Tabletops in Motion: The Kinetics and Kinematics of Interactive Surface Physical Therapy

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Abstract
Technology-based rehabilitation methods have shown promise for improving physical therapy programs, but much of the research is lacking quantitative analysis. We present a study conducted with healthy participants where we compared traditional “table-based” therapy with technology-based methods. Using motion analysis and electromyography recordings, we assessed the kinetic and kinematic dimensions of participant motion on four activities. While technology-based methods are more enjoyable, our results indicate that it is the design of an activity that has a significant impact on the movements performed.

Keywords
Physical Therapy, Multi-touch Tabletop, Motion Capture, Electromyogram, Empirical Study

ACM Classification Keywords
H.5.2. [Information interfaces and presentation]: User Interfaces – Input devices and strategies; H.5.2. [Information Interfaces and Presentation]: User Interfaces – Interaction styles; K.4.2. [Computers and Society]: Social Issues - Assistive technology for persons with disabilities

General Terms

Experimentation, Human Factors, Measurement, Performance

Introduction

It is widely hypothesized that an increase in engagement will lead to an increase in activity level and that patients will spend more time performing therapy activities [1]. If this is true, it is of great benefit to therapy programs, as patients often neglect their prescribed activities because they are monotonous and frustrating. Over the last decade, therapists have been looking towards virtual reality and tele-rehabilitation [5,7,8], the Nintendo Wii [3,4], and multi-touch tabletops [1,2,9,10] to increase patient engagement.

With rich interactions, animations, and sound, technology has the potential to transform a dreary, unexciting rehabilitation task (such as sorting playing cards by suit) into an exciting, immersive activity. Multi-touch tabletops, for example, provide natural and intuitive interaction that can stimulate both gross and fine upper-extremity motor movement in a dynamic, engaging context. This type of technology also enables therapists to customize activities to meet a patient's needs as they change throughout a program or make activities more meaningful (e.g., change the content of a virtual puzzle to a photograph of their grandchildren).

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 [4,5,8] or a therapist's subjective account of a patient's progress [6]. 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. No matter how fun an activity is, if it does not provide a benefit to patients, therapists will not use it. Understanding the changes in movement and force that occur when activities are performed on a different medium (e.g., a multi-touch tabletop instead of a physical table) is an important step before widespread adoption of new therapy methods can occur

To better understand patient movement while using technology-based rehabilitation, we conducted a study in which 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 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 have initially chosen 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.

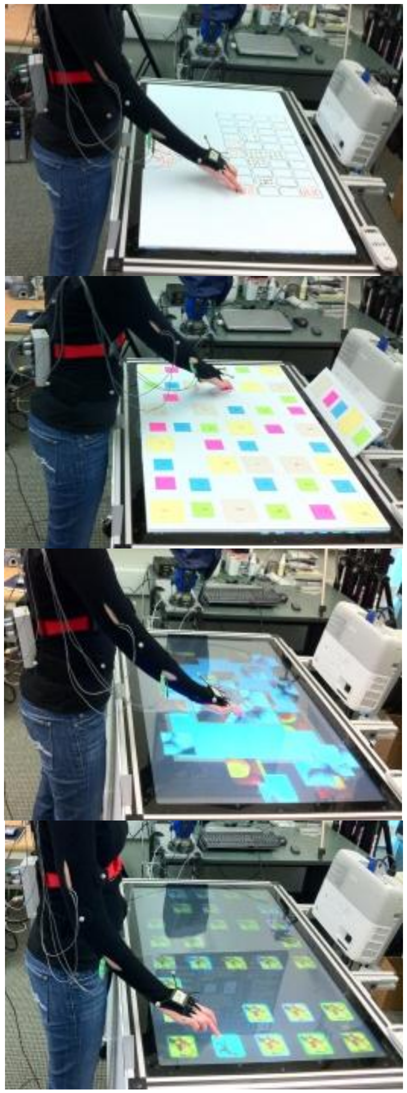

Figure 1. Participant activities. From top: Card Sorting, Grid of Stickers, Puzzle, and Memory.

Methods

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 (σ = 12.5) years. Each participant was paid $20 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

A custom-built, FTIR-based multi-touch tabletop was used in this study. The tabletop surface measured 61 x 91 cm, and was positioned 80 cm above the ground. 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) was used to measure the muscular activity of each participant. Four pairs of electrodes were placed on the skin of the dominant arm (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.

Procedure

Participants stood in front of the multi-touch tabletop and performed four activities with their dominant (right) limb. Participants were restricted to using a single limb, as many rehabilitation programs tend to focus on a single affected limb, as in constraint-induced movement therapy [11]. Participants were given 5 minutes to perform each activity and were allowed to rest between activities. If participants finished before the 5 minutes elapsed, the activity was reset and they were asked to perform it again. The activity presentation order was randomized, and alternated between technology-based (multi-touch) and traditional therapy activities. The experiment took approximately 45 minutes to complete.

Activities

Four activities were used in the study (Figure 1). Two of the activities, Puzzle and Memory, are activities that are currently in use by therapists at the Glenrose Rehabilitation Hospital (in Edmonton, Alberta, Canada) and required participants to interact with the multi-touch tabletop. The other two activities, 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 of 'standardized' activities would seem appealing, the activities and exercises used in therapy programs today vary widely between hospitals and therapists.

Card Sorting: A deck of miniature playing cards (with face cards removed) was shuffled and placed face up on a white plastic board in a circular area close to participants. 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.

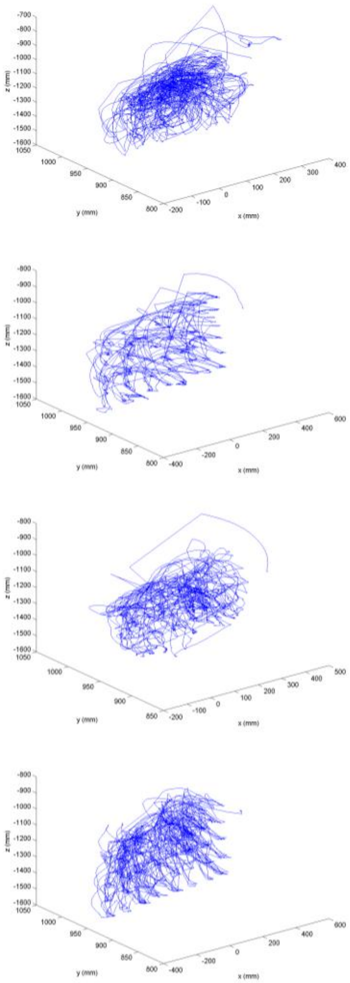

Figure 2. Participant P5's trajectories from Card Sorting, Grid of Stickers, Puzzle, and Memory. The viewpoint is rotated to show movement on and above the tabletop (located at y ≈ 925 mm).

Grid of Stickers: This activity used a white plastic board with a 9 x 6 grid containing 45 rectangular stickers (and nine empty spaces). Five different colors of stickers were used, each numbered sequentially from 1 to 9. 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).

Puzzle: 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. Participants completed the puzzle by dragging matching pieces next to each other, causing them to 'snap' together. The finished puzzle was 10 pieces x 4 pieces.

Memory: An 8 x 5 grid of tiles was presented on the multi-touch tabletop. 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.

Kinematic and Kinetic Measures

To assess the kinematic components (i.e., those related to spatial movement) of each trajectory (Figure 2), several measures were computed. 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 (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 (those related to force production), the *total muscle activity* was computed as the summation of the rectified, filtered signals from the four muscle sites.

Results

The statistical analysis was conducted with Stata on the outcome measures described above. A one-way repeated-measures ANOVA was performed with *activity* as the factor (with levels Puzzle, Memory, Card Sorting, Grid of Stickers). The ANOVA tests for *total path length*, *x-dispersion*, *z-dispersion*, and *smoothness* were all significant, $p < 0.001$ (see Table 1). The y-dispersion was not found to be significantly different in any condition, 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.

Post-hoc tests were conducted on the four significant measures using Tukey's HSD with a significance level of $p < 0.05$. The mean and standard error of the mean (SEM) are presented in Tables 2 through 5. Regarding *total path length*, post-hoc tests revealed the means between the Puzzle and Memory activities were significantly different ($p < 0.05$) as were the means of the Puzzle and Card Sorting activities ($p < 0.001$). Regarding the *x-dispersion* (left/right), all activities were found to be significantly different from each other ($p < 0.01$ for Memory-Grid of Stickers and Puzzle-Grid

	$F_{(3, 39)}$	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	$p < 0.001$ ***

Table 1. ANOVA results.

	Mean	SEM
Card Sorting	86.6 m	2.14 m
Grid of Stickers	75.9 m	4.84 m
Puzzle	66.5 m	4.33 m
Memory	78.4 m	4.75 m

Table 2. Path length mean and SEM

	Mean	SEM
Card Sorting	117.9 mm	4.20 mm
Grid of Stickers	173.2 mm	6.17 mm
Puzzle	149.0 mm	4.38 mm
Memory	197.2 mm	2.78 mm

Table 3. x-dispersion mean and SEM.

	Mean	SEM
Card Sorting	138.3 mm	3.53 mm
Grid of Stickers	131.8 mm	4.73 mm
Puzzle	108.7 mm	3.66 mm
Memory	145.6 mm	4.09 mm

Table 4. z-dispersion mean and SEM.

	Mean	SEM
Card Sorting	3.32	0.040
Grid of Stickers	3.53	0.067
Puzzle	3.61	0.029
Memory	3.54	0.067

Table 5. Smoothness mean and SEM.

of Stickers, $p < 0.001$ for all other conditions). The post-hoc tests also revealed that the *z-dispersion* (forward/back) of the Puzzle activity was significantly different from all other activities ($p < 0.01$ for Grid of Stickers, $p < 0.001$ for Memory 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 Memory and Grid of Stickers, $p < 0.001$ for Puzzle).

Discussion
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 Puzzle activity was significantly lower than the Memory and Card Sorting activities. We observed that many participants hesitated before reaching for a puzzle 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, 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 trajectory 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 Memory, many participants selected tiles from alternating sides of the table, perhaps thinking that matching pairs would not be placed next to each other (although all tiles were randomized).This led to frequent left-right movements. The small *z-dispersion* for the Puzzle 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 a visual search, often leading to 'Aha!' moments. These moments caused participants to quickly touch stickers that were difficult to find, resulting in sharper motion. If an activity is intended to minimize intense movements, it may be beneficial to avoid 'surprise' elements that trigger such motion.

Conclusions and Future Work
Our 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 naively 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 are actually producing the desired effect.

The results of this study have allowed us to improve the existing activities so they best meet both therapist and patient needs. The interactive tabletop (and activities) is currently in use in the Glenrose Rehabilitation Hospital, and a clinical study with an adult stroke population is planned. We expect that this study will bring notable differences in the use of the activities due to the higher age of patients, the level of mobility, and motivational factors between the subject pools. We hope that the results of the current and future studies will further technology-based rehabilitation and provide more effective and engaging treatment options.

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