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

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ABSTRACT

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 touch 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, haptic feedback

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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).[1] 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.[2] Haptic perception in children develops through environmental exploration and object manipulation in their infancy and throughout their childhood,[3,4] particularly in the context of play,[5] and education.[6] Piaget's research[7–9] 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. As children grow, they intuitively learn more sophisticated manual activities as a result of advanced hand functions.[10] 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.[11] The perceptual cost of constraining haptic manipulation and exploration on object recognition has been studied with non-disabled participants by [12] and [13]. 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.[13,14]

Direct object manipulation provides information about the properties of an object (e.g., roughness and compliance) that cannot be obtained via seeing and hearing.[15] 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.[16] Different hand movement patterns that are used to recognize objects during manipulation and exploration have been defined in previous literature.[16–19] In a series of studies,[16,20–22] 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. 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, the 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[23–26] and children with disabilities in the context of education,[27–29] and play[30,31] 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”.[32, p16] In other words, a haptic interface generates touch, weight and rigidity sensation to the muscles and skin.[33] The early haptic interfaces[34–36] were costly and sophisticated. Thus far, within the history of haptic interfaces,[33] most research-based interfaces have been application-specific.[37]

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;[38] a typical application is using haptic exotendons for hand rehabilitation therapy.[e.g., 39] 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., 40] or customized haptic joysticks for people with motor and cognitive impairments to better control power wheelchairs.[e.g., 41] 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.[42] With increased opportunities for manipulative activities, it is possible that children with disabilities may 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,[43] 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.

HAPTCI 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*,[44,45] *motion-impaired adult computer users*,[46–48] *adult computer users with visual impairments*,[49,50] and *adult power wheelchair users*.[51,52] Studies on children with disabilities involved only *toddler wheelchair users* (specifically, a child with severe motor impairment[53] and a child with spina bifida[54]). 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.[50,55–58]

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).[59] 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.[60] Users reported that the system helped to perceive a mental representation of the map. Brayda et al. [61] evaluated a haptic mouse for representation of a cognitive map of virtual objects with blindfolded sighted users. 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.[49] 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.[62] 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. 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.[63] Major difficulties occur during point-and-click computer activities [63] when the user wants to click on the target.[64] Involuntary clicks and sliding over the target are also a major cause of errors.[65] 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.[66]

The effect of haptic forces on the operator's perceived comfort has been studied. Dennerlein et al.[45] investigated the effect of haptic feedback on musculoskeletal loading. 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.[46] 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. 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.[47,66,67] and Langdon et al.[48,64] 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.[48] 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.[68] 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.[63]

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.[69] highlight the "inadequacy" of wheelchair control interfaces for users with severe impairments. The most commonly used control interfaces are joysticks[69], which according to Nilsson et al.,[70] apply low cognitive load on the user due to their obvious mapping to the environment; 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,[71] 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. [72] 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., 73–75] 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.[76] Additionally, haptic feedback has been integrated into wheelchair control interfaces to potentially increase safety, independence, and maneuvering skills.[71] 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.[77–79] In a study with power wheelchairs, Fattouh et al.[80] used a Microsoft SidewinderTM Force Feedback joystick with adults with severe motor disabilities. 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.[51,72,81] 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.[41] 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,[76] and obstacle avoidance,[82] 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,[53] and a child with spina bifida[54] 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.[82] Robotic rehabilitation has been shown to foster recovery based on several clinical studies and assessments, [see review in 83] for instance, in increased strength and range of motion.[84,85] 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.[86] reviewed the rationale of integrating haptics into the rehabilitation of hand, the "haptic exploratory organ".[87] Authors point to previous studies in which the loss of haptic information has resulted in poor recovery rates in the hand after stroke.[88,89] Haptic robotic rehabilitation can stimulate the kinesthetic system by providing force feedback about physical properties of objects, resulting in increased potential of motor recovery.[86] Further advantages are provision of task-specific properties in order to practice activities of daily living,[e.g., 90] and improved range-of-motion in repetitive tasks.[e.g., 39] 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.[91]

There have been a number of studies in rehabilitation of the hand in *post-stroke*. [see review in 86] 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.[92,93] 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.[90] 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.[94,95] 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 [91]). Kang Xiang et al.[96] 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. 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.[86] 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.[39] 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. The repetitive therapy movements were substituted with haptic/visual error augmentation[1] 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.[97] 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[98] and in robot-supported training during upper limb related activities of daily life in persons with multiple

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[1] 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 [127]

sclerosis.[99] The intensive and long-term motor training exercises can be motivated by developing rehabilitation exercises in VEs.[100,101] Acquired skills from training in VEs can eventually be transferred to a real environment (e.g., in a "steadiness tester" task[102]). However, according to Burdea,[103, p10] some challenges with VEs are "lack of natural interfaces, lack of child-size equipment, technical expertise, clinic and clinical acceptance, and cognitive load".

VE-based arm rehabilitation and training has been facilitated through different haptic robot-assisted media such as a system called HapticMaster. Vanmullken et al.[104] studied the feasibility of the HapticMaster in improving the arm-hand performance in five individuals with different levels of cervical spinal cord injury. 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.[99] investigated the effectiveness of a HapticMaster in arm training with seventeen individuals with multiple sclerosis. 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.[105] 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.[106] 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.[107] highlighted the need for further investigation on whether applied forces will hamper or improve learning performance in sensorimotor tasks. 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[108] or training practitioners to learn how much force to apply during a surgical procedure.[e.g., 109] 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),[53,106] or it allows training novice users or children with disabilities on how to use the wheelchair controls.[106] 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,[110] or Chinese language learners[111]). Kindergarten children with poor handwriting, dysgraphia, [112,113] as well as adult participants [114] 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.[115] investigated the overall effectiveness of a visuohaptic training paradigm on performing a trajectory following task to learn an abstract motor skill. 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*.[116–120] 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.[121] 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. Additionally, it has been observed that vision alone can be more beneficial in extracting object properties compared to haptics alone.[122] Yet, visuohaptic feedback has overall contributed to greater improvements in task performance as opposed to visual or haptic modalities alone.[e.g., 123] Sound feedback has been added to visual and haptic information but its effectiveness on improvement of performance was not always conclusive.[e.g., 118] In studies with blind people, the addition of sound was reported to be complementary to the haptic modality.[e.g., 56,62] 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., 41]

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.[108,110,111] However, it can degrade or hamper performance improvement when guidance is removed.[106] 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.[45] 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,[68] it may result in increased cognitive demands of the task or the control interface.[63] 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[23] but only 5-year olds are expected to have the required cognitive demands to understand a switch-controlled robot with lateral movements and sequences.[124] In tasks with higher cognitive or motor skill demands, different levels of haptic guidance (e.g., "fixed guidance" or "guidance as needed")[e.g., 106] can be applied to compensate for a child's cognitive limitations. An alternative approach is applying an adaptive shared control paradigm,[125] 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.[91,98–101] Some wheelchair studies have also shown the advantage of training maneuvering skills in VEs.[e.g., 106] 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.[3,15,87] Manipulation of real objects provides unique information about an object that cannot be obtained via other modes of manipulation.[15] 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[126] 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.

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