Activities and Evaluations for Technology-based Upper Extremity Rehabilitation

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Recent advances in projection and sensing have resulted in an increased adoption of virtual reality, video games, and interactive interfaces to improve patient compliance with rehabilitation programs. In this chapter, we describe the application of multi-touch tabletop surfaces to physical and occupational rehabilitation programs that are focused on the upper extremities. First, we detail the participatory design processes undertaken with local physical and occupational therapists to design and integrate a 'patient-friendly' multi-touch tabletop system in their workplace. We then explore the design considerations that informed the development of a suite of sixteen multi-touch interactive activities. The design considerations highlighted the need for customization and flexibility in the software, as well as the importance of supporting a variety of activity types. We then detail the laboratory-based methods that were used to evaluate the efficacy of the activity interventions as well as our deployment of the system in a local rehabilitation hospital. Our evaluation, which employed both qualitative and quantitative components (i.e., the Intrinsic Motivation Inventory, semi-structured interviews, kinetics and kinematics recorded from motion trackers and an electromyogram recorder), determined that it is the design of activities, rather than the utilization of technology itself, that impacts the success of technology-assisted rehabilitation. The chapter concludes with a discussion of the implications of our system and its deployment.

General Terms: Design, Human Factors, Measurement

Additional Key Words and Phrases: technology-assisted rehabilitation, upper extremity, multi-touch, multi-touch tabletop, Electromyography, motion capture

1. Introduction

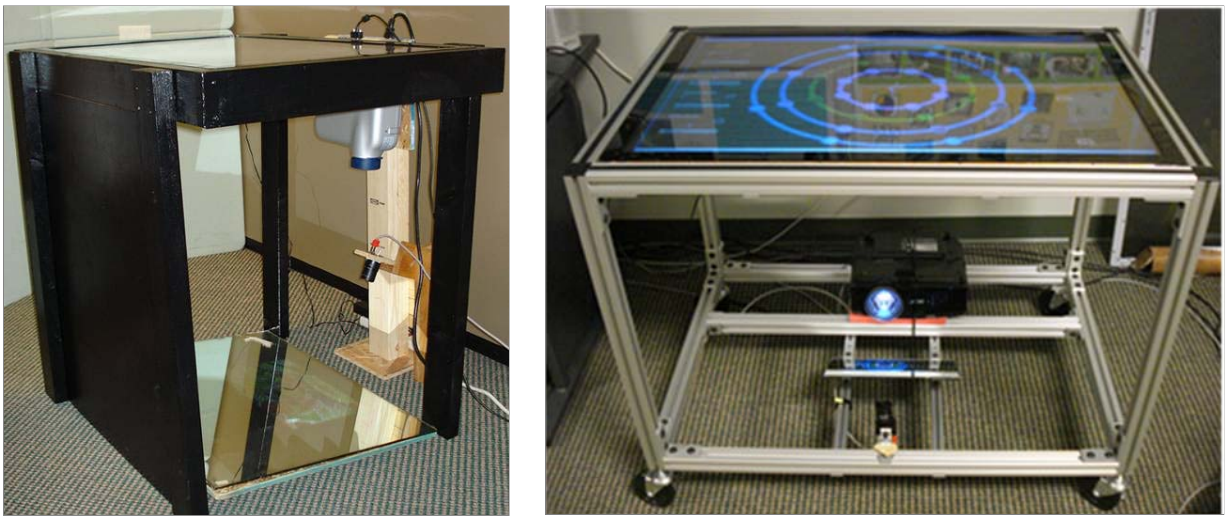
More than 10% of Canadians are afflicted with impairments that influence their ability to perform everyday activities (CANSIM, 2009). These disabilities stem from a variety of causes, including aging, disease, stroke, trauma, or congenital health issues. Most commonly, patients have decreased motor functionality, memory problems, and an inability to focus on, or attend to, stimuli, leaving many unable to live independently or perform daily activities such as cooking, eating, or dressing. In traditional rehabilitation programs, occupational and physical therapists work closely with patients to perform exercises to regain or maintain physical (e.g., range of motion, coordination, balance, muscle strength, and muscle endurance) and cognitive (e.g., attention, short-term memory, visual-spatial abilities, and problem-solving skills) function to improve the patient's quality of life.

Current upper extremity rehabilitation activities, such as drawing images on paper, tracing letters in the air, or reaching for imaginary targets, require patients to perform repetitive movements that focus on increasing range of motion, coordination, muscle strength, and muscle endurance. Most traditional motor and cognitive rehabilitation activities are monotonous and unexciting, providing sub-optimal patient engagement and immersion. It is very common for these activities to cause patients to exert only moderate amounts of effort or neglect them completely. In addition, therapists are limited in how they can manipulate the activities with respect to intensity and difficulty, and the subjective nature of patient performance makes the monitoring and evaluation of patient progress very difficult.

A new area of Human-Computer Interaction, *technology-assisted rehabilitation*, has begun to focus on the role that technology can play in improving patient abilities. It has been widely recognized that patient motivation and patient compliance with rehabilitation exercises are critical problems in physical therapy programs (Chang et al., 2011; Flynn and Lange, 2010; Gupta and O'Malley, 2006; Mumford et al., 2008; Rizzo and Kim, 2005; Saposnik et al., 2010). One approach to encourage compliance and increase motivation has been to use video games, as it is believed that patients can become as highly engaged with their therapy exercises as video game enthusiasts are with their games (Rizzo and Kim, 2005). For this reason, various technologies such as the Microsoft Kinect (Chang et al., 2011; Delbressine et al., 2012), PlayStation EyeToy (Rand et al., 2008), and Nintendo Wii (Saposnik et al., 2010) have become pervasive in therapy programs (Flynn and Lange, 2010). Preliminary research into integrating gaming, virtual reality, and haptics into rehabilitation programs has illustrated that technology-assisted rehabilitation can decrease the length of a patient's rehabilitation program, increase a patient's range of motion, muscle strength, and coordination, and provide rehabilitation opportunities in out-patient or rural settings (Gupta and O'Malley, 2006; Mumford et al., 2008).

Over the last decade, interactive surfaces and multi-touch tabletops have become very popular, partially due to their decreased cost. Interactive tabletops have several advantages (Hutchins et al., 1985) that make them excellent candidates for the rehabilitation process. By their very nature, multi-touch tabletops support natural and direct interaction (Wigdor and Wixon, 2011), that is, the user touches and manipulates an object or target directly instead of using a proxy device such as a mouse, keyboard, or joystick for interaction. As patients with cognitive disabilities often have trouble creating a mapping between a proxy object and target, this direct interaction provides an important advantage. Interactive tabletops also provide a large interaction space, which is to exercise gross motor function and encourage lateral upper-body movement (Annett et al., 2009; Mumford et al., 2008). Such interaction is not possible on small hand-held devices or tablets. Multi-touch tabletops have the potential to greatly enhance patient motivation and compliance with rehabilitation activities as they are highly interactive and immersive, and they support natural methods of user interaction. As immersive tasks can help to reduce the amount of pain or discomfort that patients experience (Berger-Vachon, 2006), we believe that the integration of multi-touch tabletops into the rehabilitation process can provide many benefits for both patients and therapists. Lastly, the sheer size and construction of tabletops allow them to support a patient's upper-body weight during an activity, thus allowing those with poor balance or muscular endurance to participate and benefit from activities as well.

In close collaboration with occupational therapists from the Glenrose Rehabilitation Hospital in Edmonton, Alberta, Canada, we have developed an interactive, multi-touch tabletop and a suite of upper extremity, motor-based applications. Our open-source system, *Ammi Interactive Rehabilitation Touch*, or AIR Touch (Figure 1), aims to provide therapists with an easy-to-use tool that can 1) be customized to meet a patient's abilities and needs, 2) increase patient motivation and engagement, and 3) record a variety of objective measurements.



(a) **(b)**

Figure 1. The Air Touch System, (a) Version 1 and (b) Version 2.

2. Related Work

The development of applications for multi-touch tabletops has steadily increased in the last decade due to the novelty, potential, and ease of construction and development of tabletop technologies. Multi-touch tabletops have been used for applications as diverse as remote interface control (Seifried et al., 2009), collaboration on navel ships (Domova et al. 2013), music composition (Jorda et al., 2007), children with autism (Bauminger-Zviely et al., 2013), and to explore genomic data (Shaer et al., 2010).

It has, however, only been in recent years that multi-touch tabletops have been used for rehabilitation. Mumford et al. (2008) describe an interactive surface that can be used to assess and treat traumatic brain injury. Mumford et al.'s system provides only coarse measures of patient progress, the implemented activities do not appear to be intrinsically motivating, and the use of tangible objects prevents patients with poor fine-motor skills from using the system. Facal et al. (2009) describe a multi-touch surface that can be used to develop cognitive skills in the elderly, as did Augstein, M. et al. (2013, 2014), Dunne et al. (2010), Gamberini et al., (2009), Jacobs et al. (2013), Jung et al., (2013), and Kwon et al. (2013). As with Mumford et al.'s system, these systems do not support therapist interaction and do not appear to be overly engaging or motivating, nor do they have a breadth of activities suitable for a range of participant interests and abilities. In a slightly different vein, Hancock and colleagues sought to replicate sand-tray therapy, a type of therapy that allows children to use tangible objects to tell stories and talk about their emotions (2010). While Hancock et al.'s digital implementation did made use of digital 3D models and encouraged fine and gross motor movements, the focus of their work was not to improve upon these functions.

Work by Khademi and colleagues sought to compare the benefits of direct versus indirect interaction for stroke-rehabilitation (2014). Using objects, participants played a simplified version of the Fruit-Ninja game and found that direct interaction lead to higher player scores and higher scores on the Fugl-Meyer Assessment and Box and Block tests. Although this work demonstrated that direct-tangible interaction is preferable to indirect, the present exploration focuses exclusively on non-tangible interaction, to ensure that our system could be utilized by those who have decreased fine-motor skills and cannot grasp objects.

Apted et al. (2006) and Al Mahmud et al. (2008) have developed design guidelines for tabletop-based applications for the elderly. Some of their suggestions include maximizing the size of interface elements, reducing the number of interface elements, and utilizing familiar metaphors and common knowledge to increase user learnability and understanding. As motor skills, vision, and cognitive abilities are reduced in both, elderly and rehabilitation populations, we feel that these same guidelines should be applied to multi-touch tabletop activities.

While many existing works have advocated the use of engaging activities to encourage rehabilitation adherence, few have thoroughly considered the importance of activity design. In this work, we examine how activity design can affect the success of rehabilitation programs, examine evaluation techniques for technology-based rehabilitation activities, and provide design guidelines for developers of such technologies.

3. System Goals and Iterative Design Process

To better inform and situate the utilization of multi-touch tabletops within rehabilitation settings, we underwent a multi-stage, user-centric iterative design process with occupational and physical therapists from a local rehabilitation hospital in Edmonton, Alberta, Canada (i.e., the Glenrose Rehabilitation Hospital). The Glenrose Rehabilitation Hospital is the largest tertiary rehabilitation institution in Canada, with 220 clinical researchers, a school program for 300 children, 250 inpatient beds, and 30,000 outpatients a year, including both children, adults, and the elderly. The large diverse in-, out-, and day- patient population at the hospital provided a unique opportunity to immerse ourselves within a real-world clinical setting and provided first-hand contact with everyone involved in the rehabilitation process, from patients and caregivers to therapists and hospital administrators.

To better understand the needs of therapists and clients, we conducted a variety of large focus-groups with therapists and hospital administrators, organized one-on-one interviews with practicing therapists and administrators (before and after the installation of our prototype system), and shadowed a number of therapists and clients throughout the course of our iterative design process. It was through these events that rich information about the rehabilitation process and the current state of the art of rehabilitative activities and technologies was attained.

3.1 Goals

Given the variation in age and level of motor dysfunction in our target population, we learned that there is no single activity or exercise that can be used for every individual. Some patients have near-normal functioning, while others cannot move their fingers or wrists and rely exclusively on gross motor movements. In collaboration with our occupational therapist colleagues, four guiding objectives were developed to situate our research and development:

Objective 1: *Engage patients and ensure that activities are easy to learn*

- If activities are not intrinsically motivating or immersive, patients will not exert much effort.
- When patients are immersed in an activity, they are less affected by their pain and thus may perform an activity longer.
- Activities should build upon known metaphors and existing knowledge to maximize a patient's comfort level, especially for those with cognitive deficits.

Objective 2: *Ensure that activities are repeatable and that meaningful performance measures can be recorded*

- Objective performance measures can help to quantify a patient's progress.
- Having repeatable activities ensures that the measures are meaningful and can be compared to past performance.
- Informing patients about their performance can motivate them and may speed their recovery.

Objective 3: *Leverage therapist expertise and their knowledge of a patient*

- No system can or should replace the expert judgment and abilities of a therapist.
- Therapists should be able to adjust the difficulty and type of activities to match a patient abilities, goals, and outcomes.

Objective 4: *Decrease the setup and customization time so that the totality of a rehabilitation session can be spent on actual rehabilitation exercises*

- Currently, too much time is wasted setting up and configuring equipment or activities to match the needs of the patient.
- Ensure that any changes or modifications that need to be made can be done so without needing to restart an activity, log into the computer, etc.

3.2 System Design

The AIR Touch (Figure 1) is a cross-platform, multi-touch system that combines open-source software with a readily available multi-touch surface. Our multi-touch tabletop screen (90 cm x 55 cm) was designed and manufactured by NOR_/D[1] and was composed of layers of acrylic and diffuse materials. It uses the principle of Frustrated Total Internal Reflection to detect touch events (Han, 2005). The system uses a short-throw projector and mirror to rear-project digital content onto the acrylic screen.

All touch events are captured by a Point Grey Firefly MV infrared camera and processed using the open source, openFrameworks software library. The openFrameworks software library

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[1] There are a number of tutorials available that describe how to construct a multi-touch surface (Castle, 2015; NOR_/D, 2015).

allows one to modify the touch sensitivity of the tabletop. As the target population has different levels of motor dysfunction, it was imperative that therapists were able to modify the amount of pressure required to generate touch events on the tabletop.

After a touch event is detected, it is relayed to our Apache Flex-based activities. Flex is an open-source extensible framework that combines ActionScript with an XML-derivative. Flex also has a large library of visually appealing user interface objects and animations that can be combined to create highly interactive, easy to use activities and interfaces for therapists and patients. To ensure that therapists would be able to customize activities as needed, all of the activity interfaces were designed such that parameters could easily be changed ‘on the fly’ with little to no effort on the part of the therapist (e.g., on-screen buttons, sliders, menus, colour pickers, etc. controlled the changing of colours, width of strokes, size and location of targets, etc.).

3.3 Feedback

The first version of the tabletop was rapidly constructed using plywood and lumber to quickly experiment with the form factor and gather feedback. Testing with the initial hardware configuration proved invaluable as it allowed therapists to quickly experiment with the potential of the technology. The feedback they provided was crucial in shaping later iterations of the hardware platform.

Some of the initial feedback we received regarded the physical configuration of the table. Several therapists requested the ability to adjust the height and angle of the interactive surface to support various patients (Figure 2). Portability was also a concern, as the initial prototype was heavy and not easily moved. Sanitary concerns were also raised, as the porous wood surface was not able to be sufficiently cleaned and disinfected for hospital use. Lastly, the aesthetics of a black, wooden table was a concern, especially as the table was meant to be a ‘technological innovation’ in the therapy process. Many therapists stated that it was important for patients to use technology and equipment that was commonplace for their able-bodied counterparts. The black table’s appearance did not reflect the capabilities of the system and further created a divide between those with and without dysfunctions.

Taking this feedback into consideration, a second version of the interactive table was fabricated. This version was made out of extruded aluminium and plastic, allowing it to be easily sanitized and provide a more refined aesthetic. The table was mounted on lockable caster wheels with the computer, projector, and all the necessary hardware mounted to the frame. This allowed the table to easily be moved from room-to-room as necessary. The extruded aluminium also had an added benefit of making the tabletop appear similar to a large iPad, and thus removed some of the stigma regarding the use of old, out-dated equipment that had initially been reported.

As part of the feedback process, we determined that it was important to temper expectations and make therapists and patients aware of what was feasible and possible. For example, although we consulted with industrial designers and mechanical engineers to develop methods to adjust the height and angle of the table automatically, it was too difficult and expensive to implement many of the designs. Given the weight of the components, the rigidity and stability that the tabletop needed to have, and the calibration that was required to align the images from the projector with the touch events detected by the cameras, we opted to maintain the second version of the tabletop throughout the remainder of our iterative design process.

Figure 2. The Air Touch System in use by therapists and clients at the Glenrose Rehabilitation Hospital.

4. Rehabilitation-Focused Activity Design

Guided by the design objectives identified above, as well as Apted et al. (2006) and Al Mahmud et al.'s (2008) guidelines, we developed a suite of sixteen rehabilitation activities. Some activities were designed to replicate real-world activities (e.g., Finger Painting, Match Me, Touch Tessellation, Nomis Says) whereas others were novel and targeted specific motions and movements (e.g., Touch-A-Tap, Therapist Do-It-Yourself, Pop Those Balloons!). In addition, some were focused on harnessing creative expression and flow (Csikszentmihalyi, 1997; e.g., Photo Scrapbooking, Finger Painting), whereas others employed simple gamification elements (Deterding et al., 2011; e.g., Drumhab, Pop Those Balloons!, Touch Mazes).

Across all activities, we strove to ensure that any customizations or personalization that was possible would result in the

4.1 Activities

Herein, we describe each of the activities that were designed, detailing the rehabilitation goals that each targets and the activity-specific measures that can be recorded.

Finger Painting

Finger Painting is a multi-touch adaptation of traditional finger painting (Figure 3a). Patients are encouraged to use their hands and fingers as paint brushes. They are able to select various colors to paint with and are given the freedom to draw whatever they choose. The activity natural encourages fine and gross motor movements and artistic expression, while also camouflaging rehabilitation goals within a creative endeavour. As the activity is relatively unrestricted, it can be used leveraged by therapists as a 'blank canvas' for their own activities. For instance, therapists might ask patients to draw increasingly larger circles to encourage greater range of motion. During interaction with the activity, logs are recorded with the colors chosen, the length of paths drawn, and the resulting drawings are also saved.

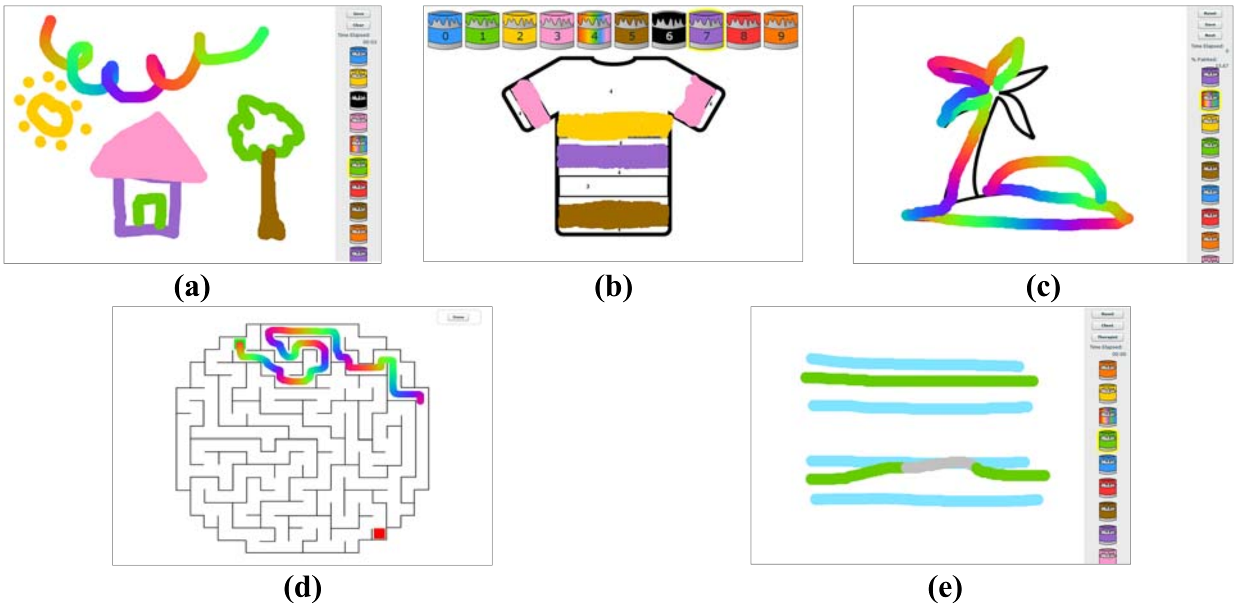


Figure 3. Examples of the various stroke-based multi-touch activities that were implemented. (a) Finger Painting, (b) Paint-By-Number, (c) Touch Tracing, (d) Touch Mazes, and (e) Track Trace.

Paint-By-Number

Similar to Finger Painting, the Paint-By-Number activity also encourages the patient to use their hands as a paintbrush, but this time, to fill in a numbered outline (Figure 3b). The patient can touch one of the numbered paint buckets located on the screen to change the colour of their 'paintbrush'. This activity can be used to improve fine motor skills and to encourage gross motor movements such as flexion and elevation.

This activity can be customized by changing the image that is displayed, the location and size of the image, and the number of colours that are used. AIR Touch determines the accuracy of a patient's painting (i.e., if the painting was within the lines), if the correct colours were used, the number of paint strokes the patient made, the number of paint bucket selections that occurred, and the proportion of the image that was painted.

Touch Tracing

The Touch Tracing activity closely mimics an existing rehabilitation activity in which a therapist draws a pattern on a whiteboard and then asks the patient to trace overtop the pattern (Figure 3c). In the tabletop adaptation, therapists can draw a pattern on the surface and then ask the patient to trace overtop of it. Alternatively, the therapist can load image files for tracing (e.g., complex patterns, letters, words, or outlines of emotionally salient images such as faces or animals). Both the therapist and patient can choose from a variety of different paint colours to make the activity more salient and meaningful.

Similar to the Paint-By-Number activity, therapists can change the size and location of the tracing pattern or image. This flexibility permits therapists to target both fine and gross motor skills. While this activity is performed, a number of measurements are recorded, including the accuracy of tracing (using a root-mean squared error formula), the average tracing speed, the percent of the pattern that was successfully traced, and the number of paint strokes the patient made.

Touch Mazes

Touch Mazes are based on traditional pen-and-paper mazes found in many children's books. During the activity, the patient traces their finger along the screen from the start point of the maze (indicated by a green square), through to the exit (indicated by a red square; Figure 3d). Similar to the Finger Painting and Touch Tracing Paint-By-Number activities, the colour of the paint strokes can be changed to increase activity enjoyment. A variety of maze complexities are available. Simpler mazes have larger tracks and are less cognitively challenging, whereas higher complexity mazes have narrower trackers and require more forethought. This allows for a wide range of patients to use the activity. As patients regain function, they can progress through different difficulty levels. This activity records the number of errors (i.e., maze wall crossovers), the average stroke speed, and the number of completed mazes.

Track Trace

The Track Trace application (Figure 3e) allows therapists to draw a set of tracks for patients to practice drawing through. Each track is defined by two therapist-drawn strokes, and the patient must then draw a line between them. This task is similar to the steering tasks commonly found within human-computer interaction (Accot and Zhai, 1999). This allows the therapist to control the length of the defined track, as well as the width, allowing precision control over fine motor difficulty (track width), as well as challenging the patient's range of motion (path length). Therapists can also make the track complex, with curves and corners, to add more of a cognitive challenge. The color of the tracks and the patient's paint color can also be changed to add more dynamism to the activity. Measures recorded during Track Trace include time-on-task, accuracy (total root mean squared error distance from track center), number of errors (track crossovers), as well as the paths themselves.

Touch-A-Tap

The Touch-A-Tap activity is a digital implementation of the Dynavision[1] systems that are common in rehabilitation institutions. With Touch-A-Tap, an array of targets is displayed on the screen, with only one 'activated' for the patient to touch at a given time (Figure 4a). After the patient touches the activated target, it deactivates, the next one activates, they touch it to deactivate it, and so on. Unlike the traditional Dynavision system, therapists can control a wide assortment of parameters, including the layout of targets (e.g., radial, rectilinear, random), the target size and spacing, and specific spatial areas to emphasize with the activation patterns. Both the colour of the targets and the activation color can be customized. These parameters give the therapist fine-grained control over the content of the activity and can help tailor the activity to a variety of patient needs. During performance, the activity logs the reaction times (per target), the target positions and layout, the touch error (using a root mean-squared error metric), and the total number of correct and incorrect selections.

[1] dynavisioninternational.com

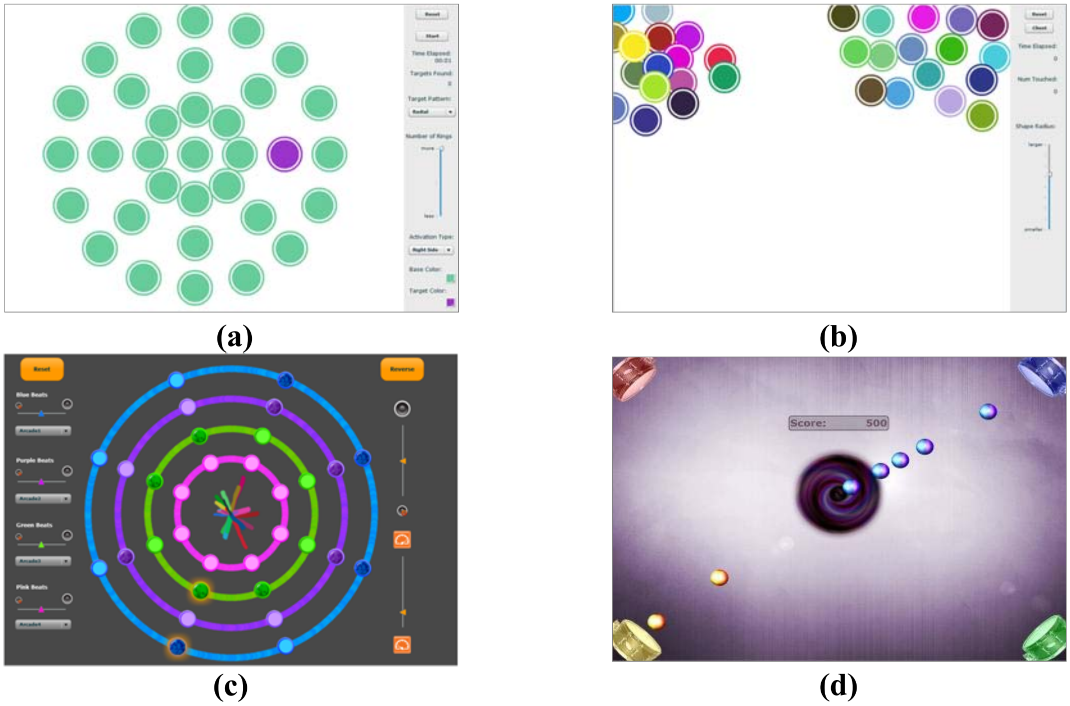


Figure 4. Examples of the various targeting-based multi-touch activities that were implemented (a) Touch-A-Tap, (b) Therapist Do-It-yourself, (c) BeatGen, and (d) Drumhab.

Therapist Do-It-Yourself

This activity is analogous to an existing rehabilitation activity that requires therapists place targets in different spatial locations on a table so that a patient can reach out and touch them. In our table-based implementation of this activity, the therapist can touch the tabletop to define target locations. The defined targets are then presented to the patient in random or sequential order. Once the patient has touched a target, it 'flies away' and the next target in the sequence is presented.

For patients with asymmetric dysfunctions or with regions of neglect, this activity provides therapists with a tool to target their disability directly (Figure 4b). As a patient performs this activity, the target touch accuracy (as measured using the root mean squared error formula), the time between correct target selections, and the number of non-target touches are recorded.

BeatGen

The BeatGen activity is a music generation activity that allows patients to create audio loops through a simple, touch-based interface (Figure 4c). By touching various nodes, patients can add or remove audio samples from the loop. They are also able to configure the samples used, the volume of each sample, as well as the master volume and tempo. As the patient uses the activity, the loop is continually played in real-time, allowing for instantaneous feedback of their effects. This activity is especially appealing to younger patients, as it allows them to create electronic music in an analogous way to DJs. The application supports a wide range of motion, from the gross motor movement needed to touch the nodes on the far side of the table, to the more fine-grained motion of the slider. This allows the application to be used with a more diverse population. As the patient uses the activity, the time on task is recorded, along with the number and distribution of touch events, the parameters that were changed, and the resulting audio file.

Drumhab

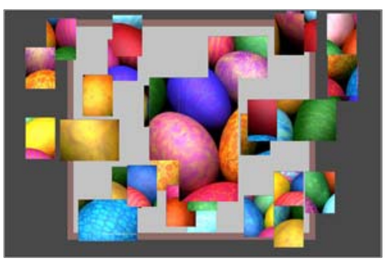
We created a music-centric tabletop activity inspired by the popular Rock Band and Guitar Hero video games. In this activity, there are ‘beats’ that radiate from a centre orb and move towards four drums located in the corners of the tabletop (Figure 4d). The beats are synchronized to music and as each beat reaches its target drum, patient must use their hands as drumsticks to ‘hit’ the target drum to score points. If the drum is hit at the correct time, the beat ‘explodes’.

A therapist can change the difficulty of Drumhab by choosing to display more or fewer beats on the screen, changing the speed of the beats, and selecting which drums are targets. As the drums are located in the corners of the tabletop, this activity promotes an increased range of motion. The speed at which the beats move can help to develop a patient’s reflexes. As a patient performs this activity, a number of measures are recorded: the final score, the number of beats touched, the total number of beats that were presented, the number of false hits, and the beat touch accuracy (as defined by the root-mean squared error formula).

(a)

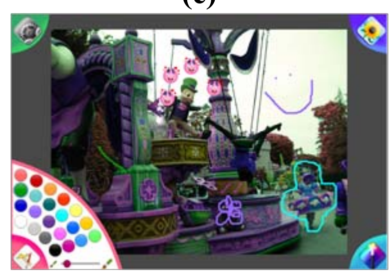
(b)

(c)

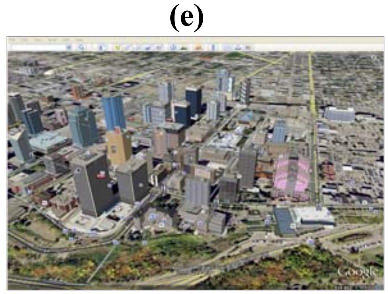


(d)

(e)



(f)



(g)

Figure 5. Examples of the various game-based and creative multi-touch activities that were implemented. (a) Nomis Says, (b) Match Me, (c) Pop Those Balloons!, (d) Touch Tessellation, (e) Foggy Windows, (f) Photo Scrapbooking, (g) Third Party Applications (e.g., Google Earth).

Nomis Says

Nomis Says is a virtual implementation of the classic Simon^{TM} game. In Nomis Says, a therapist can modify the number of coloured quadrants that appear, change the size and location of each coloured quadrant, or change the number of times a patient can try to repeat a light-up sequence if they have made an error. Multiple patients, or a patient and caregiver, can take turns repeating the light-up sequences, or players can be responsible for one or two quadrants and touch them at the appropriate time (Figure 5a). Nomis Says provides many cognitive and motor challenges to patients (e.g., sequencing, divided attention, immediate recall, gross motor skills, and dexterity). Similar to other activities, Nomis Says records the length of each correctly reproduced sequence, the touch quadrant error (using the the root-mean squared error formula) and the number of false touch events.

Match Me

Match Me is a digital implementation of the popular Concentration tile game that presents patients with an array of face-up or face-down touch tile pairs that need to be matched. This activity challenges gross motor movements, can increase sustained attention, and aims to improve visual neglect. To increase patient compliance and social interaction, family photos can appear on the tiles. A therapist can also choose to modify the number of touch tile pairs that are presented or change the location, pattern, or card background of the tiles. The Match Me activity supports both cooperation and competition: a patient can work with a partner to find matching touch tiles or complete against another player to find the most touch tile pairs (Figure 5b).

Pop Those Balloons!

In Pop Those Balloons! (Figure 5c), the patient is presented with a landscape that has floating balloons and is encouraged to think of their hands as stick pins. Using their stick pins, they must pop as many balloons as possible. Once a balloon has been popped, it ‘fades out’, disappears, and a popping sound is played. At this time, the patient’s score increases, providing immediate positive feedback.

This activity aims to enhance hand-eye coordination as well as dexterity. Therapists can tailor this activity to meet the needs of a particular patient by modifying the number of balloons that appear, changing the speed at which the balloons float from bottom to top, or modifying the area of the screen to which the balloons float. While the patient is performing this activity, a number of metrics are gathered: the time between balloon pops, the number of popped balloons, the total number of balloons that appeared, and the balloon touch accuracy (using a root-mean squared error measurement).

Touch Tessellation

In Touch Tessellation, patients are presented with a number of tile-like puzzle pieces and must touch and drag each piece to complete the puzzle (Figure 5d). Touch Tessellation can test planning, decrease visual neglect, increase spatial relation skills, and challenge fine and gross motor skills. To customize the activity, a therapist can specify the size and number of puzzle pieces or modify the starting location of the puzzle pieces (e.g., to encourage patients to converse or perform gross motor movements). Patient photographs can be used and meaningful sounds can be played to encourage social dialog and emotional immersion. The activity records the number of puzzle pieces touched and drug, the number of joined pieces, and the patient’s accuracy in touching each piece (using a root-mean squared error measurement).

Foggy Windows

In Foggy Windows, a patient is presented with a 'foggy window'. Patients must use their fingers or hands to 'defog the window' and reveal the hidden picture underneath. Foggy Windows can help patients exercise their gross motor skills and challenge figure-ground discrimination. To maintain patient engagement and compliance, therapists can modify the amount of fog that each window contains, the location of each window on the tabletop, or the size and type of the hidden object that is displayed (i.e., patient photographs, emails, or documents such as news stories can all be hidden). Foggy Windows can be used cooperatively, i.e., patients work with a partner to clean a window, or competitively, i.e., a patient and his or her partner have their own 'foggy window' and compete to clean them the fastest (Figure 5e). With Foggy Windows, it is possible to record the percent of the image that was defogged, the speed of each defogging stroke, and the areas where defogging occurred the most or least.

Photo Scrapbooking

In the Photo Scrapbooking activity, patients are encouraged to work cooperatively with a partner to modify personal pictures and make a scrapbook page. Patients can flip through a collection of their personal photographs to decide which one to modify and add to the scrapbook. In Photo Scrapbooking, patients can crop pictures, add stickers, paint, annotate, or alter picture attributes such as brightness or contrast (Figure 5f). Once a picture has been modified, it can be added to a scrapbook page, which can be saved, printed, or emailed to others. Photo Scrapbooking is an ideal collaborative activity because photographs naturally encourage emotional reactions and storytelling, and activate long-term memory. The editing of photos also challenges patients to exercise their fine and gross motor skills. This activity records the number and type of tools that were utilized, the length and duration of strokes (if one 'painted' on their image), the length and duration of touch events (if stickers were added), and the resulting images that were created.

Third Party Application Support

We have added a keyboard and mouse emulation extension to the AIR Touch system to support the use of third party applications. Interaction with Google Earth, for example, encourages patients to use their hands or fingers to navigate to places they have travelled to before or walk around their old neighbourhood (Figure 5g). Third party support also allows patients to play games with their family members, such as chess or checkers, browse the internet, or send emails using a virtual keyboard. This support allows patients to continue to stay connected to the outside world and practice skills that could be valuable once they finish their rehabilitation program. Given the variety of applications that can be used, this application only records the basic touch information (e.g., touch up, down, move, time between touch events, etc.).

4.2 Feedback

As mentioned, during our iterative design and implementation cycle, we consulted with a number of practicing occupational therapists. Discussions with these experts produced a number of guidelines that have influenced the design of our rehabilitation-centric activities and should be beneficial for others working in the area (Figure 6).

Figure 6. Elements identified by therapists as being crucial to the success of rehabilitation programs.

Communication
Encouraging communication during multi-user activities allows the trust between a patient and therapist to increase. It can also encourage patients to share their feelings and difficulties with their caregivers, and if using activities collaboratively, create bonds with other patients over their shared life or rehabilitative experiences. This can help improve not only the emotional state of the patient but also those they work with and depend on.

Cooperation
Including elements of cooperation is beneficial for rehabilitation because it provides patients with motivation from others who are in similar situations (i.e., fellow patients). As depression and feelings of helplessness often accompany serious injury, this can help make patients feel as if they are 'not alone' and have a support network. Using cooperation in rehabilitation activities also encourages patients to learn from the people they are interacting with and promotes turn taking, teamwork, and patience.

Customization
Activities should be configurable and have elements of uncertainty. Configurable activities allow therapists to tailor activities to match a patient's motor or cognitive abilities, demographic, background, or specific interests. Activities that contain surprises, uncertainty, and variability can be reused many times throughout a patient's recovery. Even something as simple as allowing a patient to choose the color of their stroke provides the patient with feelings of control over their rehabilitative process.

Immersion
Including positive, salient elements in multi-user activities can help patients to become emotionally immersed. This immersion allows patients to temporarily forget the pain or cognitive deficits they may have and instead focus on the activity at hand, i.e., they can experience and maintain a state of flow (Csikszentmihalyi, 1999). If a patient is working on an activity that has a picture of a loved one, they will likely be more motivated to put in effort and spend more time performing the activity.

Similarly, if patients can become competitively immersed in an activity, they are more likely to try harder and work longer to 'beat their competitor'. Patients can also receive encouragement and motivation from onlookers who are supporting them. Care does however need to be taken to ensure that the patient does not push themselves too far and incur further injury.

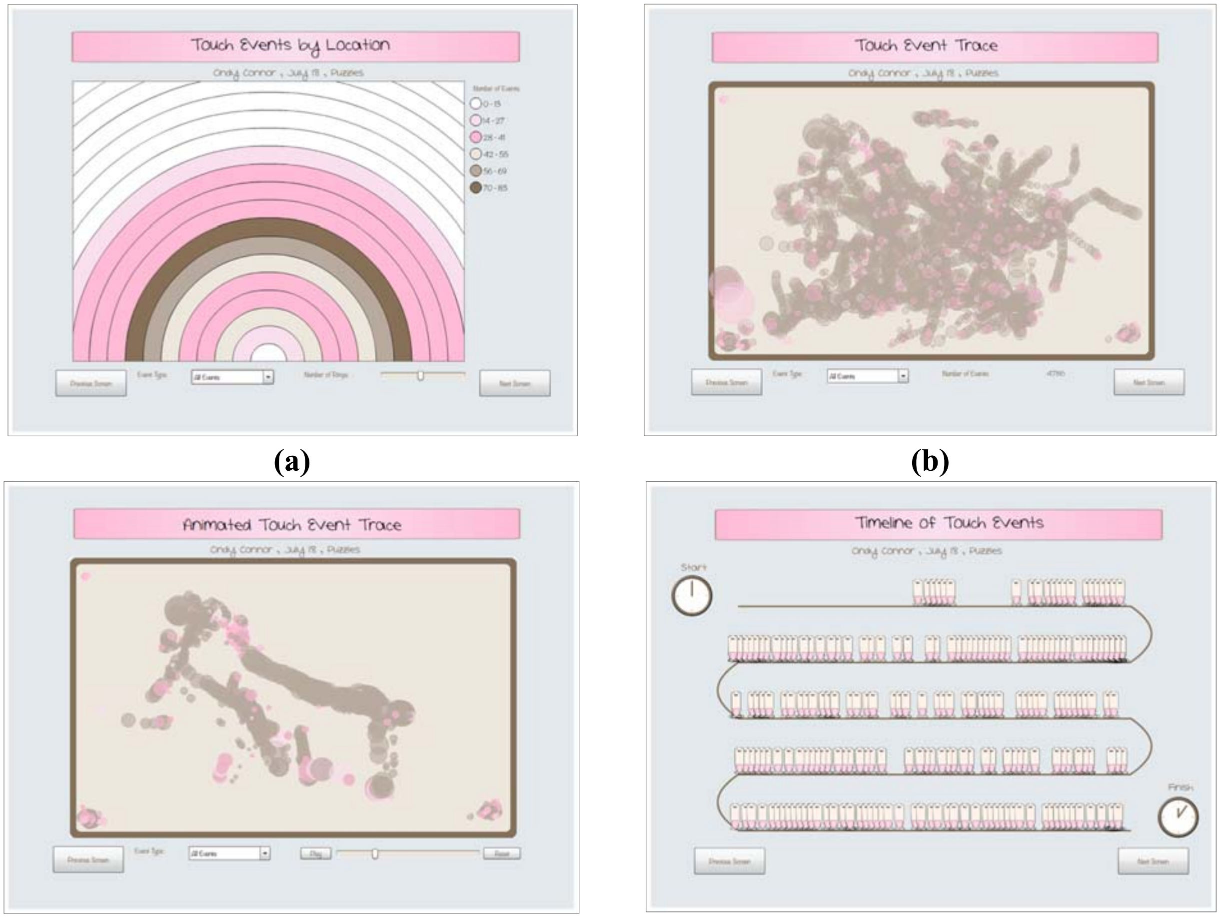
4.3 Visualizing Patient Interactions

Across all activities, there are a number of common events that can be recorded and utilized by a therapist to better understand a patient's progress (Table 1). These measures were further refined and four different visualizations were developed to allow for automatic comparisons between current and past performance and enable therapists to store patient-specific activity configurations for later comparison (Figure 7).

The first, a *radial touch map,* displayed the distribution of touch events from the patient's current standing location. This allowed therapists to identify and illustrate issues with flexion and extension. Another visualization, *touch event traces*, provided a 'heat map' style graphic that illustrated the location of each touch event that was generated by the patient along with the touch radius that was recorded, which illustrated the pressure exerted on the screen. This graphic enabled therapists to understand range of motion issues, and also identify areas of neglect that should be targeted in the future. The third visualization provided therapists with an animated rendering of each touch event, enabling therapists to 'scrub' through a session quickly and provide the patient with immediate feedback about their progress. Instead of focusing on the location of each touch event, the last visualization provided therapists with a timeline of the interaction that occurred during the session and allowed them to compare activity and touch durations across multiple sessions. This also allows one to quickly assess each session to understand possible fatigue or motivation factors.

Table 1. Measures identified across all activities as being important to the monitoring of patient progress.

Measure	Associated Rehabilitative Goal
Average touch event radius	Pressure and force exerted, muscle strength
Time of each touch event	Muscle Endurance
Duration of each touch event	Muscle Endurance
Speed of each touch event	Agility, muscle endurance
Time between touch events (i.e., between successive 'touch down' events in a given time period)	Fatigue, cardiovascular endurance, agility, interest, motivation
Number of touch events within a certain spatial location	Range of motion, flexibility, visual-spatial abilities
Time elapsed in activity per day and throughout the week	Interest, motivation, etc.



(a) (b) (c) (d)

Figure 7. Examples of the different touch visualizations that were developed. (a) A radial visualization of touch-events, b) a heat-map-style visualization to understand areas of neglect and range-of-motion issues, c) animated touch event traces, and (d) a touch-event timeline.

The visualizations allowed therapists to readily evaluate the performance of the patients on the various activities. Additionally, the visualizations supported longitudinal tracking and analysis of patient performance. This feature provided motivation and feedback for the patient as they could see how they were progressing throughout the course of an intervention and receive immediate feedback at the end of their activity or session.

5. Kinetics and Kinematics of Interactive Surface Physical Therapy

It is widely hypothesized that an increase in engagement leads to an increase in activity level and that patients could spend more time performing therapy activities. If this is true, it is of great benefit to therapy programs, as patients often neglect their prescribed activities as they are monotonous and frustrating. As mentioned, therapists have been looking towards virtual reality and tele-rehabilitation (Burdea et al., 2000; Holden et al., 2006, 2007), the Nintendo Wii (Dixon, 2008; Deutsch et al., 2008), and multi-touch tabletops (Mumford et al., 2008, Wall Street Journal, 2015) to increase patient engagement.

While the integration of technology into rehabilitation programs has been widespread, the evidence to support its usefulness has been lacking. Most studies in this area are small case studies, focusing on one or two outcome measures (Deutsch et al., 2008, Burdea et al., 2000, Holden et al., 2006) or a therapist's subjective account of a patient's progress (Halton, 2008). With multi-touch tabletops, there have been no controlled studies comparing patients along multiple quantitative dimensions or directly comparing traditional table-based therapy (i.e., making a puzzle, tracing a picture, touching static targets, etc.) with technology-based approaches. Without such evidence, it is unclear if technology-based rehabilitation is beneficial to patients.

Although technology can make activities more enjoyable, the movements that each activity encourages or requires must be safe and effective. Before widespread adoption of new therapy methods can occur, understanding the changes in movement and force when activities are performed on a different medium (e.g., a multi-touch tabletop instead of a physical table) is an important step.

To understand patient movement while using technology-based rehabilitation, we conducted a lab-based study where we performed a controlled comparison of traditional (table-based) and multi-touch tabletop (technology-based) rehabilitation methods. In this study, we analyzed the hand motion and muscle activation of participants as they completed four activities that were representative of those typically performed in a stroke rehabilitation program. As patient safety is of great concern, we chose healthy individuals as participants. By monitoring the movement patterns and forces exhibited by those who are healthy, we should be better able to understand what impact a change in presentation medium could have on the movement kinetics and kinematics of patients.

5.1 Methods

To analyze the potential benefits of technology-based therapy interventions, a within-subject study design was conducted with able-bodied participants.

Participants

From the general University population, 14 right-handed individuals (7 females and 7 males) participated in our study. Participants had a mean age of 27.9 years (SD = 12.5, range 18-77 years) years. Each participant was paid $20 CAD for their time, and did not have prior experience with a multi-touch tabletop, motion capture, or electromyography. The study was approved by the Research Ethics Board at the University of Alberta.

Apparatus

The AirTouch table was used in this study. The upper body movement of each participant was captured using a NaturalPoint 12-camera Optitrack system. Participants wore a motion capture jacket with 19 retro-reflective markers, providing the position of the chest, waist, upper arm, lower arm, and hand at 100 Hz. Surface electromyography (EMG) measured the muscular activity of each participant. Four pairs of electrodes were placed on the skin of the dominant arm (i.e., on the biceps-brachii, on the triceps brachii, on the forearm flexors, and on the forearm extensors). The electrodes were connected to a Bortec AMT-8 amplification system that was then connected to a National Instruments Data Acquisition Card that sampled at 1000 Hz. The EMG signals were filtered using a band-pass filter (20 - 400 Hz), a 60 Hz notch filter, and a

Root-Mean-Square filter (with a window size of 300 ms) to remove noise and rectify the signal.

For the traditional, non-interactive activities, a white, corrugated plastic board (91 cm x 61 cm x 0.4 cm) was placed on top of the acrylic surface of the multi-touch tabletop. The repurposing of the multi-touch tabletop in this way allowed participants to remain in the same location and use the same region of interaction across all activities.

Procedure

Participants stood in front of the multi-touch tabletop and performed four activities. Participants performed each activity for 5 minutes, with the order of activities randomized between participants. If participants finished the activity before the allotted time elapsed, the activity was reset and the participant repeated it until 5 minutes elapsed. Resetting the activity was acceptable as we were not concerned with the learnability of the activities or the cognitive strategies employed, and it also reflects a real-world usage scenario. A short 3-minute break was allowed between activities to mitigate possible fatigue effects and allow for the next activity to be set up. Similar to constraint-induced movement therapy (Kunkel et al., 1999; Taub et al., 2004), participants were restricted to use only their dominant (right) arm to complete each activity.

Though some patients may sit at the table in a clinical setting, many stand so that they may work to improve their balance along with upper extremity function. The experiment took approximately 45 minutes to complete.

Activities

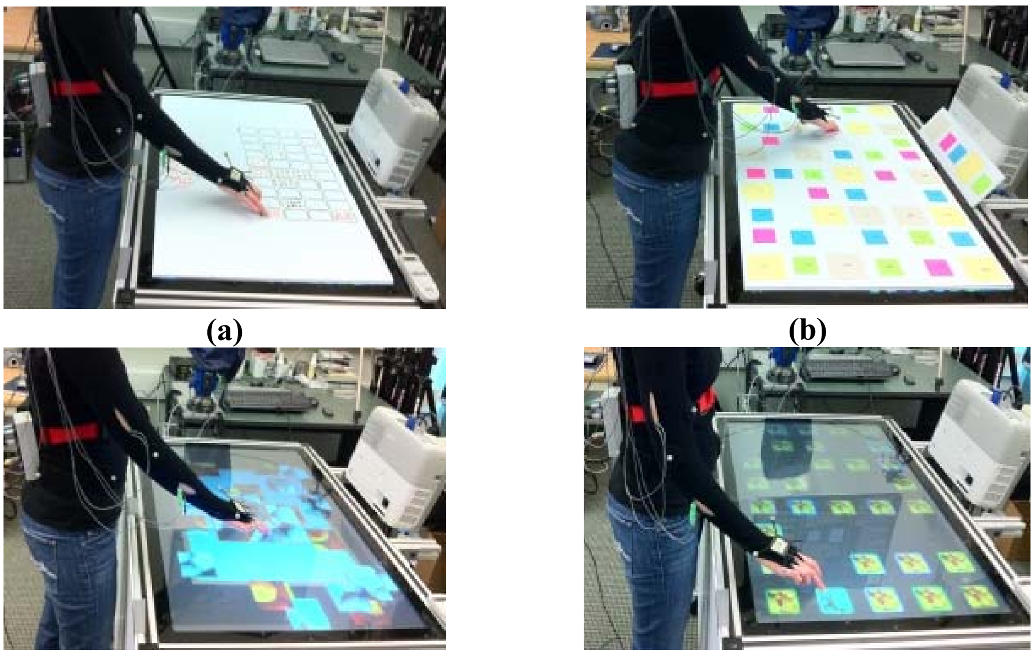
Four activities were used in the study (Figure 8). Two of the activities, Touch Tessellation and Match Me, are activities that are currently in use by therapists at the Glenrose Rehabilitation Hospital and required participants to interact with the multi-touch tabletop. The other two activities, i.e., Card Sorting and Grid of Stickers, are similar to traditional table-based activities that patients currently perform in therapy sessions and did not make use of the interactive tabletop. While a comparison with 'standardized' activities would seem appealing, the activities and exercises used in therapy programs today vary widely between hospitals and therapists.

- *Card Sorting (Physical)*: A deck of miniature playing cards (with face cards removed) was shuffled and placed face up, in a pile, on a white plastic board in a circular area close to participants (Figure 8a). Opposite the cards was a 10 x 4 grid where participants could drag each playing card. Participants sorted the pile (into ascending order, by suit) by sliding each card into the grid.

- *Grid of Stickers (Physical)*: This activity used a white plastic board with a 9 x 6 grid containing 45 rectangular stickers (and 9 empty spaces). Five different colors of stickers were used, each numbered sequentially from one to nine (Figure 8b). Participants were required to touch each number in order, cycling through a predefined sequence of colors (i.e., Brown 1, Pink 1, Blue 1, Yellow 1, Green 1, Brown 2, …., Green 9).

- *Touch Tessellation (Digital)*: Forty square-shaped puzzle pieces were presented to participants on the multi-touch tabletop. To eliminate the need to rotate tiles, all tiles were presented in the correct orientation (Figure 8c). Participants completed the puzzle by dragging matching pieces next to each other, causing them to 'snap' together. The finished puzzle was 10 pieces wide x 4 pieces high.

- *Match Me (Digital)*: An 8 x 5 grid of tiles was presented on the multi-touch tabletop (Figure 8d). On the underside of each tile was one of 20 images. As participants touched the tiles, they flipped over to reveal an image. Participants touched two images sequentially, trying to find a match. If a match was found, the tiles disappeared from view; if not, the tiles flipped back over and they continued finding matching pairs.



(a) **(b)** **(c)** **(d)**

Figure 8. Examples of the participant activities. (a) Card Sorting, (b) Grid of Stickers, (c) Touch Tessellation, and (d) Match Me.

Measures
To assess the potential for technology-assisted rehabilitation, measures of movement (kinematics and kinetics) as well as measures of user-attitude were recorded.

Kinematics and Kinetics
To assess the kinematic components (i.e., those related to spatial movement) of each trajectory (Figure 9), several measures were computed. The quantity of movement was assessed using *total path length,* computed as the sum of the distance between successive points on the trajectory of the hand. Looking at the trajectory distribution and the motion smoothness enabled us to assess the form of participant's movement. The standard deviation of each trajectory was used to compute the *dispersion* of the signal along each axis: left/right (x), up/down (y), and forward/backward (z). The *smoothness* of participant's motion (i.e., the degree to which the trajectory changes direction at each point in time) was computed using the median value of the trajectory's curvature.

To assess the kinetic components (i.e., those related to force production), the *total muscle activity* was computed as the summation of the rectified, filtered signals from the four muscle sites.

These measures were chosen based on prior experience analyzing gestures and surgical movement, and represent meaningful simplifications of the complex 3D trajectories. More complex analysis tools (e.g., using HMMs or Dynamic Time Warping) may give more insight, but were beyond the scope of the work.

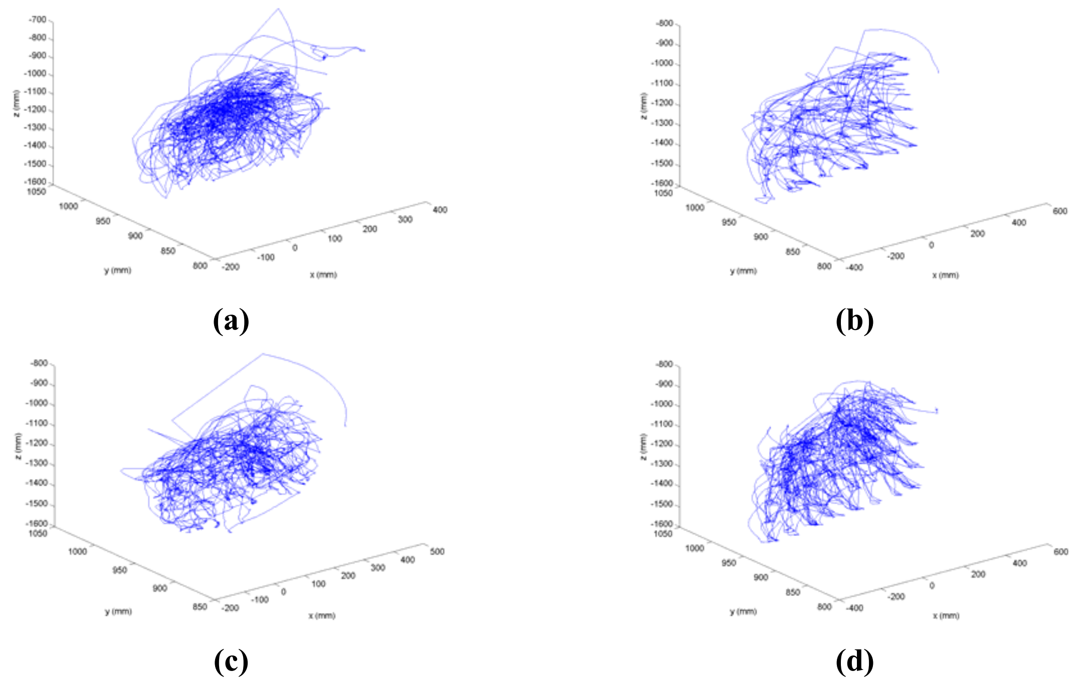


Figure 9. Participant P5's trajectories from (a) Card Sorting, (b) Grid of Stickers, (c) Touch Tessellation, and (d) Match Me. The viewpoint is rotated to show movement on and above the tabletop (located at y ≈ 925 mm). Of interest in the graphs is the grid structure visible in the Grid of Stickers and Match Me graphs, the dense region in the Card Sorting corresponding to the initial pile of cards. The density of the trajectory also indicates path length.

Motivation and Perceived Usage

The Intrinsic Motivation Inventory (IMI; McAuley et al., 1989) was used to assess participants' subjective opinions towards each of the activities using Likert-type responses to statements such as "I would describe the activities as very interesting". From the responses, scores along four separate dimensions (i.e., interest and enjoyment, effort and importance, mental tension and pressure, and perceived competency) were computed and represent the participants' subjective feelings towards the different activities. Two IMI's were administered, one assessing both of the traditional activities (*Card Sorting* and *Grid of Stickers*) and the other assessing both of the technology-based activities (*Match Me* and *Touch Tessellation*). At the conclusion of the experiment, a semi-structured exit interview was conducted. The following guiding questions were used during the interview and participants were encouraged to engage in open discussion:

- Which activities did you enjoy the most? Which did you enjoy the least?
- If you could change any of activities, what would you change?
- Which category of activity (traditional or technology) did you prefer?
- Imagine you are in a therapy program. Which of the activities would you prefer to use?

5.2 Results

Herein we detail the quantitative and qualitative results that were attained, first detailing those relating to the Kinematics and Kinetics and then those relating to the preferences of the participants.

Kinematics and Kinetics

The statistical analysis was conducted with Stata on the kinematic and kinetic outcome measures described above. A one-way repeated-measures ANOVA was performed with *Activity* as the main factor (levels: Touch Tessellation, Match Me, Card Sorting, and Grid of Stickers). The ANOVA tests for *total path length*, *x-dispersion*, *z-dispersion*, and *smoothness* were all found to be significant, $p < 0.001$ (Table 2). The y-dispersion was not found to be significantly different between any of the conditions, indicating that the vertical movement of participants' right hand did not vary greatly between activities. The *total muscle activity* was not significantly different between any of the conditions, implying that similar amounts of force were used for all activities.

Table 2. ANOVA Results. The movement data as well as subjective responses were analyzed and are presented separately.

	$F_{(3, 39)}$	Significance
Path Length	7.3	$p < 0.001$ ***
EMG Activity	1.99	$p > 0.05$
x-Dispersion	50.32	$p < 0.001$ ***
y-Dispersion	2.66	$p > 0.05$
z-Dispersion	15.63	$p < 0.001$ ***
Smoothness	10.59	$p < 0.001$ ***

Post-hoc tests were conducted on the four significant measures using Tukey's HSD (Figure 10). Regarding *total path length*, post-hoc tests revealed the means between the Touch Tessellation and Match Me activities were significantly different ($p < 0.05$) as were the means of the Touch Tessellation and Card Sorting activities ($p < 0.001$). Regarding the *x-dispersion* (left/right), all activities were found to be significantly different from each other ($p < 0.01$ between Match Me and Grid of Stickers, and between Touch Tessellation and Grid of Stickers; and $p < 0.001$ for all other conditions). The post-hoc tests also revealed that the *z-dispersion* (forward/back) of the Touch Tessellation activity was significantly different from all other activities ($p < 0.01$ for Grid of Stickers, $p < 0.001$ for Match Me and Card Sorting). Post-hoc tests also showed that the smoothness of the Card Sorting activity was significantly different from all other activities ($p < 0.01$ for Match Me and Grid of Stickers, $p < 0.001$ for Touch Tessellation).

Motivation and Perceived Usage

The Intrinsic Motivation Inventory responses (Figure 11) were analyzed using Bonferroni-adjusted, Wilcoxon signed-rank comparisons. Participants rated the multi-touch activities (i.e., MatchMe and Touch Tessellation) as significantly more interesting and enjoyable than the traditional activities (i.e., Card Sorting and Grid of Stickers; $Z = 2.79$, $p = .0052$). There were no significant differences along the other dimensions (i.e., effort: $p = .45$, competence: $p = .71$, and tension: $p = .68$). As all four of the activities were quite simple and participants were instructed to perform each activity at their own pace, the lack of statistical differences is unsurprising.

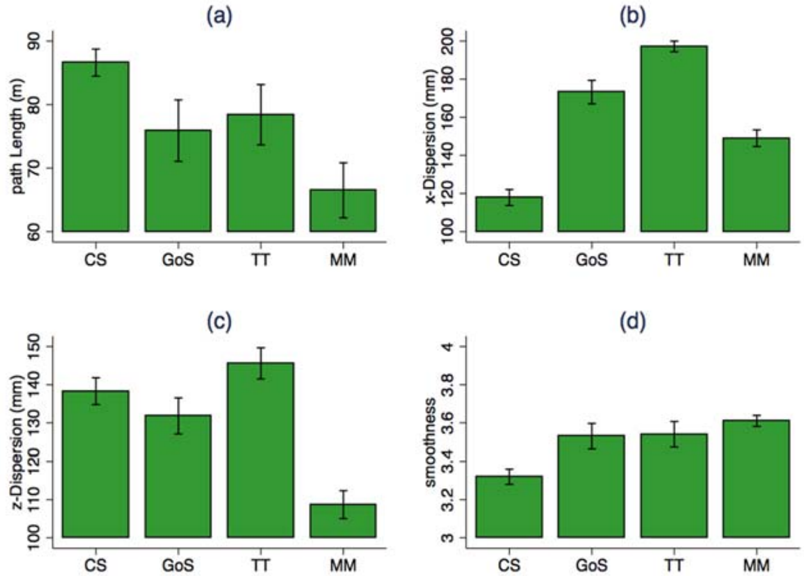


Figure 10. The mean kinematic and kinetic results for the four activities (i.e., Card Sorting (CS), Grid of Stickers (GoS), Touch Tessellation (TT), and Match Me (MM)) for the (a) path length, (b) x-Dispersion, (c) z-Dispersion, and (d) smoothness measures.

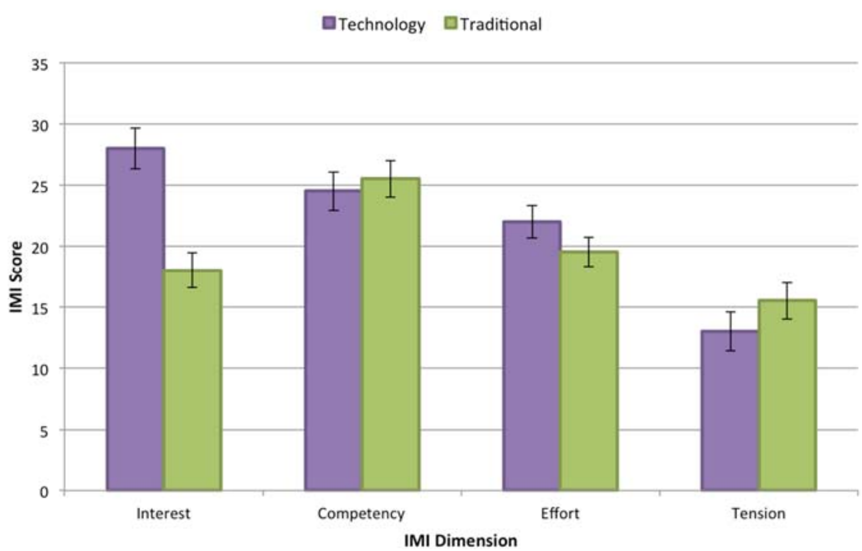


Figure 11. The median scores for each of the dimensions of the IMI. The error bars depict the standard error of the mean. The 'Interest' dimension is statistically higher with the technology-based activities (i.e., Match Me and Touch Tessellation) than the traditional activities (i.e., Grid of Stickers and Card Sorting).

5.3 Discussion

Results from the participant's subjective responses matched well with the presumed benefits of technology-based therapy, however, the motion data presented interesting and surprising results.

Kinematics and Kinetics

The results indicate that technology is not the sole factor determining the quantity of motion. Any differences in *total path length* and *total muscle activity* did not appear to be caused by the use of technology, but rather the content of the activity. The *total path length* during the Touch Tessellation activity was significantly lower than the Match Me and Card Sorting activities. We observed that many participants hesitated before reaching for a Touch Tessellation piece. These hesitations led to less frequent movements and thus lower path lengths. Additionally, the Card Sorting activity produced a substantial amount of movement. This is likely because participants did not have to perform a visual search or engage in substantial cognitive processing to find their next target. By designing activities so that targets are easily located and known, thus cutting down on visual search time, we can maximize a patient's movement during therapy sessions.

The analysis of the movement form demonstrates the importance of an activity's spatial layout and a user's strategy. From the dispersion, we see that while most participants kept their hand at approximately the same height above the tabletop, the dispersion of movement along the surface of the table was quite variable. From the *x-dispersion*, we see that all activities produced very different motion, with no clear separation between technology and traditional activities. During Card Sorting, participants often slid cards up the center of the table and then returned their hand to the bottom of the board to get their next card. With Match Me, many participants selected tiles from alternating sides of the table, perhaps thinking that matching pairs would not be placed next to each other (although the tiles were randomized). This led to frequent left-right movements. The small *z-dispersion* for the Touch Tessellation quantifies a strategy that a number of participants used, namely dragging pieces close to themselves so they could more easily see, manipulate, and combine them into smaller groups before they were moved to their final location. This strategy allowed participants to make more efficient movements, leading to small dispersion values. For an activity that emphasizes range of motion, designers should give thought to whether targets are static, dynamic, or user-movable, and what strategies users may employ to complete them.

During Card Sorting, participants made smoother movements, most likely because Card Sorting has a low cognitive load, resulting in continuous, flowing motion. In contrast, the Grid of Stickers required extensive visual search, often leading to 'Aha!' moments. These moments caused participants to touch stickers that were difficult to find quickly, resulting in sharper motion. To minimize intense movements, it may be beneficial to avoid 'surprise' elements that trigger such motion.

Motivation and Perceived Usage

The semi-structured interviews help explain the reasons behind the increased scores of enjoyment and interest. Several participants commented that they enjoyed the technology-based activities more because they contained dynamic elements and feedback about their progress: "hearing the Touch Tessellation tiles click together and having the tiles disappear in front of me was super motivating" (P1). Although the activities were completed individually, many participants mentioned that they took a competitive stance towards completing them, "[the tech] wasn't frustrating at all! For me it was like a competition" (P10). When using the multi-touch tabletop, several participants indicated that they were motivated to accomplish a worthwhile goal: "I like the Touch Tessellation one because you're actually playing a game and trying to finish something instead of just touching stickers" (P3).

These comments suggest that technology-assisted rehabilitation might be more enjoyable because it provides meaningful, achievable challenges and real-time, dynamic feedback to users. The participant's feedback is consistent with beliefs that dynamic gaming elements lead increased enjoyment and adherence to therapy programs. When designing activities for therapy, it is not enough to only rely on the use of technology to increase engagement and adherence. It is important for designers to think carefully about the goals of the activities they are designing and employ feedback at the correct frequency, using the correct medium, and at an appropriate cognitive level. Designers should also work to provide engaging and challenging, yet accomplishable, elements in their activities that are intrinsically motivating to patients.

Other comments alluded to the role that prior exposure with technology had on participants' expectations and experiences with the multi-touch tabletop. Many participants compared the multi-touch tabletop (and its activities) to commercial multi-touch devices: "if you have an iPad you can see that it registers every motion and gesture ... the design of [iPad] games are better" (P13); "I'm just so used to playing those iPhone games" (P12). Many participants expressed that they would definitely prefer to use the multi-touch tabletop in a rehabilitation setting if it was as refined as the commercial products they use every day.

As the quality of commercial technology increases and the budgets for therapy-driven software remain comparatively low, these observations become particularly relevant. The user-facing aspects of therapy software need to be improved to meet the growing expectations and familiarity patients will have with multi-touch technologies. In the near future, many patients will be intimately familiar with software products and video games released by large production studios with equally large budgets. Unfortunately, custom therapy-targeted projects will likely not have these budgets so designers will have to be creative in finding ways to meet such expectations. To create engaging, high-quality games at low costs, designers should leverage existing content and technologies where possible, and use openly available video-game engines to ensure that the rehabilitation games do not feel similar to ad-hoc prototype applications, instead appearing robust, well designed, and thoroughly tested.

Several participants were also quick to cite technology (i.e., the multi-touch tabletop) as the source of any errors that occurred rather than their own actions. As the multi-touch tabletop provides direct-touch interaction, there is a much smaller gulf of execution than with indirect-touch interfaces (Hutchins et al., 1985), causing more ambiguity with regard to the source of errors. During our experiment, the largest sources of frustration were situations in which false touches were being detected and situations where the user received little or no feedback. When this happened, many users were unsure if they were not touching the surface with enough force (even though it was not pressure sensitive) or were not touching in the right location, leading to confusion and annoyance. For example, one participant was "irritated at how the tabletop wasn't too responsive" (P7) and continually exerted more force on the surface. In contrast, none of the participants complained about the mechanics of the traditional activities when they made an error and one participant commented that they "felt [they] could handle the physical materials more easily than the digital ones" (P8).

Guidelines
The study has provided insight into the impact that the design of the activity can have on the movement of the patient. It is not enough to naïvely place targets, as this does not consider all factors of the motion that is used to touch them. While technology-based approaches seem to be more enjoyable for patients, it is essential that the underlying movements actually produce the desired effect and can be performed by users in a reasonable manner. As with most interactive surfaces, it is important that the surface texture of the device does not introduce extra friction that can decrease the fluidity of one's movements; Annett et al., 2014).

To minimize user frustration during input, tabletop activities must have responsive sensing, as users will otherwise become quickly irritated and feel that they are not in control of an activity and potentially their therapy progress. While hardware is a large determinant of the responsiveness and accuracy, some steps can be taken in software to reduce the apparent effects of these parameters. For direct-touch devices with coarse sensing resolution or noisy sensing, on-screen targets can be made larger so that pixel-level accuracy is not required.

Feedforward and feedback is also very important within the design of any technology-based therapy system. Feedback should also be used to indicate the exact location where the user's touch was registered. Providing as much information before and after touch events occur can allow users to adjust their interaction to accommodate for any offsets or input warping and will help reduce the ambiguity caused by positioning errors. The use of the hover-state (Buxton, 1990) may be an important data stream to consider in future rehabilitation-based systems. To mitigate latency issues, developers should ensure that feedback regarding a sensed touch is displayed as soon as possible and not delayed by complex application-specific processing. If complex processing is required, the system should first provide the feedback on where the touch was registered before processing the application-specific response.

6. General Discussion

The broad scope of the presented work has allowed us to generate insights into the use of technology for rehabilitation and how to best design and implement effective, usable systems. Herein we discuss four of the most prominent factors that need to be considered before one integrates technology-based initiatives or interventions into a rehabilitation program.

Activity Design

The design of the software activities was found to be very influential in the movements made by participants, as well as for engagement with activities. When designing activities or selecting from pre-made activities, consideration should be given to both of these aspects to ensure maximal benefit for the patient.

A wide range of activities should be available to maximize the chances that patients will be able to select an activity that interests them. Just as people have different preferences for various genres of video games, different patients will prefer different types of activities. Many may not want to play games at all, but might prefer to perform productivity tasks, read books, or communicate with loved ones. While these types of activities were not explored, aside from providing third-party application support, they present interesting and fruitful avenues for future research. Lastly, activities should support end-user customization where possible, allowing the patient to use their own photos and stories and draw upon information from local sources or personal history for content.

Evaluation Techniques

Robust evaluation techniques are needed in the development of all therapy-focused technology. Currently, clinical trials are out-of-scope and too cumbersome for most developers of therapy-based technology and proxy-evaluations need to be conducted. We presented methodology for one such proxy-evaluation, in which we evaluated both quantitative measures of motion as well as subjective aspects of the experience. It is important for developers to consider both aspects of their proposed intervention, as getting both ‘right’ is crucial to the success of the therapy sessions.

Future work is needed to reduce the complexity of these evaluations, however. The presented evaluation used optical motion trackers and electromyogram technology, both of which are out-of-reach of many developers. Lower-cost alternatives may be useful in many situations, such as using a Microsoft Kinect to capture and record motion data and using simple force-sensitive-resistors to instrument the user or environment to record kinetic data.

Necessity for User-Centric, Iterative Prototyping

Integrating the therapists and clients into the development cycle was an important aspect of the success of the technology. The consultations provided opportunities to uncover various usability issues unique to clinical use that would have otherwise gone unnoticed until the time of deployment. These sessions also helped illustrate the importance of simplicity, responsiveness, and ease of use, as therapy sessions are often quite short with little time available to setup, login, and configure systems, tools, or activities that will be used. All of the activity customization that was included in our activities was touch-based and could be modified in-activity in real-time. This allowed for a decreased learning curve on the part of the therapist and increased freedom to change options and parameters on the fly.

Feedback from the therapists drove the design of the data-visualization component of the software. Their input helped understand which useful measures and data were relevant to the successful tracking of patient input. This also helped provide useful and motivating data to the patients to maintain their long-term interest in the activities and ultimately their rehabilitation program.

Tabletops for Interactive Rehabilitation

Interactive tabletops are a great form-factor for upper-extremity rehabilitation tasks. Their large size supports a wide range of abilities and range of motions from fine motor tasks to large, gross movements that span the width and length of the table. They also provide a familiar form-factor (horizontal surface) which makes affordances such as touching and dragging objects more direct. Lastly, patients are able to use the table for support during standing, if necessary, or can even be seated while using the table. This increases the population that is able to use the table.

The tabletops used in our presented work represented leading-edge technology at the time the work was conducted. Recent advances in commercial displays have provided off-the-shelf solutions which may be better suited for rehabilitation tasks. For instance, SMART Technologies and Microsoft now offer large, high resolution screens (e.g., 55”, 65”, 84” diagonal size) with touch, stylus, and some tangible input support. These displays can be mounted to actuated stands to allow the angle and height of the screen to be modified, greatly increasing the utility of the hardware. While more expensive, using such commercially available hardware can speed development time and lead to fewer technical issues compared to developing in-house solutions.

7. Conclusion

This work has revealed important insights into multi-touch therapy, activities, equipment, and outcomes. While direct-touch interaction can continue to offer a number of benefits when used in therapy-based activities, there are a number of drawbacks that need to be considered and addressed before rehabilitation facilities should consider developing technology-only interventions and programs. An iterative design process that was undertaken identified many goals, requirements, and guidelines that should be of great benefit to the human-computer interaction and rehabilitation communities.

Given the previous work demonstrating that technology itself is not enough to modify the movement patterns of individuals in therapy programs, it is clear that the benefit of technology lies in its ability to provide responsive, dynamic content. To that end, we have studied user attitudes towards interactive tabletops and found that while users do typically find them more engaging, there are some limitations that must be overcome before they can become truly beneficial for clinical populations. Using our design recommendations, the engagement and enjoyment patients experience during therapy can be improved, and should lead to higher motivation and ultimately compliance and satisfaction with the therapeutic process.

There are several avenues along which this work can be extended. One next step is to refine our activities based on the observations gathered during the current study and perform a long-term study with a patient population. While we expect many of our conclusions and recommendations to generalize to both populations, studying the usage behavior of the target end users (i.e., patients) will likely produce additional insights that will be of great value. Additional future work could also involve studying those aspects of tabletop-based therapy that contribute to success and enjoyment for the end user, for instance, examining the relative importance of customization, dynamic feedback, emotional saliency, and game content.

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