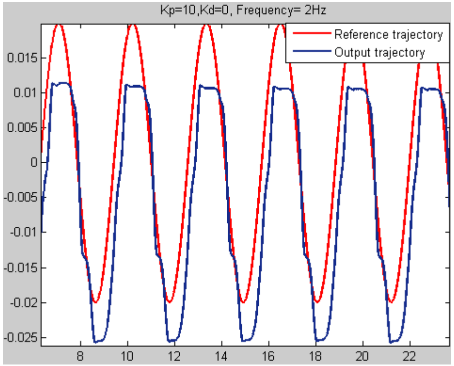

Figure 3-8 Premium's trajectory under an untuned PD controller

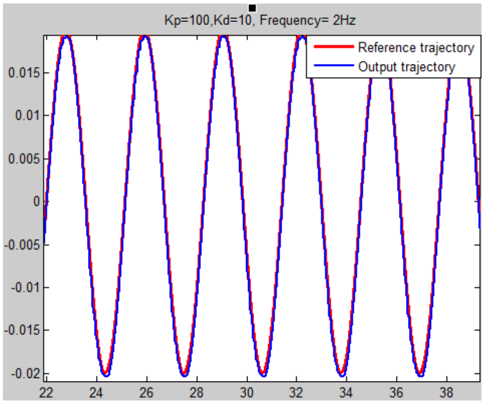

Figure 3-9 Premium's trajectory under a tuned PD controller

Next, the Falcon's controller was tuned in a closed-loop PEB control to achieve the best transparency. A marker pen was attached to the Premium robot's distal link, and the master-slave position tracking performance was experimentally examined in a drawing task under unilateral (without haptic feedback) and bilateral (closed-loop with haptic feedback) controls (Figure 3-10). The best position tracking performance was obtained under bilateral control with K_p= 350 and K_d= 13. The presence of haptic feedback in the bilateral control mode has led to smoother positions for the slave robot and better drawing task performance.

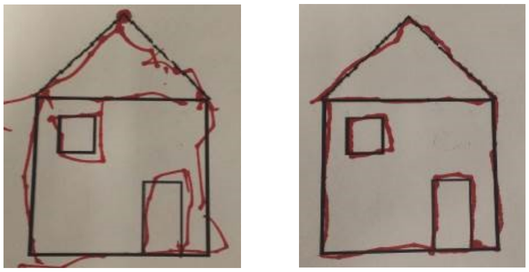

Figure 3-10 Drawing task using a) unilateral controller, and b) bilateral controller

Discussion and Conclusion

The Novint and Premium were selected as the master and slave robots, respectively, on the basis of general features of parallel and serial robots as well as the system's proposed application. However, future experiments will establish the reliability and feasibly of these robots with our target users and tasks. There are also some salient points worth mentioning:

- A "fair comparison" of two robots happens if their joints are only prismatic (slide in and out) or rotary (have rotational movement), and they have the same working volume (Briot & Bonev, 2007). Though our robots have only rotary joints, they are varied in their DOFs. This can be neglected since 3-rotational DOFs in the Premium's interface are attributed to the gimbal attached to its arm and will not be used for our tasks. So, we end up having two 3-DOF robots with only rotary joints and translational DOFs in the task space (Cartesian space). As suggested by Briot and Bonev (2007), the varied workspace can also be compensated for by constraining the robots' workspaces to an identical geometry and evaluating their performances on a given task.
- The Falcon's delta joint arrangement (Clavel, 1989) has the advantage of having high operation speed and high positional accuracy (Martin & Hillier, 2009). Yet, it introduces singularities (points where maximum extension and foldback of links

occur). The haptic sensations caused by singularities can confound the user's perception of slave's interaction forces with the environment.

- Though perceived forces by the Falcon seem sufficiently accurate for our future tasks, gravity compensation and joint friction estimation methods (e.g. Grotjahn) will be applied to increase the transparency.
- The Falcon's limited workspace will be suitable for users with a limited range of motion. For those with gross hand movements (larger range of motion), we may consider a different robot which provides bigger range of motion.

Future work will be to expand the functionality of system to haptically guided play environments compatible with the children's abilities. Virtual fixture (software generated forces) will impose virtual constraints on geometry of drawing and painting tasks (to guide the user's input interface) in virtual and physical environments to investigate the effect of virtual fixture guidance as well as different environments on user performance.

Chapter 4

PAPER 3: DEVELOPMENT OF AN ASSISTIVE ROBOTIC SYSTEM WITH VIRTUAL ASSISTANCE TO ENHANCE PLAY FOR CHILDREN WITH DISABILITIES: A PRELIMINARY STUDY

Children with disabilities typically have fewer opportunities for manipulation and play, due to their physical limitations, resulting in delayed cognitive and perceptual development. A switched-controlled device can remotely do tasks for a child or a human helper can mediate the child's interaction with the environment during play. However, these approaches disconnect children from the environment and limit their opportunities for interactive play with objects. This paper presents a novel application of a robotic system with virtual assistance, implemented by virtual fixtures, to enhance interactive object play for children in a set of coloring tasks. The assistance conditions included zero assistance (No-walls), medium level assistance (Soft-walls) and high level assistance (Rigid-walls), which corresponded to the magnitude of the virtual fixture forces.

The system was tested with fifteen able-bodied adults and results validated the effectiveness of the system in improving the user's performance. The Soft- and Rigid-walls conditions significantly outperformed the No-walls condition and led to relatively the same performance improvements in terms of: (a) a statistically significant reduction in the ratio of the colored area outside to the colored area inside the region of interest (with large effect sizes, Cohen's d>.8), (b) and a substantial reduction in the travelled distance outside the borders (with large effect sizes). The developed platform will next be tested with typically developing children and then children with disabilities. Future development will include adding artificial intelligence to adaptively tune the level of assistance according to the user's level of performance (i.e. providing more assistance only when the user is committing more errors).

KEYWORDS: Haptic, haptic interaction, haptic interface, virtual assistance, task performance, object manipulation, children with disabilities.

Introduction

Children with disabilities, whose reaching and manipulation is impaired due to their physical difficulties, may experience delayed perceptual and cognitive skills as a result of reduced opportunities for object manipulation and learned helplessness (Harkness & Bundy, 2001). Loss of touch or haptic feedback, as one of the modes of direct manipulation, results in impaired manual exploration and object identification (R. L. Klatzky et al., 1993; Lederman & Klatzky, 2004). Haptics is comprised of both perception of touch (or tactile feedback) and kinesthetic (or force feedback) ("BS EN ISO 9241-910-," 2011). Haptic perception pertains to bidirectional sensory information between a human and the environment through object manipulation and environmental exploration. According to developmental theories, development of perceptual, cognitive, linguistic and social skills, particularly during infancy and throughout early childhood, rely on environmental exploration and object manipulation through different modes of exploration and manipulation including seeing, hearing and touching (Power, 2000). One can acquire unique information about surrounding environment and object properties via haptic feedback (or interaction) provided by *direct* manipulation, which cannot be perceived through other modes of exploration and manipulation (Taylor et al., 1973).

Research has been carried out on *remotely* manipulating objects using switch-controlled assistive robots, controlled by head or hand switches, to facilitate task performance by individuals with disabilities, mostly in the area of play for children with disabilities (Cook et al., 1988; Kronreif & Prazak-Aram, 2008; Rios-Rincon et al., 2015; Robins et al., 2012; Smith & Topping, 1996; Tsotsos et al., 1998). The limitation of these assistive robots is that they do not support *direct* object manipulation, isolating children from their environment and limiting their opportunities for *interactive object play*. Here, interactive play means bi-directional child-environment interaction in which the child can directly feel and access the play environment. Furthermore, *remote* manipulation leads to the loss of haptic feedback from the object being manipulated by the assistive robot in the remote environment to the child's control interface (e.g. feeling of pushing, lifting, grasping, etc.). Thus, the child misses some environmental information.

Haptic interfaces have been used to transfer interaction forces sensed in the remote environment and to give assistance to individuals with physical limitations. A review of the applications of haptic interfaces for use by individuals with disabilities (Jafari, Adams, & Tavakoli, 2015) revealed that the areas most frequently studied include applications for adult wheelchair users (L. M. Marchal-Crespo & Reinkensmeyer, 2008; R. H. Wang et al., 2011), adult computer users with physical impairments (e.g. Langdon et al., 2000) and visual impairments (C. Sjostrom, 2001; Sjöström, 2001; Xiaolong, 2010), and adults who had a stroke (e.g. Rozario et al., 2009). There is very little research on the functionality of haptic technology aiming at enhancing performance in direct manipulative and exploratory tasks in people with disabilities.

Remote manipulation usually happens through a teleoperation system where the human user does not have direct contact with the environment. In one study, a teleoperation system consisting of two haptic interfaces was used to enhance the accuracy of placement of remote objects by an individual with cerebral palsy (F. Atashzar et al., 2016). The system assisted the user by scaling her convenient range of motion up to the required dimensions of the task. Additional assistance provided by the system was (a) filtering the involuntary hand movements (or high frequency component of the motion) to enhance coordination, and (b) damping of the energy of the involuntary movements by applying 'resistive dissipative forces' at the user interface to smoothen the jerky hand movements. The system ultimately led to overall task performance improvement in a goal-oriented pick-and-place task.

Haptic-based assistance in the form of virtual fixtures (VFs) using haptic interfaces can also assist people with disabilities. VFs are defined as computer-generated assistance and are generally implemented as forbidden region VFs or guidance VFs. The forbidden region VFs helps to maintain the user's hand movements within the region of interest (ROI) by creating walls on the borders of the ROI. Guidance VFs guide the user towards a target by applying directional forces along a desired path. Previous studies have represented the mathematical modeling and design of VFs (e.g. Abbott, Marayong, & Okamura, 2007). The concept of forbidden region VFs has been mostly implemented in computer access applications, for example by creating haptic cone- or tunnel- shaped VFs around computer icons to pull the cursor towards the target (Asque et al., 2012). Guidance VFs have typically been applied to path following and peg-in-the-hole tasks (Abbott, Hager, & Okamura, 2003; Alessandro Bettini, Marayong, Lang, Okamura, & Hager, 2004; Rosenberg, 1993; Wrock & Nokleby, 2011). In a series of experimental studies, Covarrubias et al. (Covarrubias et al., 2011, 2015, 2012; Covarrubias, Gatti, et al., 2014) projected guidance VFs into a set of path following tasks, such as sketching and foam cutting, to assist adults with Downs syndrome and developmental disabilities. Implementations of VFs have demonstrated increased precision and speed performing remote tasks (A Bettini, Lang, Okamura, & Hager, 2001; Alessandro Bettini et al., 2004; Sayers & Paul, 1994) and faster manipulation (Rosenberg, 1993).

Virtual (or VF-based) assistance can potentially increase a child's independence during tasks by reducing the need for the physical presence of a helper. Children with disabilities often need someone such as their parents, playmates or caregivers to mediate their interaction with the environment during play. This can reduce opportunities for the bi-directional *interactive play* with the environment. In addition, the helpers oftentimes dominate children's play, which in turn reduces children's sense of independence over the play (Blanche, 2008). Provision of virtual assistance could give children a sense of independence over task execution and provide the assistance needed to be more successful in the task execution.

Coloring is a playful way to facilitate a child's fine motor skills, artistic thoughts, focused attention and imagination (Gruber & McNinch, 1994; Mayesky, 2009). It starts with initial scribbling in toddler years and later, the obtained skills evolve into the meaningful symbols and drawing (Gruber & McNinch, 1994) and use of writing tools (McGee & Richgels, 2011). Children may first press very hard on the coloring surface, and color the whole page but they gain physical skill and fine motor control through repetition over time and learn to use appropriate force and stay within the lines. However, children with disabilities who have fine motor deficits, such as hand tremor or spasm, often lack the required skills for coloring that involves coordination and fine motor movements. They may cross the borders, color a large area outside the ROI, and scribble all over the sheet instead of coloring inside the intended ROI. As a result, the child may require help or experience frustration or disappointment. A child's self-efficacy may also be affected. Self-efficacy contributes to one's belief in his/her personal capabilities to succeed in a specific task, which highly relies on the past performance and experiences (Bandura & Adams, 1977). In the event of failure or poor performance, children may become more vulnerable to fail, less optimistic about their abilities and show loss of motivation and self-efficacy (Dweck, 2002).

The use of haptic-based assistance may enable some children with disabilities to be successful in the physical task of coloring. A haptic interface could be adapted to accommodate a child's abilities such as range of motion, and various grips could be attached to the interface to match the grasp ability of the child. Provision of forbidden region VFs, as needed, can potentially improve the overall accuracy. Additional assistive features such as dampening, the approach taken by Atashzar et al. (2016), could facilitate movement difficulties such as hand tremor, or coordination deficits (F. Atashzar et al., 2016). However, before using haptic-based interfaces with children with disabilities, testing the system with adults without disabilities can inform system performance and design, since adults are able to articulate opinions. Later, testing with children without disabilities, can inform possible implications for use by children with disabilities such as cognitive and perceptual demands.

Purpose

The purpose of this study was to validate the effectiveness of a forbidden region VF system for coloring with adult users who had never used a robotics system before. This paper specifically examines a new application of virtual (or VF-based) haptic assistance to enable robotic-assisted access to manipulation of a play environment for coloring, which could ultimately lead to overall task performance improvement. Two types of tasks were performed, exploring forbidden region VFs and coloring. For exploring, a novel and systematic procedure called "System Validation by Virtual Object Exploration" was performed to test and validate the robotic system in terms of its stability, safety and perceptibility of the implemented forbidden region VFs. The exploration task was evaluated based on the user's opinions upon completion of the task. The coloring task tested the effectiveness of the VF-based assistance on user's performance and involved coloring some template ROIs images on a tablet computer. Forbidden region VFs were imposed on the borders of the ROI in order to assist the user's movements to stay inside the ROI while coloring. Each coloring operation was carried out under three assistance conditions corresponding to the rigidity of the forbidden region VF walls including no assistance, a medium level and a high level of assistance. The goal was to compare different conditions of assistance and determine their effect on coloring performance. The research objectives were:

1. To validate the system, with able-bodied adults, in terms of stability and safety, and perceptibility of the implemented forbidden region VFs through virtual object exploration tasks.
2. Compare the user's performance in the coloring tasks between no assistance, and medium and high level of assistance in terms of ratio of the colored area outside to the colored area inside the ROI, travelled distance outside the ROI (displacement) and number of collisions with the borders of the ROI.

Method

A preliminary evaluation of the system with abled-bodied participants was used to reveal the possible technical demands or required modifications in the system or the tasks. A repeated measures design across all subjects was applied to test the effectiveness of each assistance condition on performance. Fifteen able-bodied adult participants were recruited among grad students. The inclusion criteria were able-bodied adults 18 to 65 years old with no motor difficulties in arms and hands. Attention, cognitive and hearing impairments were the exclusion criteria.

System Description

As shown in Figure 4-1, the experimental setup consists of a desktop haptic interface PHANToM Premium 1.5A (Geomagic, Cary, NC) as the user interface, a tablet computer which plays the role of the coloring surface, and a wooden box to hold the robot and tablet steady. As outlined by Jafari et al. (2015), the Premium has a serial kinematic design, despite its parallel linkages, providing a flexible workspace in terms of the robot range of motion, 381 W x 267 H x 191 D mm. In addition, the Premium has a pen-shaped stylus that makes it appropriate for the coloring operation by acting as a coloring pen. The Premium is interfaced to a PC via a parallel port using a Phantom Communication Converter and FireWire Card (requires IEEE-1394a-2000 compliant FireWire Port).[6] Quark software (Quanser Inc., ON, Canada) was used for interfacing the robot with the computer. Quark is a real-time control software toolbox developed and integrated into Simulink toolboxes in MATLAB to support some haptic devices including the Premium. The tablet was placed within the reachable workspace of the Premium.

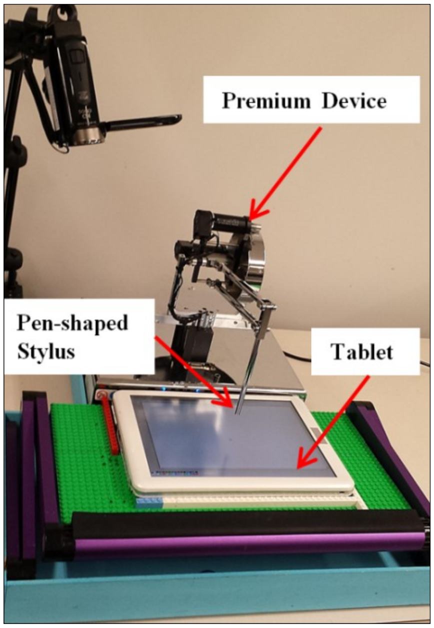

Figure 4-1 The experimental setup consisting of a 3-DOF PHANToM Premium device with a pen-shaped stylus, and a tablet computer

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[6] http://dl.geomagic.com/binaries/support/downloads/Sensable/3DS/Premium1.0_1.5_HF_Device_guide.pdf

Virtual Assistance

Note that VFs in the remainder of this paper refers to the forbidden region VFs that were implemented for this system. The VFs used prior knowledge about the shapes of the desired ROIs to be colored and imposed virtual walls on the borders of the ROIs. VFs were developed and implemented as spatial open-ended cylindrical and cubical objects. Thus, a user would feel a cube or a cylinder surrounding the robot's arm end-effector when moving it around in 3D space. Side views of the 3D VF-shaped cylinder and cube are shown in Figure 4-2, as obtained by continuously moving the robotic arm on the inner surface of the VFs.

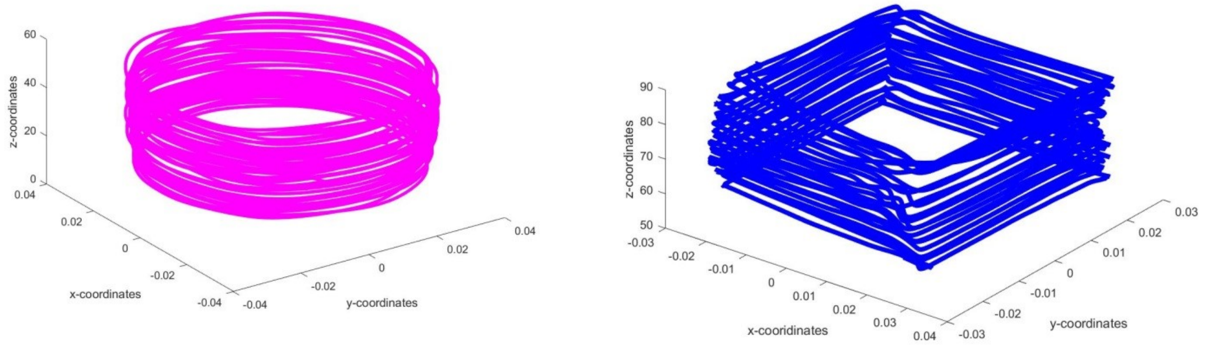


Figure 4-2 Visual illustration of the cylindrical- and cubical -shaped VFs

The projection of the cylindrical and cubical VFs on an *xy* plane (e.g. the tablet) generates 2D ROIs roughly resembling a circle (radius=2.25cm), and square (side length=5.5cm), respectively. Due to a discrepancy in the robot's encoders, the *y* values changed when moving the robot's end-effector along an arbitrary $y = a$ line (a = constant). This resulted in having an ellipse (minor axis = 6.2cm, Major axis = 6.5cm) and a rectangle (width side = 7cm, length side = 7.5cm) when enlarging the shapes. The large ROIs were generated to test possible performance differences with different sized shapes. Four corresponding template 2D ROIs (e.g. resembling a circle, a square, an ellipse, and a rectangle) were saved as images on the MS Paint program on the tablet as template ROIs for the coloring tasks.

In the case of the cubical-shaped VFs, VF_{cube}, four points were determined as the vertices to create the corresponding faces of the cube. Two more points, P_{s1} and P_{s2}, were assigned, which generated the centerline of the cube.

The VF_{cube} was implemented as a spring model system connecting the current position of the robot's end-effector, P_{e-e}, with an Euclidean point, $P_{Euclidean}$ (as shown in Figure 4-3). The $P_{Euclidean}$ was calculated in real time (with a sample rate of 10kHz) by the inner product of the P_{e-e} and the cube centerline that generated the Euclidian distance, $distance_{Euclidean}$. The P_{e-e} being outside the walls implied that a collision incident had happened (defined as P_{e-e} being on the border of the ROI) and that the distance from the P_{e-e} to the $P_{Euclidean}$ ($distance_{current}$) was greater than the $distance_{Euclidean}$. If this condition held true, the VF_{Cube} forces were generated as follows:

$$VF_{cube} = \begin{cases} k * displacement, & if\ distance_{Euclidean} < distance_{current} \\ 0 \quad , & Otherwise \end{cases} \tag{1}$$

$$displacement = distance_{Euclidian} - distance_{current} \tag{2}$$

where *k*, the gain ratio of spring, determines the magnitude of the force. The larger the *k* value, the greater the VF_{cube} forces and therefore, the more rigid the walls of the cube. The linear relationship of the force and displacement implied feeling a small force when just coming into contact with the walls and a gradual increase of the force when pushing further against the walls. This was to prevent the exertion of a sudden force to the robot, which could lead to instability issues. The VF_{cube} forces in the *z*-direction (the top and bottom faces of the cube) were set to zero for the purpose of letting users freely move the robotic arm along the height of the cube. There was zero force when navigating inside the cube, while directional forces were generated when hitting the walls. The direction of the force was determined by the vector connecting $P_{Collisions}$ and P_{e-e} which was applied so as to push the user away from the walls and towards the $P_{Euclidian}$:

$$direction = \frac{P_{collision} - P_{e-e}}{norm(P_{collision} - P_{e-e})} \tag{3}$$

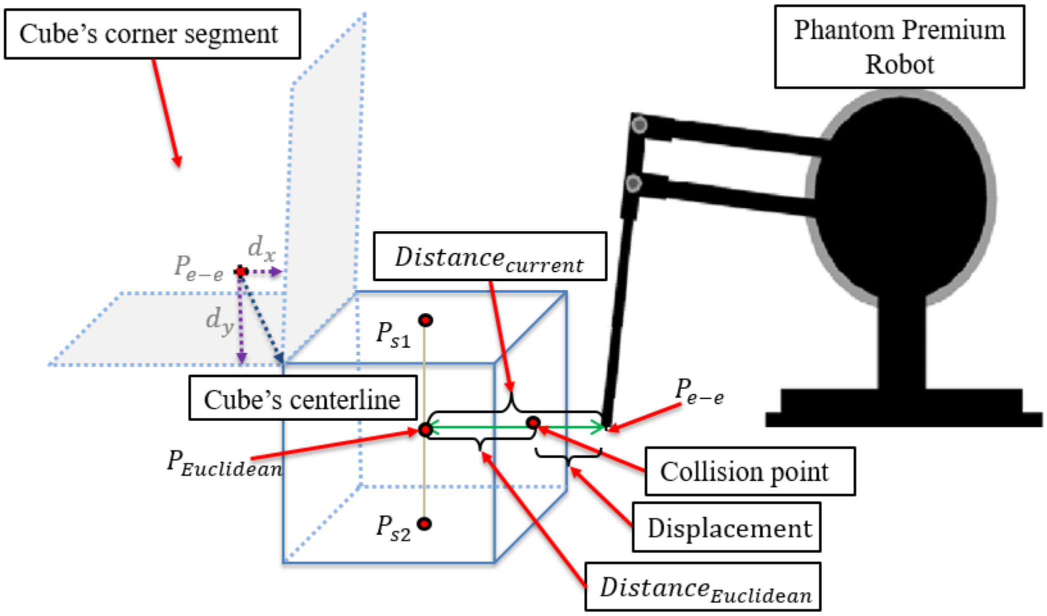


Figure 4-3 Illustration of the implementation of the cubical-shaped VF forces when the robot crosses over the ROIs. Two samples points, P_{s1} and P_{s2}, and a sample $P_{Euclidean}$ are shown

It should be noted when P_{e-e} was located at any of the cube's corner segments (as depicted in Figure 4-3), displacement was calculated based on the Pythagorean Theorem of the x and y projections of the P_{e-e}, d_x and d_y, on the closest face of the cube:

$$displacement_{corner} = \sqrt{d_x^2 + d_y^2} \tag{4}$$

This was to direct the robot's stylus towards the nearest vertex and to take the shortest distance to return to the cube.

The same logic was applied to implement the cylindrical-shaped VFs, $VF_{cylinder}$ except that implementation of the cylinder required less computation. By knowing the cylinder's CenterPoint and radius, the P_{e-e} was tracked until a collision happened. This implied that the $distance_{current}$ was greater than the cylinder radius and thus, $VF_{cylinder}$ were generated.

Virtual Assistance Conditions

By setting the gain ration, k, three different levels of assistance were generated, each associated with a specific level of virtual wall rigidity, namely No-walls, Soft-walls, and Rigid-walls. Assistance approaches were as follows:

No-walls: This approach was to obtain a baseline condition where no assistance was provided. Accordingly, a user accomplishes the tasks without VF assistance, which provides an indication of an individual's typical performance.

Soft-walls: In this approach, the rigidity of the implemented VFs were set to a medium level to not entirely constrain the movements, but still allowing a user to feel the VF forces on the ROI's borders. This resembles a sensation of moving through gel when pushing against the VF walls. This way, a user maintains some control over the movements when coming into contact with the walls while it is still possible to cross over the borders (thus, coloring outside of the lines).

Rigid-walls: In this case, the movements of the stylus were rigidly constrained to the specified ROI providing maximum control for staying inside the ROI. This setting results in fewer chances of crossing over the borders, which in turn reveals the maximum performance available from the system. A user can still move the stylus freely inside the ROI in any direction.

Procedure

The following describes the protocol that was developed to systematically test and validate various features of the system.

Experimental Task 1 - System Validation by Virtual Object Exploration

A procedure, virtual object exploration, was established to test the validity of the system in terms of its *stability* (i.e. no vibration of the robot was sensed by the user) and *safety* (i.e. the robot did not go out of control) as well as the *perceptibility* of the implemented VF_{cube} and $VF_{cylinder}$. Exploration was carried out only with the Rigid-walls condition. This was to ensure that the objects were clearly tangible. The participants were expected to *explore the contour* (or the inner surface) of the virtual spatial objects by holding the robot stylus with their dominant hand. Prior to starting, the participants were given a brief description of the required hand movements to continuously maintain the tip of the robot's stylus on the inner surface of the virtual objects. This procedure was in accordance with the '*contour exploration*' procedure outlined by Lederman and Klatzky (1987): "dynamic exploratory procedure in which the hand maintains contact with a contour of the object" (p. 347). Participants' speed and interaction forces with the virtual objects could contribute to the overall perception. Therefore, the participants were also instructed to maintain a medium (not too large, not too small) amount of speed and force throughout the exploration. This procedure was aligned with the Occupational Therapy definition of *calibration skill* as "using movements of appropriate force, speed, or extent when interacting with task objects (e.g., not crushing objects, pushing a door with enough force that it closes)" (Barbara A. Schell, Glen Gillen, Marjorie Scaffa, 2014, p. 1237). Eventually, the participants were asked to identify the shape of the explored objects taking as much time as needed until they could identify the shape.

Experimental task 2 - Validation of Virtual assistance in Coloring

In order to systematically assess the contribution of VF assistance, coloring tasks were carried out for the four ROIs (circle, square, ellipse and rectangle) and the three different levels of assistance (No-walls, Soft-walls, and Rigid-walls). Both Soft- and Rigid-walls were tested to examine participant preference as well as best performance. The intention was to determine the appropriate amount of assistance that made the user feel being assisted but not resisted.

The order of coloring tasks was kept the same to facilitate technical implementation of the protocol. The assistance levels were counterbalanced before the session to control for order effects (Field, 2011). The assistance level was blinded to the participants. Participants were asked to use their non-dominant hand to color inside the ROI templates. The use of non-dominant hand was intended to increase the challenge and sensitivity to detect benefits from virtual assistance. Participants were given a limited amount of time (11sec for smaller and 12sec for bigger ROIs). Reasonable amounts of time for each task were determined from pilot tests. The participants were aware there was a time limit but were not told how much time they had. The participants were prompted to color as fast as possible and cover as much area as possible within the given time and to firstly aim for the areas close to the borders; this was to ensure the VF-walls were engaged during the performance. Observation notes were taken by the researcher during the sessions to document the interaction of the participants with the VF-walls.

Data Collection

The participant's report of shape of the explored object, and the time to make the identification were recorded. The level of system stability and safety and the VFs' perceptibility in the exploration task were assessed on the basis of a Likert 5 point scale (Likert, 1932), where 1 = *strongly disagree* and 5 = *strongly agree*) in response to the statements displayed in Table 4-1.

Table 4-1 Survey questions administered after completion of the explorational task

Feature of the system & VFs	Survey questions	Additional clarification, if needed
Stability	The system was stable.	No vibrations were sensed on the robot.
Safety	The system was safe to work with.	The robot didn't go out of control.
Perceptibility	The contours and edges of the virtual objects were clearly tangible on the robot.	The VFs were properly implemented and the virtual objects (cylinder and cube) were perceivable.

The position data was collected to plot the user's data in the coloring tasks. The performance was measured on the basis of the following *Quantitative robot measures* (dependent variables, DV) including:

1. *Ratio of Colored area outside to the colored area inside* the ROI ($\text{Ratio}_{\text{out-in}}$) that described the proportion of the amount of the colored area outside the template ROI to that of inside. It should be noted that the points on the border were considered as inside area since the positional displacement is zero on the borders and therefore, $VF = k * displacement$=0.
2. *Positional displacement* of the robot stylus from the borders of the ROI (Displacement) that described error at each sample time (as shown in Figure 14)
3. *Number of collisions* with the borders of the ROI (#OfCollisions). It was considered a collision when the robot stylus went outside of the ROI. The return to enter inside the ROI was not considered as a collision.

Qualitative measures including a *Robot usability questionnaire* (Table 4-2) was administered at the end of the session to assess the participants' overall insight into the system. The questionnaire statements were based on the System Usability Scale (SUS) (Brooke, 1996) and were modified to fit the current system and tasks. The goal was to provide insight into the features of the system including: ease of use, effectiveness of the system and the actions taken by the system (e.g. the implemented VFs), reliability and safety, and usefulness. Statements on stability, safety and perceptibility (as indicated in Table 4-2) were conceptually similar to the survey questions used in the exploration task, but in this case assessed the participant's overall perception of the system.

Table 4-2 Usability robot questionnaire administered at the end of the session. The numbers indicate the order in which the questions were asked

SUS Category: Feature of the system & virtual assistance	Associated robot feature	Usability robot questionnaire
Ease of use	-	1. The system can be used without much training.
Reliability of the system	Safety	3. I felt confident using the system.
Reliability of the system	Stability	6. The system was stable (there was no vibration).
Effectiveness of the system	-	4. I think the system helped me to do the coloring task more easily and quickly.
Effectiveness of actions taken by the system	-	2. The virtual forces were effectively applied into the coloring tasks.
Effectiveness of actions taken by the system	Perceptibility	5. The contours and edges of virtual objects were clearly tangible on the robot.
Usefulness (or effectiveness) of actions taken by the system	-	7. I didn't feel any forces when I was moving the robot inside the virtual objects.

Data Analysis

Algorithms were developed in Matlab to analyse the amount of colored area inside and outside the ROIs, displacement, and the number of collisions. One-way ANOVA measures (within-subjects factors) with Bonferroni correction were performed to determine whether there was a significance ($p<.05$) between the three VF assistance conditions (No-walls, Soft-walls and Rigid-walls) on the user's performance. The Mauchly's Test of Sphericity was conducted to examine the homogeneity of variances. Effect sizes were reported as Cohen's d statistics (*d*) (Jacob Cohen, 1988). The questionnaire responses from participants were described by the parametric statistics of median, mode and range.

Results

This section presents the results of the two experimental tasks: 1) virtual objects exploration as assessed by the survey questions, participant's responses to object identification and elapsed time, and 2) coloring as assessed by the quantitative robotic measures including the $\text{Ratio}_{\text{out-in}}$, Displacement, and #ofCollisions. Finally, the results of the overall insight into the system and its features as assessed by the robot usability questionnaire are presented.

System Validation by Virtual Object Exploration

Almost all participants endorsed "strongly agree" for all three survey questions (Mdn = 5, Mode = 5, Range from 4 to 5).

The average time to identify the shape of the virtual objects was 20:05 seconds for the circle and 10:53 seconds for the square. Eleven out of fifteen participants correctly perceived the shape of cylinder (or circle on the surface); two subjects had similar guesses (e.g. mentioned egg-shape and oval) and two failed to perceive the shape (e.g. mentioned triangle and diamond). All participants perceived the shape of the cube (or square on the surface); three of them perceived a rectangle, which was considered a correct answer since the user only relied on spatial inspection and could not visually discriminate the side lengths.

Validation of Virtual Assistance by Coloring

Quantitative Robot Measures

In the following, the results of the ANOVA Bonferroni correction test are presented (Table 4-3). The underlying test of Sphericity and Normality were met ($p < .05$) for the dataset. Although the measure of #ofCollisions was decreased in most cases in the presence of either Soft- and Rigid-walls, the overall differences were not large. This can be explained by the VF equation generating zero force on the borders as a result of zero displacement. This implies the software counting any cross over as a collision incident even if the user had only a slight touch with the borders. Therefore, the corresponding results were excluded from further analysis.

In Table 4-3, the effect of altering assistance conditions on performance are presented in terms of the level of significance (*p*), Cohen's *d* effect size (*d*) and mean difference between the conditions (*MeanDiff*). Note that a negative *MeanDiff* indicates that the corresponding dependent variable value decreased from the first condition to the second.

Table 4-3 ANOVA test results for different assistance conditions within the four tasks using Bonferroni correction

Task	**VF assistance condition**		**Measures**	**Dependent variables**	
				Ratio$_{out-in}$	**Displacement(mm)**
Circle	**No-walls**	**Soft-walls**	*p*	<.001*	<.001*
			Effect	2.88	2.80
			MeanDiff	0.24	2.87
		Rigid-walls	*p*	<.001*	.001*
			Effect	2.45	2.55
			MeanDiff	0.22	2.75
	Soft-walls	**Rigid-walls**	*p*	1.0	1.0
			Effect	.21	-.14
			MeanDiff	-0.02	.11
Square	**No-walls**	**Soft-walls**	*P*	<.001*	.1
			Effect	1.60	.85
			MeanDiff	0.11	2.49
		Rigid-walls	*p*	<.001*	.1
			Effect	2.23	.74
			MeanDiff	0.14	2.36
	Soft-walls	**Rigid-walls**	*p*	.5	1.0
			Effect	.48	-.1
			MeanDiff	0.02	-.13
Ellipse	**No-walls**	**Soft-walls**	*p*	.003*	.05*
			Effect	1.14	1
			MeanDiff	0.06	1.91
		Rigid-walls	*p*	.003*	.005*
			Effect	2.29	1.5
			MeanDiff	0.11	3.05
	Soft-walls	**Rigid-walls**	*p*	.003*	.006*
			Effect	1.23	1.33
			MeanDiff	0.05	1.138
Rectangle	**No-walls**	**Soft-walls**	*p*	<.001*	<.001*
			Effect	1.83	1.91
			MeanDiff	0.15	2.93
		Rigid-walls	*p*	<.001*	<.001*
			Effect	1.93	1.89
			MeanDiff	0.16	3.08
	Soft-walls	**Rigid-walls**	*p*	.6	1.0
			Effect	.22	.21
			MeanDiff	0.01	.15

*Statistically significant difference $p < .05$.

In the following, the effect of each assistance condition on users' performance in terms of the two dependent variables (**Ratio$_{out-in}$** and **Displacement**) are summarized. The mean differences and standard deviation errors are represented in Figure 4-4 and Figure 4-5. Also, scatter plots of the performance of participant #1 under all conditions in terms of the colored area inside and outside of the template drawings are illustrated in Appendix A (Figure 4-6 to Figure 4-9).

Soft-walls condition**:** As shown in Table 4-3, the user's performance improved significantly, compared to typical performance (No-walls), when Soft-walls assistance condition was provided. Large effect sizes with statistically significant differences between the No-walls and Soft-walls conditions occurred in terms of the **Ratio$_{out-in}$**, meaning that the users colored less area outside the template shapes and therefore, more of their time was devoted in coloring the inside area (Circle: d=2.88, p<.0001; Square: d=1.6, p<.0001; Ellipse: d=1.14, p<.003; Rectangle: d=1.83, p<.0001). Also, a significant reduction in the travelled distance outside the lines (**Displacement**) was obtained, as indicated by the large effect sizes between the No-walls and Soft-walls conditions (Circle: d=2.80, p<.0001; Square: d=.85, p=.1; Ellipse: d=1, p=.05; Rectangle: d=1.91, p<.0001).

Rigid-walls condition: In the presence of Rigid-walls assistance, the same trend as for the Soft-walls condition emerged. The user's performance improved as seen by the large effect sizes with statistically significant differences between the No-walls and Rigid-walls conditions, as assessed by the **Ratio$_{out-in}$** (Circle: d=2.45, p<.0001; Square: d=2.23, p<.0001; Ellipse: d=1.14, p<.003; Rectangle: d=1.83, p<.0001). In addition, the travelled distance outside the lines, **Displacement**, was significantly reduced as indicated by the large effect sizes for Circle (d=2.55, p=001), Ellipse (*d*=1.5, *p*=.005) and Rectangle (*d*=1.89, *p*<.0001), and medium effect size for Square (*d*=.74, *p*=.1).

Soft-walls compared to **Rigid-walls** condition**:** The Soft-walls and Rigid-walls conditions overall did not show significant differences from each other. There were small effect sizes between the two conditions for all tasks. Only for Ellipse, large effect sizes were obtained (**Ratio$_{\textbf{out-in}}$**: *d*=1.23, *p*=.003; **Displacement**: *d*=1.33, *p*=.006).

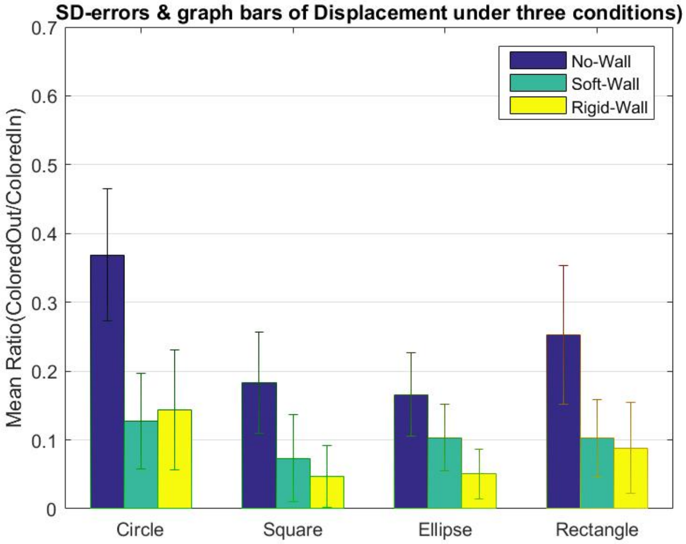


Figure 4-4 Illustration of mean variances of the Ratio of the ColoredAreOut to the ColoredAreaIn under different assistance conditions. The Ratio has significantly decreased by altering from No-walls to either Soft- or Rigid-walls conditions

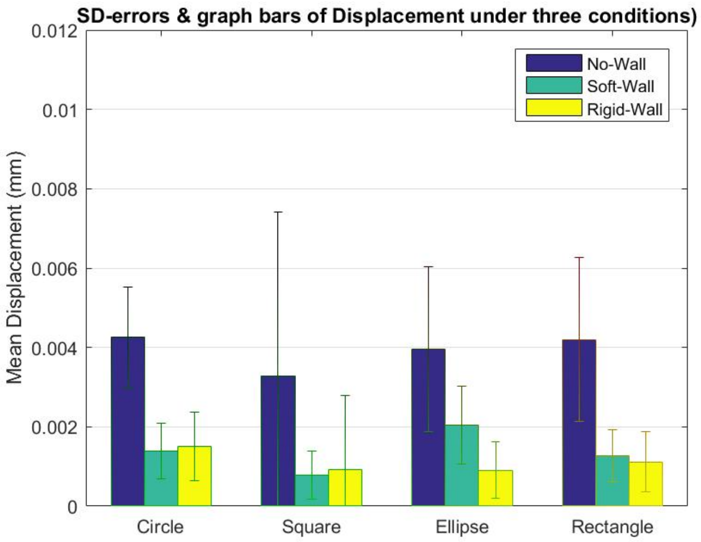


Figure 4-5 Illustration of mean variances of Displacement under different assistance conditions. The Displacement has significantly decreased by altering from No-walls to either Soft- or Rigid-walls conditions

Qualitative Measures

The responses and comments of the participants are presented in Table 4-4.

Table 4-4 Results of the participants' responses to the robot usability questionnaire administered to assess the overall features of the system and the implemented VF-based assistance

Questions (evaluated feature)	Mdn	Mode	Range	Summary of comments
The system can be used without much training (ease of use).	4	5	2 to 5	Several participants referred to the system as easy and fun to work with.
The virtual forces were effectively applied into the coloring tasks (effectiveness of actions taken by the system)	5	5	1 to 4	There were comments saying that the participants liked how the virtual forces helped to stay inside, felt more controlling with forces than without, and found coloring a lot easier when borders were on. Two of the participants commented that the Rigid-walls were somewhat restricting.
I felt confident using the system (reliability (or safety) of the system).	5	5	2 to 5	No comments.
I think the system helped me to do the coloring task more easily and quickly (effectiveness of the system).	5	5	3 to 5	Some of the participants found the "handle" (the robot's metallic stylus) slippery and suggested to add some texture into it, although it was comfortable. One participant stated that she had to modify her grip to hold the grip straight up and down and may need some time getting used to.
The contours and edges of virtual objects were clearly tangible on the robot	5	5	3 to 5	One participant commented that the virtual shapes were "amazingly" tangible.

(effectiveness of actions taken by the system).				
The system was stable and there was no vibration (reliability (or stability) of the system).	5	5	3 to 5	One participant misperceived the concept of VF walls and thought of them as vibration.
I didn't feel any forces when I was moving the robot inside the virtual objects (usefulness).	5	5	1 to 5	No comments.

Observations and General Comments

A few of the participants gave additional comments regarding the shape and size of the VF-shapes. They thought that the square (or rectangle) was more difficult than the circle (or ellipse) as they needed to deal with the corners while the circle required more natural hand movements and they did not need to modify or over compensate movements. Also, one participant noticed that she was making a certain pattern of movements when the VFs were on while making more random movements when it was off.

It was observed that instead of continuously moving the tip of the robotic arm on the surface of the objects, a few of the participants randomly moved the arm from one spot to another. This resulted in mistakenly feeling several angles on the virtual object. Also, it was observed that for a few of the participants the VF-walls were initially not intuitive to interact with and they seemed very conservative when coming into contact with the walls. But after some practice, they seemed confident to hit or push against the walls.

Discussion

In this preliminary study, the validity of the developed system was initially confirmed based on its stability and safety. There was no incident of the robot going out of control and all participants felt the system was safe, as assessed by the survey questions and participants' comments. In addition, none of the participants experienced any source of vibration or noise;

moving the stylus in the sharp corners of the square VF had the potential to cause the system to become unstable due to the sudden change of the force magnitude and direction but it stayed stable. The validity of the generated VFs was also confirmed by correct perception of the shape of the virtual objects. Only two participants mistakenly perceived a diamond and a triangle instead of the circle. Additionally, the participants' overall ratings and comments about the system confirmed the system's ease of use, reliability, safety and stability, as well as the effectiveness of virtual assistance in performing coloring faster and easier. None of the participants exhibited difficulty operating the system. As for the question on usefulness, responses showed that the participants did not feel any forces inside the virtual objects. Thus, the software did not apply unnecessary force when navigating inside the ROIs.

Soft-walls and **Rigid-walls** conditions led to the best performance improvements with large effect sizes in terms of a substantial reduction in $\text{Ratio}_{\text{out-in}}$ error, and a great reduction in Displacement. Therefore, we can conclude that, regardless of shape and size of virtual objects, the virtual assistance (either Soft or Rigid) did successfully decrease the total error and elicited a significant increase in coloring performance in maintaining the movements inside the ROI borders. In terms of the #OfCollisions, it decreased in most cases in presence of the VF assistance (either Soft or Rigid); however, it was overall not a strong indicator of the user performance to track. The Soft- and Rigid-walls led to relatively the same performance improvements over No-walls. A possible reason is that our participants were abled-bodied adults who were able to maintain their control when touching the forces (either small or large) at the borders, despite being challenged by the time constraint and use of non-dominant hand. We might expect higher performance improvements with the Rigid-walls condition in future studies with children who have disabilities due to their less controlled fine motor movements.

The Rigid-walls approach enabled participants to better stay within the ROI borders, however, two of the participants commented that they preferred the Soft-walls because they found the Rigid-walls somewhat restricting. Rigid-walls can reduce the ability for autonomous control (or to intentionally making errors), which may result in reduced motivation in some users. This is a valid point to consider when user's satisfaction is a priority.

When interacting with the VFs (either hard or soft), a few of the participants made different movement patterns than when the VFs were turned off. In other words, their hand movements mimicked the shape of the implemented VFs instead of making random hand movements when coloring the ROIs. This can be a valid point for applications in which the human user needs to learn a certain pattern of movement to accomplish a specific task.

When children with and without disabilities use the system, we would expect similar results as the adults in terms of $\text{Ratio}_{\text{out-in}}$ and Displacement, i.e., the forbidden region VFs (both Soft- and Rigid-walls) will maintain the movements inside the ROI compared to No-walls. There may be differences in how adults and children perceive the forces though. Adults maintained control regardless of the rigidity of the wall, Soft- or Rigid, but performance in children may be different under different assistive conditions. However, execution of the task does not rely on how well the user perceives the rigidity of the haptic-based virtual assistance. The assistance is imposed regardless of how well the walls can be perceived.

Future studies with typically developing children at various ages are needed to evaluate how they perceive VFs, and with what resolution and also to understand if the system presents cognitive and sensory demands that may affect performance, satisfaction, and independence.

Regarding the use of system by children with disabilities, it may be appropriate to let them select their preferred assistance condition (either Soft or Rigid) for higher satisfaction. Or, the system could adapt automatically as children improve in the task over time. If the child begins to color within the defined borders, less assistance (less stiff walls) might suffice. This may give children a feeling of control over the task, letting them do the task as independently as possible. It is preferable to only provide assistance as needed, without imposing unnecessary force or restriction on the operator. In long term studies with children with disabilities, enhanced play performance in children may contribute to increased satisfaction, sense of independence, self-efficacy and motivation in the coloring activity.

This study had some limitations yet to be mentioned. There was a high variability in data, likely occurring as a result of performance differences in able-bodied participants using their non-dominant hand. There would also likely be high variability in group studies with children, due to their unique impairments. Thus, study designs where participants are their own controls will be needed. Also, the participants were asked to firstly color the area close to the borders to ensure the engagement of the VF walls in performance. This may have changed the naturalness of the coloring action. In future studies, participants will not be given any prompts in this regard. The issue with the robot encoders' discrepancy when creating symmetrical shapes will also be addressed in future development. A texture will be added to the robot's metallic stylus to prevent it from sliding out of the operator's hand.

Further development of the system will include integration of intelligence into the system to adaptively tune the level of assistance (i.e., rigidity of the virtual walls) according to the user's performance. In future studies with children, the measures of Min and Max of Displacement will also be reported for additional assessment of child's performance. Integration of guidance virtual fixtures can assist the children’s hand movements to initially create a drawing and then color inside it.

Conclusion

This study presented the preliminary evaluation of the developed system with able-bodied adults. The system’s safety and stability as well as the perceptibility of the implemented virtual objects were clearly validated. The user’s typical performance (No-walls condition) was compared against the Soft-walls and Rigid-walls assistance conditions. The results validated the effectiveness of both assistance conditions in improving the performance of the user as confirmed by the 1) significant decrease in the ratio of the colored area outside to the colored area inside the ROI, and 2) a great reduction in total displacement from the borders of the desired region. Soft and Rigid walls did not lead to big performance differences, however the Soft-walls were more preferred by some of the participants. Future experiments will address the effectiveness of the proposed system in assisting children without and with disabilities.

Appendix A

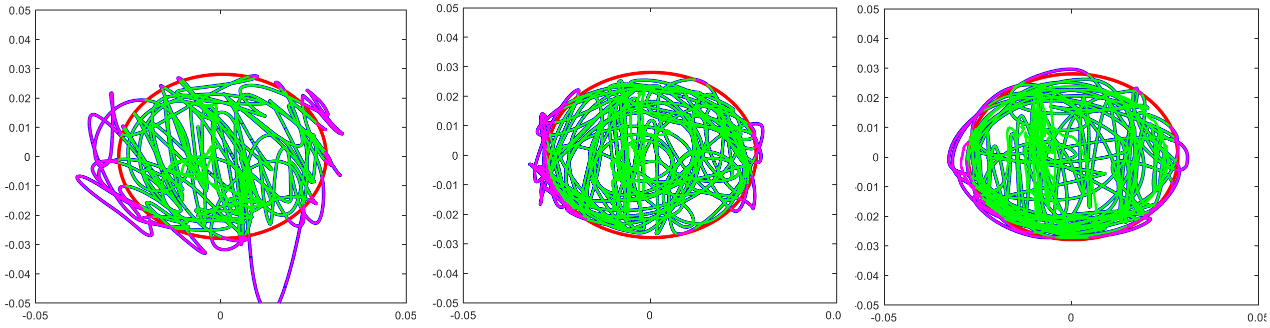


Figure 4-6 Illustration of the color-coded movement trajectories of participant #1 inside and outside the ROI under No-walls (left plot), Soft-walls (middle plot) and Rigid-walls (right plot) assistance conditions

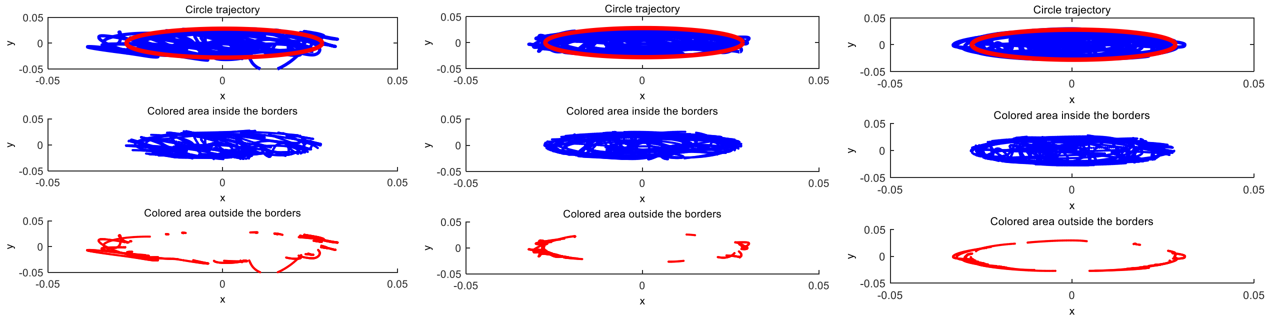


Figure 4-7 Visualization of analysis of the movement trajectories of participant #1 inside and outside the ROI under No-walls (left plot), Soft-walls (middle plot) and Rigid-walls (right plot) assistance conditions

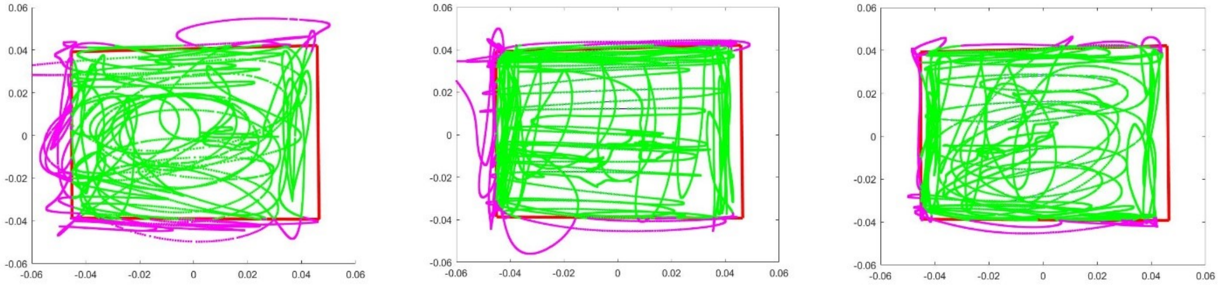


Figure 4-8 Illustration of the color-coded movement trajectories of participant #1 inside and outside the ROI under No-walls (left plot), Soft-walls (middle plot) and Rigid-walls (right plot) assistance conditions

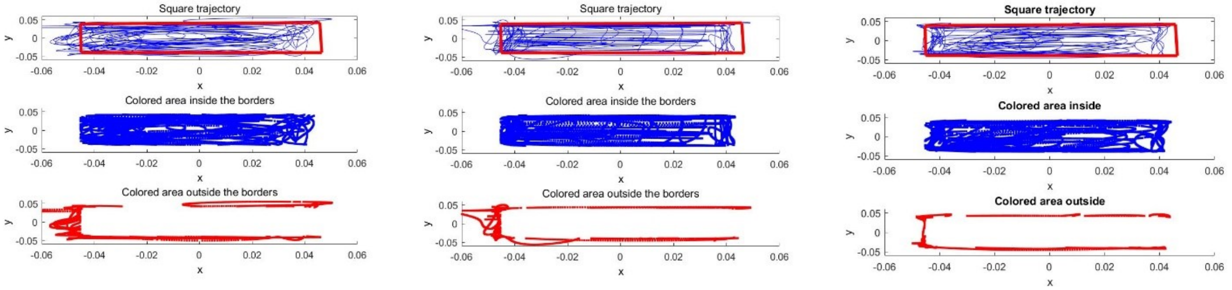


Figure 4-9 Visualization of analysis of the movement trajectories of participant #1 inside and outside the ROI under No-walls (left plot), oft-walls (middle plot) and Rigid-walls (right plot) assistance conditions

Chapter 5

PAPER 4: CLINICAL VALIDATION OF A DEVELOPED ASSISTIVE ROBOTIC SYSTEM WITH VIRTUAL ASSISTANCE FOR INDIVIDUALS WITH CEREBRAL PALSY

This paper presents a novel application of an assistive robotic system with virtual assistance to enhance manual performance of individuals with cerebral palsy. Cerebral palsy affects one's voluntary motor movements resulting in limited opportunities to actively engage in physical manipulative activities that require fine motor movements and coordination. Lack of object manipulation and environmental exploration can result in further impairments such as cognitive and social delays. The proposed assistive robotic system has been developed to enhance hand movements of people with disabilities when performing a functional task- coloring. This paper presents the clinical validation of the effectiveness of the developed system with an individual with cerebral palsy in a set of coloring tasks. *Assisted* and *unassisted* approaches were compared and analyzed through quantitative and qualitative measures. The robotic-based approach was further compared with the participant's *typical* alternate access method to perform the same proposed tasks. The robotic system with virtual assistance was clinically validated to be significantly more effective, compared to both unassisted and typical approaches, by increasing the hand controllability, reducing the physical load and increasing the easiness of maintaining movements within the lines. Future studies will inform the use of the system for children with disabilities to provide them with assisted play for functional and playful activities.

KEYWORDS: Robotic system, virtual assistance, people with disabilities, cerebral palsy, manual activity

Introduction

Cerebral palsy (CP) is associated with a group of permanent and non-progressive neurological sensorimotor impairments as a result of a brain damage prior, during or after birth (Dodd, Imms, & Taylor, 2010). Brain injuries can break the pathway between the sensory and motor systems, resulting in deficits in the sensory modalities including touch, vision and hearing. Individuals with CP have shown impairments in the detection touch feedback (Auld, Ware, Boyd, Moseley, & Johnston, 2012; Williamson & Anzalone, 2000). CP primarily affects motor performance and is sometimes accompanied by other developmental disorders including cognitive, perceptual, and communicative deficits. Oftentimes, a diagnosis of CP is suspected if a child does not reach the motor developmental milestones such as reaching, grasping and crawling. Depending on the nature of motor abnormalities, CP has been classified into spastic, dyskinetic, and ataxic conditions. Spastic CP is the most commonly occurring condition, and is caused by damage to the motor cortex, which controls voluntary movements. Spasticity is characterized by stiff, tight, and hypertonic muscles resulting in reduced coordination and fine motor skills. Dyskinetic CP happens when basal ganglia, the balance control center, is damaged. It is characterized by involuntary, repetitive and hypotonic muscle tone. Ataxic CP refers to the unsteady, shaky movements due to damage to the cerebellum. Ataxia affects fine motor activities, coordination and balance control. Mixed CP refers to a condition when an individual presents a combination of the abovementioned motor disorders. Overall, CP can significantly affect individuals' abilities for active object manipulation and environmental exploration and reduce their abilities in performing functional manual activities.

According to developmental theories, development of motor, cognitive and perceptual skills relies on environmental exploration and manipulation (Gibson, 1988b; Piaget & Cook, 1952).

Gibson's theory of development (Gibson, 1988b) describes an exploratory behavior as an ongoing cycle between action, perception, and cognition. Through exploratory actions, one can perceive the environment and build a foundation of knowledge about the world, which is the essential means for cognitive development. Restrictions in body functions in individuals with CP can break the cycle of action, perception and cognition even if perception and cognition are intact (Gibson, 1988a). Reduced opportunities for active participation and manual activities can in turn delay perception and cognition (Gibson, 1988b).

Coloring is a functional manual activity that requires interaction with the play environment (e.g. the coloring surface). It is generally advantageous in enhancing one's eye-hand coordination, focused attention and imagination, fine motor skills, and artistic thoughts (Gruber & McNinch, 1994; Mayesky, 2009). It begins with scribbling in toddlers and later, the obtained skills are used toward making meaningful symbols (Gruber & McNinch, 1994), and using writing tools through a rewarding and pleasurable experience (McGee & Richgels, 2011). The *circle* and *oval*, and later, the *square* and *rectangle* are generally the first four basic forms children scribble or draw (Mayesky, 2009), and are related to the next stages of writing and art. They initially develop when the child recognizes them in his scribbles and then, tries to repeat them. In the same way, writing is believed to usually start with imitating simple geometric shapes such as circles and squares (Feder & Majnemer, 2007). Thus, provision of access to coloring the basic shapes can potentially reinforce children's learning of geometric shapes, drawing, and writing letters.

Use of writing tools through activities such as coloring can also enhance in-hand manipulation skills (Feder & Majnemer, 2007). In-hand manipulation skills needed for coloring are: how to grasp the tool and adjust the applied pressure and direction of movements, and how to rotate or move tools between the palm and the fingers (Feder & Majnemer, 2007). In people with CP, in-hand manipulation skills might be different or delayed. They may lack the required skills for purposeful scribbling and coloring due to their fine motor deficits, such as hand tremor, spasm, or coordination difficulties. They may cross the borders, color a large area outside the picture instead of the desired picture. Failing to perform the task successfully or desirably could result in frustration, disappointment and reduced sense of self-efficacy. Self-efficacy (or self-perception of ability) is defined as “beliefs in one's capabilities to mobilize the motivation, cognitive resources, and courses of action needed to meet given situational demands” (Wood & Bandura, 1989, p. 408). In other words, it describes how one perceives his/her ability to succeed in a task and is strongly linked to previous experiences, which can influence future performance.

Various computer control interfaces such as mini-joysticks, adapted mice or keyboards can provide access to computer applications for individuals with disabilities (Cook & Polgar, 2008, Chapter 7). Accordingly, an individual with disabilities will potentially be able to perform activities such as coloring and painting through a computer interface and a computer application.

However, an assistive robotic system developed to enhance manipulative capabilities of people with CP in fine motor activities (i.e. coloring) could provide a more successful approach. A user can operate the robotic system by holding a pen-shaped end-effector adapted for their grasp abilities (e.g. by attaching various grips to the interface).The proposed system can facilitate motor movements by provision of virtual assistance, implemented as virtual walls on the borders of drawing pictures. Virtual assistance was developed and implemented in the form of virtual fixtures (VFs). VFs are computer generated forces that can either assist in maintaining the user’s movements within a desired region or guide the movements towards a desired target. A preliminary evaluation of the system was performed with fifteen *adults without disabilities* (Jafari, Adams, Tavakoli, & Wiebe, 2016). The results validated the *effectiveness* of the virtual assistance as well as the system's *stability* (i.e. no vibration or noise was sensed on the robot) and *safety* (i.e. the system did not go out of control).

The current study with *an adult with CP* informs the research in a logical sequence from adults without disabilities to individuals with CP by clinically evaluating how well the developed robotic platform can accommodate an individual with disabilities' manipulative skills. The target population is children with disabilities, but performing this study first allowed the evaluation of the system without the overlay of the challenges concerned with children. A systematic study with *children who have disabilities* will be conducted in the future.

This study evaluated through quantitative and qualitative measures whether the developed robotic system could accommodate the individual with CP's manual performance to accomplish the tasks more successfully. Additionally, the individual's *typical approach* to perform the same set of tasks was studied. This step was beneficial in understanding whether the *robotic-based approach* (i.e. using the proposed robotic system) outweighs the *typical approach* that is generally available to the individual with disabilities.

Methods

***Participant*:** A single-case study was conducted with a female individual, 48 years old, who has quadriplegic CP. Her condition is mixed CP characterized by high and low muscle tone and involuntary movements. According to the Gross Motor Function Classification System Expanded and Revised (GMFCS-E&R) (Palisano et al., 1997), she is classified at Level IV, meaning that she can perform self-mobility when using a powered wheelchair. Based on the Manual Ability Classification System (MACS) (Eliasson et al., 2006), she is at Level III, meaning that she has difficulty handling objects by hand but can perform manual tasks with help and/or adaptation of the activity.

System description

***Robotic-based* approach:** The experimental setup (as shown in Figure 5-1) consisted of a haptic robotic interface PHANToM Premium 1.5A (Geomagic, Cary, NC) as the user interface, and a tablet computer used as the coloring surface. In the proposed design, VFs were developed and implemented as spatial virtual walls on the borders of template pictures to help the individual with CP to color inside the desired regions. The virtual walls were formulated such that the user did not sense any force while navigating inside the template picture, felt a small force when just coming into contact with the walls, and experienced a gradual increase of the force when pushing further against the walls. The rigidity of the virtual walls was set to medium and high levels, referred to as Soft-walls and Rigid-walls, respectively, in order to assess the participant's preferred level of assistance. Soft-walls feel like moving through gel when pushing against them while still being able to cross the borders if applying more force. Rigid-walls provide maximum control for maintaining movements inside the desired region, and thus, less ability to cross the borders. The detailed description of the system development and preliminary results is represented in (Jafari, Adams, Tavakoli, et al., 2016).

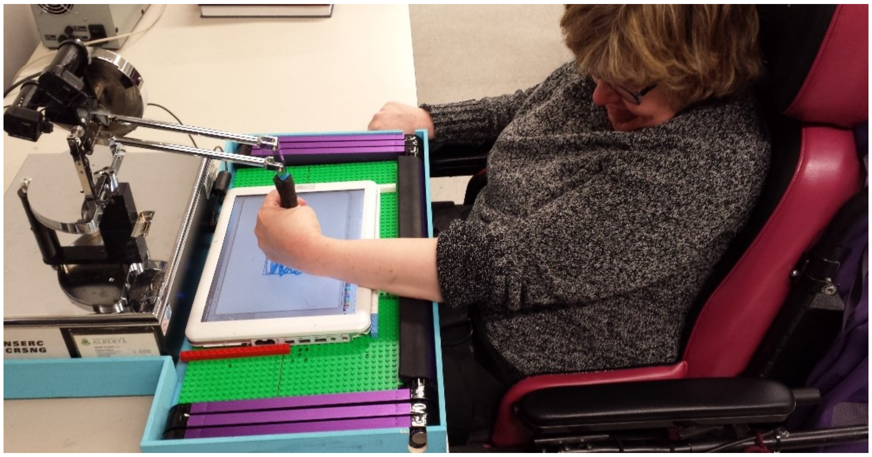


Figure 5-1 The individual with CP operating the robotic system, equipped with the virtual assistance, by holding the robotic end-effector

***Typical approach*:** The typical assistive technology setup consisted of the participant's standard keyboard with a key guard (as shown in Figure 5-2) connected to a desktop computer. The coloring tasks were implemented on MS Paint and were displayed through a regular monitor. The built-in Mouse Keys function was turned on, which uses the eight keys on the numeric keypad to move the cursor up, down, left and right as well as on the diagonal. The participant is proficient in using the keyboard for mouse control and interacting with graphical computer interfaces (GUI) through many years of experience. She was given a trackball and a joystick as alternative options, since they were assumed to provide easier and faster movements for coloring, however, after trying all three interfaces, the participant preferred the keyboard.

Figure 5-2 Individual with CP using her typical computer interface, a keyboard with a key guard, to perform the task on the computer (typical approach).

Procedure

The participant performed four coloring tasks (resembling a circle, square, ellipse and rectangle) under each assistance condition (unassisted, Soft- and Rigid-walls). The same task were performed using both robotic- and typical-based approaches. A reasonable amount of time, based on pilot tests, was given (i.e. 20 seconds). In order to control for order effects, the assistance conditions were counterbalanced. There were two sessions, an hour for the first and three hours for the second session. Session 1 was to determine the best position and orientation to interact with the robotic system within the reachable and convenient workspace of the participant. As a result, a foam pad was placed around the robotic end-effector for easier grasp. Also, the robotic end-effector's calibration height was lowered to facilitate the individual's arm-hand position. Once the adjustments were made, both the robotic-based and typical approach were performed in session 2. The participant performed the same coloring tasks on the typical computer approach as the robotic one.

Data collection

The robotic-based performance was quantified based on the following task measures (for detailed description of the measures and data acquisition, see (Jafari, Adams, Tavakoli, et al., 2016)):

1. The ratio of the colored area outside to the area inside the sample pictures, $\mathit{Ratio}_{out\text{-}in}$
2. *Positional error* indicating the travelled distance outside the boundaries

Quantitative analysis of the robotic-based performance was performed using t-tests in order to assess the effect of either Soft- or Rigid-walls assistive conditions versus the unassisted performance, No-walls.

A subjective assessment of perceived force of each system on the hand and arm was made by the participant. The participant rated her perceived load based on the Borg Rated Perceived Exertion (RPE) Scale (Gunnar, 1982) (0 = nothing at all, and 10 = maximal, as shown in Figure 5-3). Additional performance evaluation was carried by responding to the following statements on a 5-point Likert scale (Likert, 1932):

1. The level of easiness in coloring inside the sample pictures is ..., where 1 = very difficult, and 5 = very easy
2. The level of control of hand movements is ..., where 1 = very high and 5 = very low

The participant rated these items after every combination of the task and the assistance conditions (i.e., 4 tasks * 3 conditions=12).

Borg's RPE scale

0	Nothing at all
0.5	Very, very weak (just noticeable)
1	Very weak

2	Weak (light)
3	Moderate
4	Somewhat strong
5	Strong (heavy)
6	-
7	Very Strong
8	-
9	-
10	Maximal

Figure 5-3 Borg Rated Perceived Exertion (RPE) Scale to quantify the perceived physical load

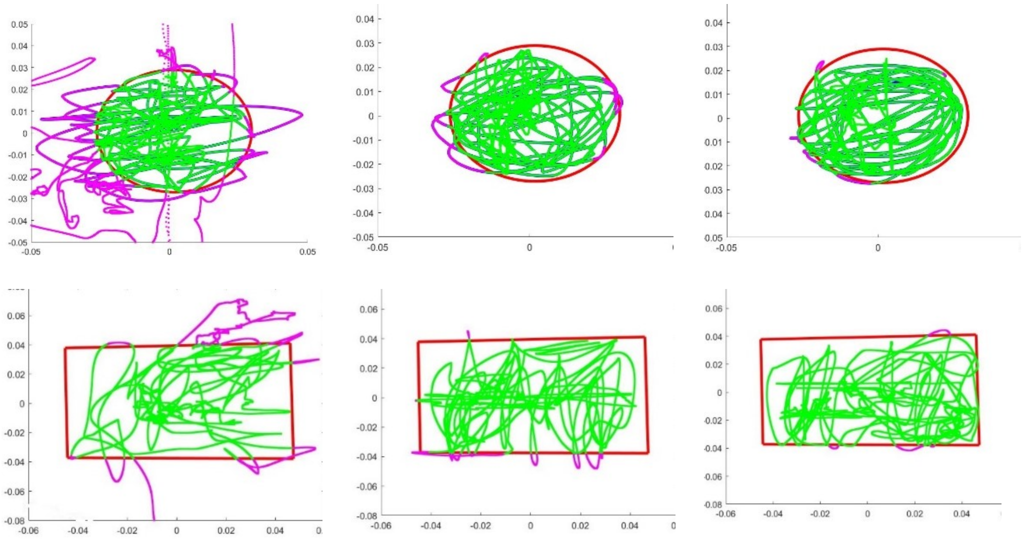
In order to assess the participant's overall perception of the system, a usability questionnaire was administered at the end of the session. The questionnaire statements were taken from the System Usability Scale (SUS) (Brooke, 1996) and modified to fit the current study (Table 5-1).

Results

In the following, the results under each assistance condition are presented as assessed by the robotic measures ($Ratio_{out-in}$ and *positional error*), RPE scale, and survey questions. The typical approach is further compared with the robotic approach in terms of the participant's response to the survey questions and visual inspection of the coloring performance. Finally, the participant's overall opinion of the robotic system is presented based on the usability questionnaire.

Robotic-based approach

The $Ratio_{out-in}$ indicated significant performance improvement ($p < 0.05$) when either of the Rigid-walls (*Cohen's* $d = 1.8$) or Soft-walls (*Cohen's* $d = 1.7$) were provided, compared to the unassisted performance. Although the measure of positional error was reduced in each individual task, there was no significant difference between the No-walls and either of the assistive conditions. Sample coloring performances under the three robotic conditions are illustrated in Figure 5-4.



(a) No-walls **(b) Soft-walls** **(c) Rigid-walls**

Figure 5-4 Illustration of the color-coded movement trajectories inside and outside the sample drawing pictures under No-walls (left plot), Soft-walls (middle plot) and Rigid-walls (right plot) robotic assistive conditions.

The physical loads were, from highest to lowest: Rigid-walls (*Mdn* = 2.5, *Range* = 1 to 5), No-walls (*Mdn* = 1, *Range* = 1 to 2), and Soft-walls (*Mdn* = .75, *Range* = .5 to 1). The participant described the Rigid-walls as triggering her hand spasm and commented that the less rigid boundaries were more helpful.

In terms of the easiness of maintaining the movements within the desired regions, the Soft-walls were rated as the easiest approach (*Mdn* = 5, *Range* = 4 to 5), and No-walls and Rigid-walls were equally rated slightly less easy (*Mdn* = 4.5, *Range* = 4 to 5). Regarding controllability of hand movements, the Soft- and Rigid-walls were equally rated as giving the highest control (*Mdn* = 1, *Range* = 1 to 2) and No-walls was rated the lowest (*Mdn* = 1.5, *Range* = 1 to 4).

Typical approach

The participant rated the keyboard, based on the RPE scale, as very weak in exerting physical load (*Mdn* = 1, *Range* = .5 to 1). As for the easiness of maintaining the movements within the desired regions, the keyboard was scored as being difficult (*Mdn* = 2, *Range* = 1 to 4). In terms of the controllability (i.e. moving fingers between keys), the keyboard was rated as giving low control (*Mdn* = 4, *Range* = 3 to 5). Based on visual inspection, the participant was not able to efficiently perform the coloring tasks using the keyboard (Figure 5-5). In the same amount of time, she colored considerably less of the inside of the picture compared to when using the robot system. In addition, she had difficulties switching between the keyboard keys and thus, over-shot the borders. Figure 24 illustrates the participant's attempt in coloring two sample pictures.

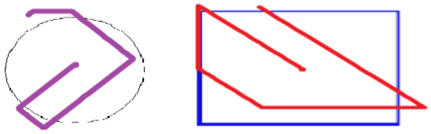


Figure 5-5 Performance of the individual with CP when using her typical computer interface

Usability questionnaire

The participant's responses to the usability questionnaire are summarized in Table 5-1. The statements were rated on a 5-point Likert scale (1 = Strongly disagree and 5 = Strongly agree).

Table 5-1 The usability questionnaire administered to evaluate the overall perception of the system, with regards to the robotic-based approach

SUS Category: Feature of the system & virtual assistance	Associated robot feature	Usability robot questionnaire	Results
Ease of use	Ease of use	The system can be used without much training.	4
		It was easier to hold on (or control) the robotic arm compared to the keyboard	5
Reliability of the system	Safety	I felt confident using the system.	5
	Stability	The system was stable (there was no vibration).	5
Effectiveness of the system	Effectiveness	I found the coloring task <u>easier</u> when using the robotic system compared to the keyboard	5
	Complexity	I found the system unnecessarily complex	1*
	Efficiency	I found the coloring task <u>faster</u> when using the robotic	5

		system compared to the keyboard	
Effectiveness (or usefulness) of actions taken by the system	Controllability	I had more control over my hand movements when using the computer interface than the robotic arm.	1*
	-	The virtual forces were effectively applied for the coloring tasks.	4
	Perceptibility of virtual walls	The contours and edges of virtual objects were clearly tangible on the robot.	5
	-	I did not feel any forces when I was moving the robot inside the virtual objects.	5

*‘1’ here is an indication of a positive result.

Discussion and conclusion

This study clinically validated the functionality of the developed robotic system with virtual assistance in enhancing the functional manipulative performance of an individual with CP in a coloring task. Overall, the quantitative and qualitative results confirmed the effectiveness of the system under Soft- and Rigid-walls assistive conditions compared to the unassisted as well as the typical approaches.

The *objective* analysis of the results in terms of the $Ratio_{out\text{-}in}$ showed relatively the same performance improvement under either of the Soft- and Rigid-walls conditions. Similarly, Soft- and Rigid-walls were scored *roughly* the same for the *subjective* measures of controllability and easiness. These results are consistent with the study with 15 abled-bodied adults where the Soft- and Rigid-walls contributed to relatively the same performance improvements. For the measure of perceived physical load, the Soft-walls were scored better than the Rigid-walls; even though both assistive conditions *objectively* showed the same effectiveness. In the same way, some able-bodied participants preferred the Soft-walls despite the higher effectiveness of the Rigid-walls.

Regarding the measure of *positional error* being insignificant, this is in contrast to how it was significantly reduced in the presence of either Soft- or Rigid-walls in the study with adults (Jafari, Adams, Tavakoli, et al., 2016). Likely, the amount of data collected for the individual with CP was not sufficient to pool the reductions that occurred in each single case (i.e. combination of the tasks and conditions) to lead to an overall significant difference.

The typical approach was noticeably less effective as compared to the robotic approach, as visually evidenced by the coloring performance (Figure 5-5). Likewise, the keyboard was given the lowest score in easiness compared to all three assistive conditions of the robotic system. Interestingly, this was despite that the resting position of the individual's hand seemed less awkward when using the keyboard (Figure 5-2) compared to the angled arm posture when operating the robotic arm (Figure 5-1). In addition, previous familiarity of the participant with the keyboard and its required movements did not make the keyboard more preferable over the robotic system.

According to the overall perception of the system, the participant strongly agreed with the safety, stability, effectiveness of the system as well as the implemented assistance feature. Furthermore, the participant strongly agreed that the robotic system performed better than the typical approach in terms of the controllability, effectiveness, efficiency, and ease of use.

In future studies with children with disabilities, we would expect similar results as adults in terms of the quantitative measures (i.e. the robotic system will accommodate and improve hand movements in the manual tasks). Additionally, by letting children to experience more success than failure or dissatisfaction in the task execution, children may feel an increased sense of self-efficacy, and motivation. Children's engagement in the play activates can be increased by inclusion of more playful drawings (e.g. a snowman) with an option to initially try the assistance conditions, Soft- and Rigid-walls, and then select their preferred assistance level. Thus, since both Rigid and Soft conditions led to significant performance improvements, choosing their preference approach could increase the child's satisfaction and level of physical comfort. The participant with CP further commented that "children would have fun with the system. There should be a way to change the color on their own though"; flexibility to the system may be important to encourage exploration and individuality. Further development of the system will include integration of artificial intelligence so the system will adaptively tune the level of assistance (i.e. the rigidity of the walls), according to the participant's performance.

Chapter 6

GENERAL DISCUSSION AND CONCLUSION

This thesis is developed as a result of a literature review, studies on system development and user studies (presented in chapters 2 to 5 of this thesis). The four papers together establish the *theoretical basis*, *technical feasibility*, and *clinical validation* of the proposed assistive technology in adults with and without disabilities (to collect evidence for establishing the intervention of the robotic system) as an alternative access method to typical manual play activities for children with disabilities.

As reviewed in paper 1 (chapter 2), the tendencies for the use of haptic-based assistive technologies for various disability populations is dedicated to the three major application areas of computer access, wheelchair (or mobile robot) control and rehabilitation, predominantly for adults. Tendencies for children's use are limited to wheelchair studies, *verifying* the need for research on developmental advantages of the technology for the child population. Haptic guidance, as the overarching feature between the application areas of haptic-based assistive systems, generally contributes to improvements in manual performance. However, utilizing haptic guidance raises uncertainty regarding the increased musculoskeletal loading in occasions where the implemented forces are against the user's intended movements. This salient point was later *reflected* in the protocol of the study with the individual with disabilities (paper 4, chapter 5) by quantifying the perceived physical load on her hand and arm while interacting with the robotic system under assisted and unassisted conditions. The assisted condition resulted in less physical loading providing that the level of assistance was set to medium (versus maximum) thus avoiding physical reactions such as triggering muscle spasm when interacting with the implemented forces.

Virtual environments (VE) are another overarching feature widely used in the abovementioned areas. It offers advantages over physical environments, particularly for rehabilitation and training purposes as well as computer access for blind people. However, regarding implications for children, developmental theories emphasize the significance of physical interactions with objects and the surrounding environment (Gibson, 1988b; Piaget & Cook, 1952; Power, 2000; Taylor et al., 1973). The system presented in chapter 4 was developed accordingly, involving a *single robot* configuration, allowing *direct physical interaction* with the environment (i.e. directly interacting with the surface of the tablet gives a physical experience). Alternatively, a *teleoperation* system can be used (presented in chapter 3), to *simulate* the physical interaction (i.e. transferring interaction forces between the drawing tool and the paper); teleoperation is particularly beneficial where the user needs further hand modulations (e.g. scaling the range of motion, filtering involuntary movements, etc.).

Paper 2 (chapter 3) presented the initial technical implementation of a teleoperation system in a master-slave configuration in implementing a *haptic-based teleoperated play* activity (i.e. drawing). The teleoperation system enables the user to feel the corresponding interaction forces between the slave robot's end-effector and the drawing surface through his interface, providing him with a simulated sense of manipulation. With respect to specifications adequate for our target population and the task, requirement criteria for the candidate robots was established to set the appropriate choices for the role of master (user-side) and slave (task-side). The criteria were developed on the basis of several robot attributes including positional accuracy, kinematic design, operational workspace, and inertia. These requirements were primarily to ensure the *safety* and ease of use for the user and the feasibility of the task implementation for the slave. After establishing the robot choices, the control parameters were determined and tuned to inform the system's *stability* and transparency, which contributed to development of the system presented in paper 3 (chapters 4). A system's *safety* and *stability* are critical considerations where humans, particularly children, are intended to operate the system. A systematic procedure, so-called *virtual object exploration*, was developed to specifically address the safety and stability considerations for the system presented in paper 3 (chapter 4). This procedure validated the system's reliability for future use by individuals, in particular children, with disabilities.

Paper 3 also presented a preliminary study to test the implementation of a *virtually assisted* manual activity, coloring, in comparison with unassisted performance (resembling typical performance). The technical feasibility of such a comparison was established through implementation of virtual assistance, integrated into a single-robot configuration, and conducting user trials with 15 abled-bodied adults. Initial testing with adults informed the system performance and design as well as required modifications in a logical sequence by evaluating how well the system can facilitate manual skills without the overlay of disabilities. Adults, compared to children, are also able to articulate opinions and give feedback.

The *perceptibility* of the implemented virtual (or haptic-based) assistance was assessed with adults without disabilities (including perceptual deficits) by merely relying on the perceptual and special inspection of the virtual objects. Even though the execution of the coloring task did not rely on the user's perceptual capabilities, it was essential to validate the correct implementation and tangibility of objects on the robot. The assistance will function in supporting the user's movements regardless of how well he/she can perceive it or distinguish between the assistance conditions (e.g. Soft-walls versus Rigid-walls).

The *effectiveness* of the virtual assistance was validated through the *coloring* task. The virtual assistance, either of the Soft- and Rigid-walls, was significantly effective as *objectively* measured by the ratio of colored number of pixels outside to the pixels inside of the region of interest as well as the displacement from the borders. The effectiveness was further assessed and validated by the qualitative measures of usefulness, and reliability of the system and actions taken by the system, and its ease of use.

Finally, paper 4 (chapter 5) clinically validated the usability of the developed system from paper 3, in enhancing the manual capabilities of people with disabilities through a single-subject case study with an individual with CP. The individual had muscle spasm and involuntary movements due to having mixed CP, making it challenging to perform a manual activity such as coloring that requires fine-motor skills and coordination. The results from the objective analysis of performance of the individual with CP were consistent with those from the study with abled-bodied adults, confirming the *significant performance improvements* when using the virtual assistance as opposed to unassisted performance. Both Soft- and Rigid-walls showed statistically significant results while not being significantly different from each other. With a larger number of individuals with disabilities, higher performance improvements with the Rigid-walls condition could be expected due to less hand controllability and harder pushes against the walls. However, the appropriate choice of the assistance conditions primarily should rely on the *user's preference* rather than the objective comparison of the performance measures provided by each condition. The Soft-walls condition was preferred by the individual with CP as well as a few of the adult participants since the Rigid-walls were perceived as being somewhat restricting. With regards to the use of the individual's typical computer interface to perform the coloring tasks, qualitative analysis strongly confirmed the advantage of the robotic system over the typical approach, as assessed by the perceived *physical load*, *easiness* and *controllability* of hand movements. In addition, the advantage was evident in visual inspection of the coloring performance. Thus, despite the availability of less expensive, more accessible and less technology-dependent methods of access to certain manual activities, typical methods may not acquire the sufficient efficiency and effectiveness to do the tasks, including coloring, or to be utilized instead of the robotic system.

With respect to children with disabilities, the use of system may further contribute to promotion of positive emotional responses. Enhanced manual play performance with unmediated help is expected to prevent children from experiencing reduced sense of self-efficacy, dependence and motivation. Children are said to be vulnerable to fail, less optimistic about their abilities and tend to show strong loss of motivation and self-efficacy in the event of failure or poor performance (Dweck, 2002). Children with disabilities may experience such disempowering feelings even more than their typically developing peers of the same age. The developed robotic system can potentially provide children with the required assistance to perform a task more successfully while letting them do the task more independently whenever possible. Allowing children to experience more success (or improved performance) can potentially contribute to an increased sense of self-efficacy and thus, increased satisfaction.

A valid point to consider when developing a haptic-based task/system for children with disabilities is the possibility of impaired sensory perception and its effect on performance. Physical impairments such as neurological damages in children with disabilities may generate sensory deficits, affecting the child's tactile and proprioceptive discrimination (Fazio & Parham, 2008). Thus, some children may not be able to entirely perceive the implemented assistance, however, they may build perception through interacting with the system. If the task involves haptic discrimination, such as object identification based on properties of objects (e.g. a hard ball versus a soft ball), a sensory deficit could critically limit the effectiveness of the haptic feedback. Thus, the simulated forces could exaggerate the differences between different properties (e.g. a hard ball vs. a soft one) to be perceivable by children with perceptual deficits.

Provision of the right amount of assistance is another factor to consider when developing an assistive system. The system should provide children with disabilities with the right stimuli for their needs and strengths (Robins et al., 2012), and not make them passive by taking all control of the task. It is necessary to provide assistance without imposing unnecessary force or restriction. Ideally, children should be allowed to select their preferred assistance condition (i.e. the amount of assistance). The right amount of assistance could increase children's attention by taking care of some of their physical challenges and allowing them to dedicate more attention to the task. Provision of the right assistance is also a point to consider as far as children's improvement in the task over time. Children may learn by repetition, and therefore, they will need less help. The system should adaptively tune the level of assistance according to the child's level of performance (i.e. providing more assistance only when the child is committing more errors).

The ultimate goal of this research is to go towards free play scenarios. Coloring is considered a semi-structured play activity that is goal-oriented with pre-established rules. The pre-stablished rule is to stay within the regions of interest. A step towards semi-free play could include allowing the child to draw his/her preferred coloring picture. Giving the child the choice of what to color increases the duration of engagement in coloring activities compared to a no-choice condition (Lough, 2011). After a picture is drawn by a child, the robotic system can then assist by automatically imposing the virtual walls on the borders of the picture; yet, the level of assistance would always depend on the child's preference.

The findings of this research provide the foundation of technology and knowledge for an assistive robotic system to enhance manipulation activities of children with disabilities. Several haptic-based technologies for assistive purposes have been developed for adult population (as reviewed in (Jafari, Adams, & Tavakoli, 2016)), however, the potential of such technology for children has remained unexplored. Research on the utility of assistive technologies for manipulative play tasks for children is limited to the use of commercially available robots (Cook et al., 1988, 2000; Kronreif & Prazak-Aram, 2008; Rios-Rincon et al., 2015, 2016; Robins et al., 2012; Smith & Topping, 1996; Tsotsos et al., 1998) that have critical limitations. This research addressed the current limitations through development of the robotic system and suggested considerations for further development of the system. This study will ultimately contribute to a rational basis for clinical and home-based implementation of the technology for children with disabilities.

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Appendix A: Recruitment Poster

Alberta Health Services

FACULTY OF
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Robotic Interface- Development of A Robotic System With Haptic Guidance For Children With Disabilities

Do you know want to inform development of a robot for chidren with disabilities?

- **Purpose:** We are developing a way to control assistive robots that will tell the user what the robot is touching. We think it will help children develop perceptual skills.

- **Participant criteria:**
  - Adult between the ages of 18 and 60 years
  - No physical, visual and/or hearing impairments

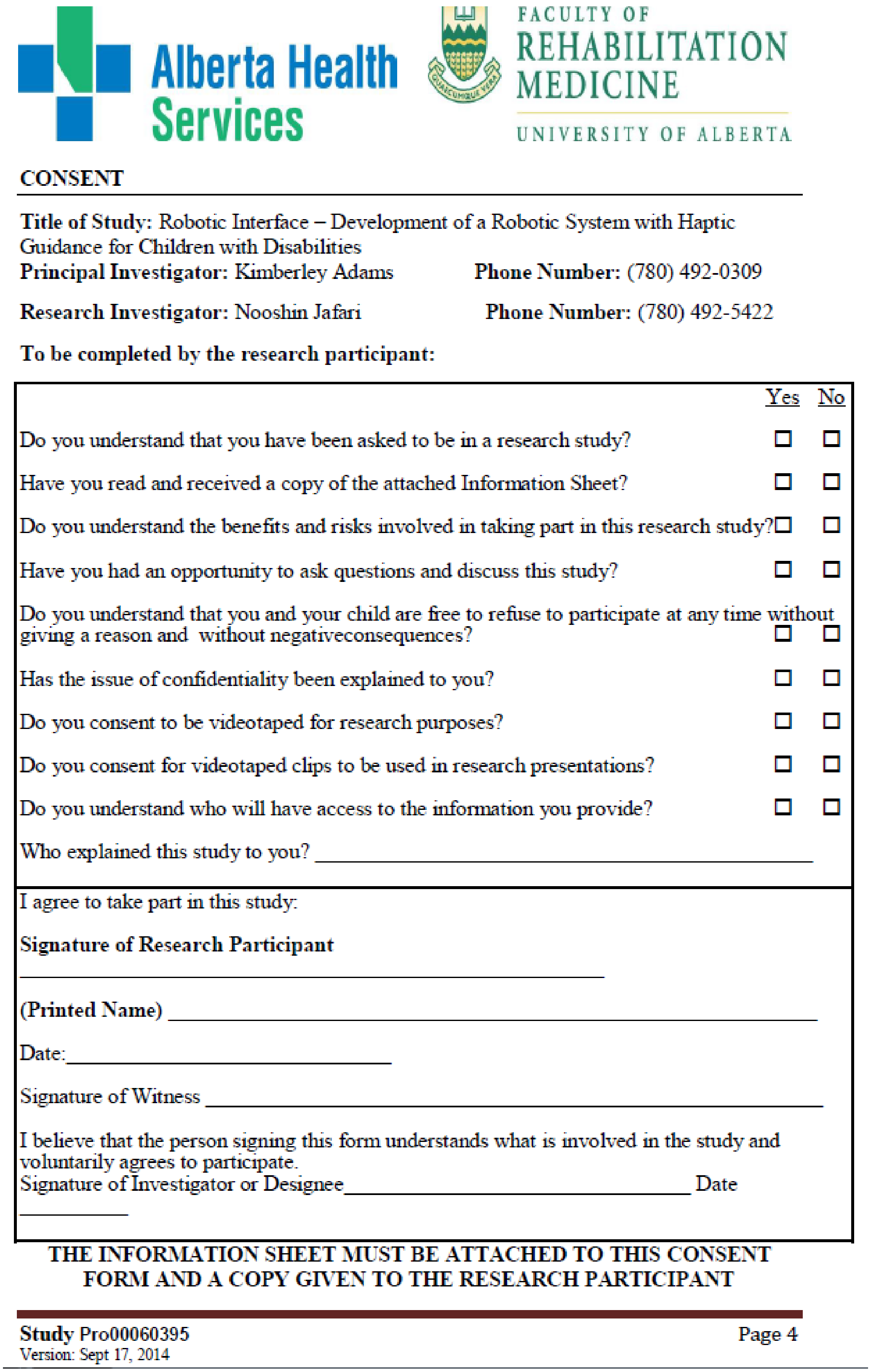
If you are interested in participating or would like more information please contact:

Nooshin Jafari

Phone: (780) 492-5422

Email: njafari@ualberta.ca

Appendix B: Consent Form



Alberta Health Services

FACULTY OF
REHABILITATION
MEDICINE
UNIVERSITY OF ALBERTA

CONSENT

Title of Study: Robotic Interface – Development of a Robotic System with Haptic Guidance for Children with Disabilities

Principal Investigator: Kimberley Adams **Phone Number:** (780) 492-0309

Research Investigator: Nooshin Jafari **Phone Number:** (780) 492-5422

To be completed by the research participant:

	Yes	No
Do you understand that you have been asked to be in a research study?	☐	☐
Have you read and received a copy of the attached Information Sheet?	☐	☐
Do you understand the benefits and risks involved in taking part in this research study?	☐	☐
Have you had an opportunity to ask questions and discuss this study?	☐	☐
Do you understand that you and your child are free to refuse to participate at any time without giving a reason and without negativeconsequences?	☐	☐
Has the issue of confidentiality been explained to you?	☐	☐
Do you consent to be videotaped for research purposes?	☐	☐
Do you consent for videotaped clips to be used in research presentations?	☐	☐
Do you understand who will have access to the information you provide?	☐	☐

Who explained this study to you? ____

I agree to take part in this study:

Signature of Research Participant

____

(Printed Name) ____

Date:_________________________

Signature of Witness ____

I believe that the person signing this form understands what is involved in the study and voluntarily agrees to participate.

Signature of Investigator or Designee__________________________ Date ________

THE INFORMATION SHEET MUST BE ATTACHED TO THIS CONSENT FORM AND A COPY GIVEN TO THE RESEARCH PARTICIPANT

Study Pro00060395 Page 4

Version: Sept 17, 2014

Appendix C: Information Letter

Alberta Health Services

FACULTY OF
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ADULT PARTICIPANT CONSENT FORM

Title of Study: Robotic Interface – Development of a Robotic System with Haptic Guidance for Children with Disabilities

Principal Investigator: Kimberly Adams, Ph.D., Joint Assistive Technology (AT)
Position: Assistant Professor Faculty of Rehabilitation Medicine, and Researcher, Glenrose Hospital (GRH)
Phone: 780-492-0309- Fax: 780.492.1626. Email: kdadams@ualberta.ca
Address: 3-48 Corbett Hall. T6G 2G4. Edmonton, Alberta, Canada

Research Investigator: Nooshin Jafari, MSc. Student, Faculty of Rehabilitation Medicine, University of Alberta

Phone: 780-492-5422, Email: njafari@ualberta.ca
Address: 3-48 Corbett Hall. T6G 2G4. Edmonton, Alberta, Canada

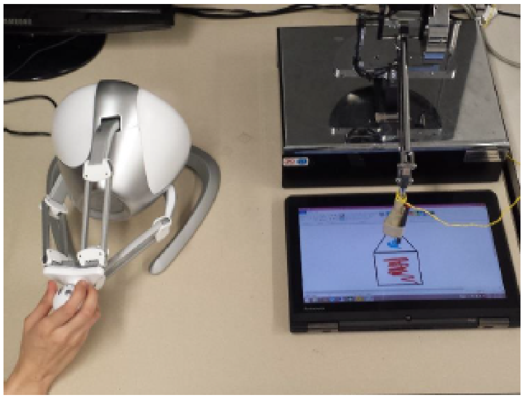
Why am I being asked to take part in this research study?

You are being asked to participate in this study because we are looking for adult participants to try our robotic system. We are studying how our robots can help children with physical disabilities in their play activities. To validate the reliability and effectiveness of the system, we need to try it with non-disabled adults. First, we want to see if our system can give the user more sensation about what the robot is touching in the environment. For instance, is the object soft or hard? Second, we want to see if our system can guide the user in performing a colouring tasks. Third, we want to see if there is any benefit using our system over using a computer to colour.

The purpose of this information sheet is to provide you with the information needed to decide if you wish your child to participate in this study. Before you make a decision, one of the researchers will go over this form with you. You are encouraged to ask questions if you feel anything needs to be made clearer. You will be given a copy of this form for your records.

What is the reason for doing the study?

Children develop perception and thinking skills when they explore objects. Children who have disabilities have trouble holding and moving objects. So, they miss a lot of chances to develop skills. We are developing robots that let the user know the properties of the objects. By moving the interface (the white robot in the picture below) the task robot moves (the silver robot in the picture below). When the silver robot hits hard or soft objects the user can feel that at the white robot. Also, the robot could help children do tasks when they can't quite do it themselves. For instance, it can help them to stay inside the lines when colouring. This could help children be more successful at accomplishing tasks.



What will I be asked to do?

You will participate in one or two sessions. The session will be one hour and half long. The session will be at a lab at the University of Alberta.

You will do some activities using the robot. Depending on where we are in the study, you could trial one or more of the following things:

a) You will use the robot to examine some objects and tell us about their properties.
b) You will use the robot to colour in a drawing on a tablet or on a paper.
c) You will use a computer to do the same coloring task.

We will make measurements like did the robot do what it was supposed to do? Videos of the sessions will be made only with your consent.
At the end of the session, you will be given a questionnaire to reflect your feedbacks regarding the use of the system.

What are the risks and discomforts?

The robots may rarely go out of control but if they do, there is a safety button to immediately switch off the robots. Also, the robot does not apply any force greater than the safe force that is defined in the software. In addition, the robots have the required safety approvals for commercial devices and there is no danger of electrical shock. The robots are securely mounted and fixed on the table.

It is not possible to know all of the risks that may happen in a study. But the researchers have taken all reasonable safeguards to minimize any known risks to study participants.

What are the benefits to me?

This project may lead to better assistive robots for children in the future. They also may develop skills to control interfaces for other activities. However, you may not get any benefit from being in this research study.

Do I have to take part in the study?
Being in this study is your choice. If you decide to be in the study, you can change your mind and stop being in the study at any time, and it will in no way affect your child's care. If you decide to end participation in the study, you can tell the researchers at any time. If the data collection has been completed, we will still use your information anonymously. If you withdraw before the data collection is completed, you can withdraw all of your data.

Will I be paid to be in the research?
You will not receive any compensation for participating in the study. You will be reimbursed for any parking fees.

Will my information be kept private?
During the study we will be collecting data. We will do everything we can to make sure that this data is kept private. No data relating to this study that includes your name will be released outside of the researcher's office or published by the researchers. Sometimes, by law, we may have to release your information with your name so we cannot guarantee absolute privacy. However, we will make every legal effort to make sure that your information is kept private. We will use the videotapes to do data analysis. If you consent, we may use video clips for research presentations. We will not identify anyone. The information will be kept for at least five years after the study has ended. It will be kept in a locked file cabinet. The information will be only available to the researchers.

What if I have questions?
If you have any questions about the study please contact: Nooshin Jafari (Phone 780-492-5422, e-mail - njafari@ualberta.ca) Faculty of Rehabilitation Medicine, University of Alberta.

If you have any questions regarding your rights as a research participant, you may contact the Health Research Ethics Board at 780-492-2615. This office has no affiliation with the study investigators.

There are no conflicts of interest with respect to remuneration received from the funding agency for conducting or being involved with any part of the study and/or the possibility of commercialization of research findings. The study is being conducted/sponsored by the Natural Sciences and Engineering Research Council/Canadian Health Research Institute. The University of Alberta and Principal Investigator are getting money from the study sponsors to cover the costs of doing this study. You are entitled to request any details concerning this compensation from the Principal Investigator.

Appendix D: Usability Questionnaire for Non-Disabled Adults

1=Strongly Disagree	2=Disagree	3=Neutral	4=Agree	5=Strongly Agree

The system can be used without much training.	1	2	3	4	5
The virtual fixtures were efficiently applied into the coloring tasks.	1	2	3	4	5
I found the various functions in this system were well integrated.	1	2	3	4	5
I found the system unnecessarily complex.	1	2	3	4	5
I think I would need the support of a technical person to be able to use this system.	1	2	3	4	5
I felt very confident using the system.	1	2	3	4	5
I think we can learn about the abilities of a child using this system.	1	2	3	4	5
The system helped me to do the coloring tasks more easily and quickly.	1	2	3	4	5
Virtual objects were clearly tangible on the robot.	1	2	3	4	5
I think the robot was stable (I didn't feel any vibrations when using the system)	1	2	3	4	5

I didn’t feel any forces when I was moving the robot inside the virtual objects.	1	2	3	4	5
What do you think about the system that you tried (What did/did not you like about it)?					
Do you have any suggestions for improving the system or the tasks?					
Can you think of other application for this sort of system for **children with disabilities**?					

Please provide any other comments you have about the system including how the system can be improved, in the space below.

Appendix E: Usability Questionnaire for Adult with Disabilities

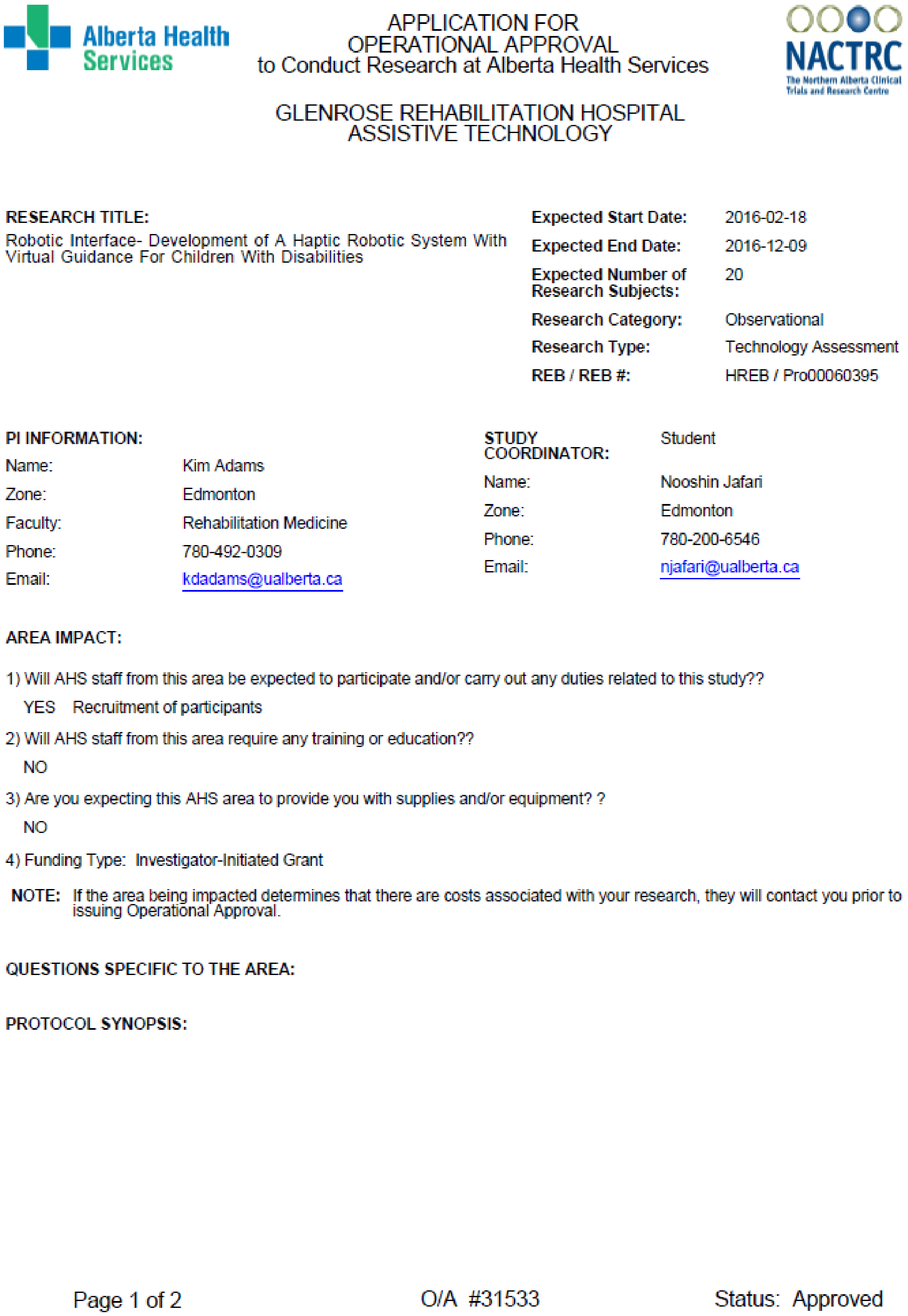
1=Strongly Disagree 2=Disagree 3=Neutral 4=Agree 5=Strongly Agree

	Strongly disagree				**Strongly agree**
I think the system helped me to do the coloring task more easily and quickly.	1	2	3	4	5
I think the robot was stable (I didn't feel any vibrations when using the system).	1	2	3	4	5
The system can be used without much training.	1	2	3	4	5
The virtual forces were efficiently applied into the coloring task.	1	2	3	4	5
I found the system unnecessarily complex to work with	1	2	3	4	5
I felt confident using the system.	1	2	3	4	5
Virtual objects were clearly tangible on the robot.	1	2	3	4	5
I didn't feel any forces when I was moving the robot <u>inside</u> the virtual objects.	1	2	3	4	5
I found the coloring task easier and faster when using the robotic system than the <u>trackball</u>	1	2	3	4	5
I found the coloring task easier and faster when using the robotic system than the <u>joystick</u>	1	2	3	4	5

I found the coloring task easier and faster when using the robotic system than the keyboard	1	2	3	4	5
It was easier to hold on (or control) the robotic arm than the trackball	1	2	3	4	5
It was easier to hold on (or control) the robotic arm than the joystick	1	2	3	4	5
It was easier to hold on (or control) the robotic arm than the keyboard	1	2	3	4	5
I had more control over my hand movements when using the computer interfaces than the robotic arm.	1	2	3	4	5
What do you think about the system that you tried (What did/didn’t you like about it)?					
Do you have any suggestions to improve the system or the tasks?					
Can you think of other applications for this sort of system especially **for children with disabilities**?					

Please provide any other comments you may have about the system including how the systems can be improved, in the space below.

Appendix F: Operational Approval



Alberta Health Services

APPLICATION FOR
OPERATIONAL APPROVAL
to Conduct Research at Alberta Health Services

NACTRC
The Northern Alberta Clinical Trials and Research Centre

GLENROSE REHABILITATION HOSPITAL
ASSISTIVE TECHNOLOGY

RESEARCH TITLE:

Robotic Interface- Development of A Haptic Robotic System With Virtual Guidance For Children With Disabilities

Expected Start Date:	2016-02-18
Expected End Date:	2016-12-09
Expected Number of Research Subjects:	20
Research Category:	Observational
Research Type:	Technology Assessment
REB / REB #:	HREB / Pro00060395

PI INFORMATION:

Name:	Kim Adams
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STUDY COORDINATOR:	Student
Name:	Nooshin Jafari
Zone:	Edmonton
Phone:	780-200-6546
Email:	njafari@ualberta.ca

AREA IMPACT:

1) Will AHS staff from this area be expected to participate and/or carry out any duties related to this study??

YES Recruitment of participants

2) Will AHS staff from this area require any training or education??

NO

3) Are you expecting this AHS area to provide you with supplies and/or equipment? ?

NO

4) Funding Type: Investigator-Initiated Grant

NOTE: If the area being impacted determines that there are costs associated with your research, they will contact you prior to issuing Operational Approval.

QUESTIONS SPECIFIC TO THE AREA:

PROTOCOL SYNOPSIS:

Page 1 of 2 O/A #31533 Status: Approved

APPLICATION FOR
OPERATIONAL APPROVAL
to Conduct Research at Alberta Health Services

GLENROSE REHABILITATION HOSPITAL
ASSISTIVE TECHNOLOGY

Haptics is the fast emerging science that studies the interaction of touch and technology; in particular, it is concerned with the haptic interface between technology and the human user. Haptic feedback can serve as one of the factors contributing to an enhancement in perception of objects. We propose to develop an assistive technology for children with disabilities - a robotic system to enable haptic feedback capability in the context of play. Haptics has been used in diverse areas such as surgical simulation and rehabilitation. However, haptics has not yet been used by children with disabilities who can potentially control an interface to sense objects being manipulated in play activities in the environment.
Participants will be ten abled-bodied adults to test the system during development and ten child participants afterwards. In usability studies, at least 5 iterations are recommended to establish if the design is appropriate, thus 10 participants in each group will be more than sufficient. The inclusion criteria for abled-bodied adult participants are: 1) Adults between 18 to 60 years old, 2) Adults with normal arm function because they will be asked to hold and move the robotic interface with their hand, and 3) Adults who understand English because the sessions will be done in English.

The inclusion criteria for children are:
1) Children between 5 to 8 years old. Typically developing children 5 years old have demonstrated to have the cognitive skills required to control the robot. Children with disabilities this severe are more likely to have delays in their developmental and educational experience, so children up to 8 could be good candidates for this study. If needed, the cognitive age will be tested with the Pictorial Test of Intelligence by an Occupational Therapist on our research team.
2) Children who are within the III, IV and V level of the Gross Motor Classification System and level III, IV and V in the Manual Ability Classification System (MACS). Motor limitations of the trunk and upper and lower limbs are categorized within the mentioned classification levels. This justifies the need for robots for manipulation. The classification levels will be assessed by an occupational therapist on the research team
3) Children who understand English because the sessions will be done in English.
The exclusion criteria include children and adults with: 1) Attention problems. Participants must be able to focus for an hour session, 2) Overly severe cognitive limitations. Participants must be able to understand verbal instructions from the investigators, 3) Vision impairments. Participants must be able to see the robot and the working area, and 4) Hearing impairments. Participants must be able to hear verbal instructions from the investigators. Participant¿s capabilities will be ascertained from report by the participant or child's parent.
There will be two experimental sessions, 1.5 hour each, on separate days in one week to address the following research objectives: 1) Examine and compare the performance of children with disabilities in explorational and manipulative play tasks using a robotic system with and without haptic feedback, 2) Examine and compare the performance of children with disabilities in a functional manipulative play task (e.g. colouring a drawing) using the robotic system with and without guidance, i.e. by adding prior knowledge to the software about the drawing to guide the child in performing the colouring, and 3) Examine the performance of children with disabilities in the same functional manipulative play task as that in objective 2, but using a computer interface (e.g. a mouse) and a computer application (e.g. MS Paint), and compare the outcomes with objective 2.
The performance in objectives 1 and 2 will be assessed by time, task accuracy and amount of guidance required to complete the tasks. Repeated measures t-test will be used to analyze the mean scores for each condition: without and with haptic feedback for explorational tasks, and without and with haptic guidance for functional tasks. For objective 3, time and accuracy will be the measures of performance which will be compared with the outcomes of objective 2 using t-test. A qualitative analysis based on a usability questionnaire (i.e., efficiency, effectiveness, and satisfaction) will be administered to the children and an interview questionnaire with the parents will also be conducted.

SUBMITTED BY / ASSESSORS / APPROVERS:

Requested By:	Nooshin Jafari	Date Requested:	2016-02-18
Assessed By:	Gail Kostiw	Date Assessed:	2016-03-15
Assessed By:	Gary Faulkner	Date Assessed:	2016-03-17