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A New Method to Evaluate Hand Function in Clients with Stroke: Test-Retest Reliability and Discriminative Validity

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Abstract

Background: A computer game-based upper extremity function assessment tool (CUE) has been developed to quantify object handling and manipulation skills of stroke patients with motor impairments affecting the hand and arm. The tool involves standardized, computer-guided tasks and was designed to be used with objects having a broad range of physical properties and functional demands.

Objectives: To determine the test-retest reliability and known group validity of the CUE.

Methods: Thirty stroke patients were assessed with the CUE on two separate occasions, one week apart.Ten object-manipulation tasks with different physical properties and functional demands were tested.CUE assessment performance measures included movement accuracy, movement amplitude, and response time. The Intraclass Correlation Coefficient (ICC) and minimal detectable change (MDC) values were computed to evaluate test-retest reliability. Twenty healthy adults were also assessed with the CUE, and performance measures were compared to the stroke participants (known group validity).

Results: Most CUE performance measures had high to moderate ICC values. Most MDC values were less than 15% of the group mean value. There was a highly significant difference in performance measures between healthy adults and stroke participants for all object manipulation tasks and performance measures.

Conclusion: This study demonstrates that the CUE assessment tool can reliably measure a function of a broad range of standardized computer-guided object manipulation tasks by stroke patients.

Introduction

The majority of stroke survivors report persistent motor impairment of the Upper Extremity (UE), in particular, manual dexteritydeficits in handling and manipulating objects [1-3]. Clients with stroke with mild to severe UE motor impairments benefit fromtask-specific therapy, such as constraint-induced movement therapy [4,5]. One-to-one supervised therapy is preferred but is challenging to deliver due to the early discharge of clients and financial/human resource pressures. Unforeseen situations (e.g. social distancing imposed by the COVID-19 pandemic) can further complicate this process. Increasing accessibility is perhaps the mostfeasible approach to overcoming these challenges. Ideally, this should be done by providing the means to transition effective therapy programs to client homes, including those in rural communities [6]. There is a need for innovation not only to increase accessibility but also to improve compliance with long-term tedious exercise regimes [7]. An emerging approach to increase participation in therapyis to incorporate computer game–assisted exercise methods in which a range of interactive challenges help to engage in repetitive motor activities.Studies have provided evidence thattask-specific exercises combined withvideo games can improve clients' motor skills [8-10].

Based on this information a computer Game-assisted Telerehabilitation Platform (GTP) has been developed [10-12]. The GTP was designed to transition stroke UE rehabilitation programsto homeandpermit extended, regular practice at times that are convenient for the clients using it. The GTP includes an embedded computer game-based upper extremity (CUE) assessmentsubsystem that provides a standardized method to quantify the motor performance of a broad rangeof object manipulation tasks and exercises [13,14]. The CUE assessment tool automatically logs the client's movement responses during goal-directed object manipulation tasks and computes various outcome measures, such as success rate, movement error, movement response time, and movement variation [15,16]. It is important to obtain objective outcome measures and track changes to guide and progress individualized home programs. Therefore, exercise programs delivered in the home (and within rural communities) can be monitored and managed regularly by clinicians.

The first objective of this study was to examine the test-retest reliability, specifically for several goal-directed object manipulation tasks. It was hypothesized that CUE performance measures exhibit high test-retest reliability. Group comparison between stroke and healthy

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Figure 1. Illustration of object manipulation task and description of movements involved

adult participants was also conducted to establish known group validity of the CUE assessment performance measures.

Methods

Inclusion criteria for participation included the following :a) Adults who experienced a single hemispheric stroke in the past 18 months,b) age 50 to 70 years,c) adequate vision to see required images on a standard computer monitor, d) able to score 26 or greater on the Montréal Cognitive Assessment scale (MoCA) [17]. Exclusion criteria included the following; a) participants with spasticity levels at fingers and wrist of 3-4 on the Ashworth scale [18], b) diagnosis of any other neurological disease, and c)any musculoskeletal injury or disorder affecting UE function. Healthy adults, aged 50-70 years with no known neurological or musculoskeletal disorder/injury, were also recruited to perform the object manipulation tasks and to examine known group validity. All participants spoke English and provided written consent. Theresearch ethics committee at the university approved the study.

Tests and Instrumentation

A miniature, wireless Inertial-Based (IB) computer mouse (e Scoop™ Pointer Remote Model: RXR1000-0302E, Hillcrest Labs) was secured using Velcro to seven test objects described below.

The IB mouse is a wireless, plug-n-play computer mouse that records instantaneous angular position. When the IB mouse is attached to a "test" object, the manipulation of the object is then used to control the motion of a computer cursor or game paddle. Importantly, the IB mouse can be attached to a broad range of objects with different physical properties (size, shape, weight degrees of freedom) and anatomical demands (manipulation using a 2-finger grip, whole handgrip, bi-manual) [10]. Figure 1 presents the seven objects chosen for the present study.

A computer application with two assessment modules was used to guideand assess the object manipulation tasks: a) the Cyclic Tracking module, and b) the Motor Skill game module [10,13,15].

1. Cyclic Tracking task: This test involves tracking a visual target that moved horizontally left and right or vertically up and down on a computer display for several cycles. Figure 2 presents a screenshot of the cycling tasks. Two cursors of different shapes appear on the monitor. As shown in Figure 2 the target object is a bright-colored circle; its

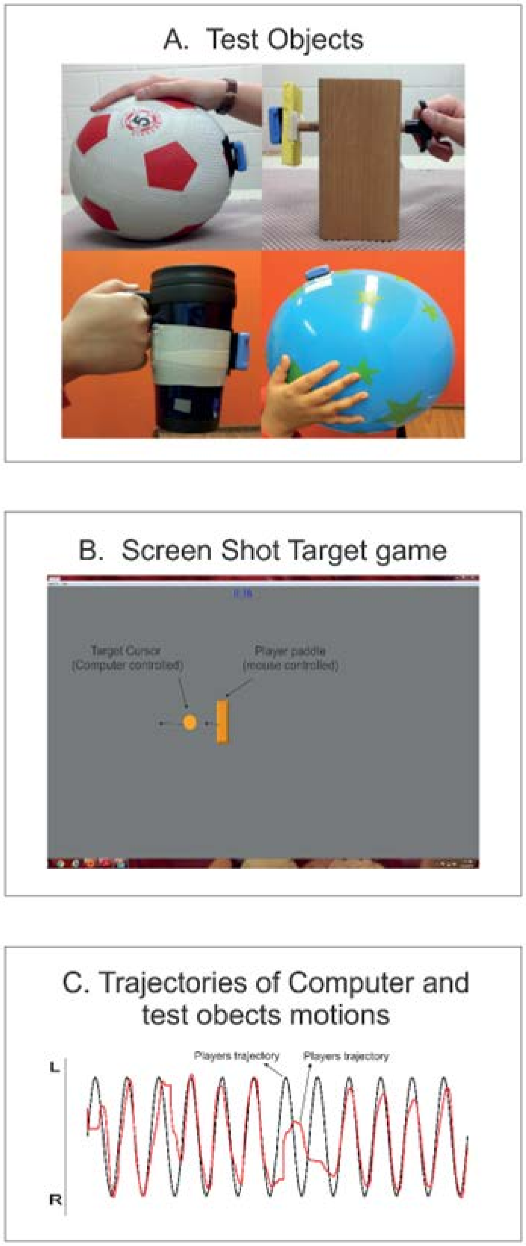

Figure 2. Illustration of the Cyclic Tracking task and software. The top panel presents one test object instrumented with an inertial mouse. The middle picture is a screenshot of the Cyclic Tracking task showing a circle target object (computer controlled) and a rectangle (slaved to the motion of the test object). The bottom plot presents synchronous plots of the (circle object) target cursor motion and user movement trajectories (rectangle object) while rolling the soccer ball

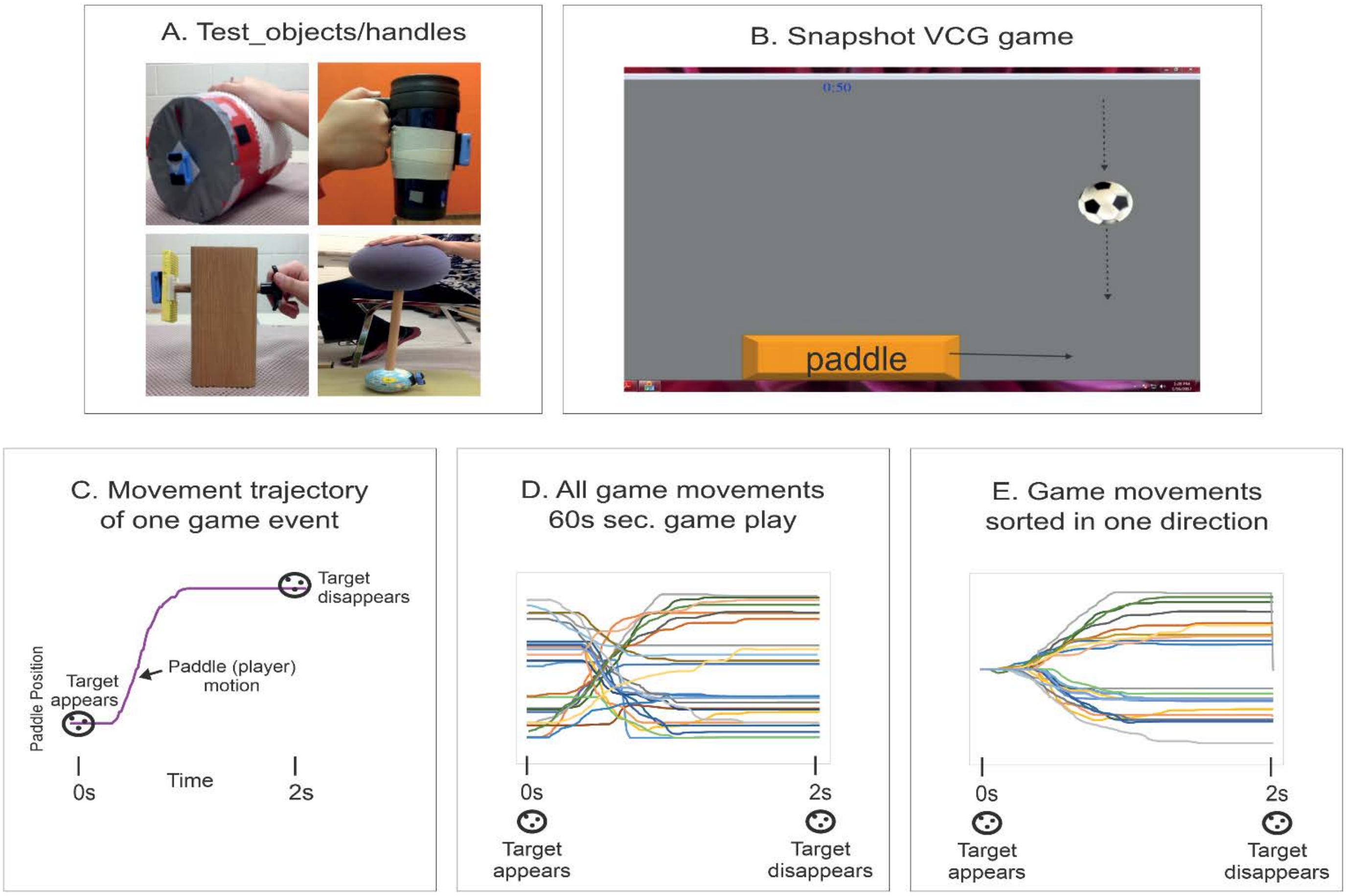

Figure 3. Illustration of the Motor Skill game tasks and Software. Panel A is a picture of one test object instrumented with the inertial mouse. Panel B is a screenshot of the Motor Skill game showing the target object (computer-controlled) and game paddle which is moved by rotation of the test object (IB mouse). Panel C presents the trajectory for one game movement response from target appearance to target disappearance (duration of 2 seconds). Panel D presents typical trajectories of game paddle coordinates of game movement responses for one game session recorded from one healthy adult and one stroke participant. In this example, each game event takes 2 seconds (target appearance to disappearance) and the game was played for 30 seconds. The location of successive target appearances is randomized, and approximately half of the 30 game events occur in each direction. The game movement responses shown in Panel D are for leftward rotations. *Y*-axis scale is in percentage (%) of display width

motion is computer-controlledandmoves at a predetermined frequency of 0.5 Hz and an amplitude of 70% of monitor width/height. The second is a rectangle-shaped object which is "slaved" to mouse motion, and therefore directly to the object motion. Participants were instructed to manipulate the test objectand movethe rectangle cursorso it overlaps the moving circle targetfor45 seconds or 22 repeated back and forth movements. The computer application records the position coordinates of the circle target and rectangle cursor at a sampling rate of 100 Hz for the offline analysis described below.

2. Motor Skill game: The software presents a target object appearing at random locations at the top of the display. It moves to the bottom of the display within two seconds and then disappears. One game event is defined as the time between the appearance of a target and its disappearance. The participantmanipulates the mouse-equipped test objectsto move the game paddle and catch the moving target objects. Figure 3 presents a screenshot of the CUE gameand a plot of the trajectory of a typical paddle movement (motion of the test object) of one gameevent. Each game was played for 60 seconds and, therefore, 30 game movement responses are recorded for analysis.One-half of the game movements are in one direction while the other half are in the opposite direction. For example, for the mug test object, one-half of the movement would be supination movements and the other half pronation. The computer application records the position coordinates of the target game objects and the game paddle at a sampling rate of 100 Hz for the offline analysis described below.

Sixty degrees of mouse/object rotation would move the game paddle (Motor Skill game) or tracking cursor (Cyclic Tracking task) from the left edge to the right edge of the display. Forty degrees of mouse/object rotation. Would move the game paddle or tracking cursor from the top edge to the bottom edge of the display. This setting was the same for all participants with stroke and healthy able-bodied control.

Protocol

Participants attended two assessment sessions, oneweek apart.The tests were performed on the same day of the week and at the same time in the morning between 10-12am orafternoon between 1-3pm. The first session included the administration of the Wolf Motor Function Test (WMFT) [19] and the CUE. Participants were seated at a table with adjustable height. Each of the test objects was placed on the table at a comfortable reaching distance. A 50 cm computer monitor was placed 1.5 meters in front of the participant at eye level, which displayed the game tasks.The participants were instructed to "rotate the test objects and move the game paddle to either track or catch the moving target objects.Participants were given a few practice trials to become familiar

Table 1. Demographic and Clinical Data

Number of Participants	30
Women/men	10/20
Age in years (mean (SD)	64.4 (±11)
Time since a stroke in months	16 (±7)
Ischemic/Hemorrhagic Stroke	25/5
Fingers and Wrist spasticity (Ashworth) – Median (range)	-1+ (1-2+)
Time in seconds to complete WMFT Mean (SD)	282.21 (±112)

with the game tasks. Most participants were quite familiar with using a computer mouse to point and click, and many had played some computer games before. Participants were also instructed not to use the movement of other body segments (i.e., associated movement). For example, care was takennot to allowtrunk motion to move the cylinder or ball forward and backward but instead to use elbow and shoulder movements.

Data Processing and Outcome Measures

Cyclic Tracking Performance: Figure 2 presents synchronous plots of the target motion (circle cursor) and that of the mouse-equipped object rotation (rectangle cursor) for a typical tracking task. The following performance measures were quantified:

1. Total Residual Error (TRE): The distance between the Target and Game cursors (residual error) was determined for each sample period (100 Hz), and summed for 45 seconds. Units are expressed in percentage of screen width/height.

2. Amplitude Variation (AV): The movement amplitude for each half cycle (movement direction) was determined. The average movement amplitude and standard deviation of the movement cycles were then computed. The coefficient of variation (COV) of the movement amplitude was computed as the standard deviation divided by the mean amplitude and expressed as a percentage of 100%.

To note the first two cycles are not included in the computation of either TRE or Amplitude Variation as it often takes one or two cycles for the subject to begin the tracking task.

Motor Skill Performance Measures: figure 3 presents the trajectory of an individual game movement response. Each game event was 2 seconds in duration, i.e., from target appearance to disappearance. Based on time indices of target appearance and disappearance the software segments all 30 game movement trajectories for each 60-second game trial. One-half of the game movement responses were in each direction. Figure 3 Present overlay plots of all game movement responses in each direction for one game trial. For a detailed description of the game movement, indexing, and segmentation, see Lockery, et al. [6]. The following performance measures were quantified:

1. Success Rate (SR): it is the percentage of the total number of Target Objects that were caught in one game trial.

2. Average Movement Onset Time (MOT): it is the time from the target appearance to the start of the game paddle movement. Values for MOT time are determined for each individual game movement response, and then the average is computed over the group of game movement responses for each direction.

Statistical Analysis

The normality of the data was checked using the Shapiro-Wilks Normality test. Results determined the data was normally distributed. Relative reliabilitywas assessed using a two-way random model intra-class correlation coefficient (ICC).The ICC scores were considered to be high when equal to or greater than 0.70, moderate between 0.5 and 0.69, and low when less than 0.50 [20]. Absolute reliability was analyzed using Minimal Detectable Change (MDC) [21]. Minimal Detectable Change was calculated with the following formula:MDC = Standard Error of Measurement times 1.96 times the square root of 2.Systematic errors between the test periods were evaluated using a paired t-test.Known group validity was evaluated using an unpaired t-test. For these twenty stroke participants were randomly selected from the group of 30 stroke participants and their performance measures were compared with those obtained from the 20 healthy able-bodied controls. SPSS software for Windows, version 20.0 (SPSS Inc.) was used for all statistical analysis procedures. The statistical significance level was set at alpha less than 0.05.

The sample size for this study was computed using Table 1 from Zou, et al. [22].Thirty participants were required for an intra-class correlation coefficient (ICC) value of 0.8, assurance of 70%, and class interval half-width of 0.15.

Results

Thirty clients with stroke (mean age, 64.4 years (±11) and20 healthyable-bodiedadults (mean age, 58.6 years (±7) participated in the study. There were 10 females and 20 malesin the stroke group, and there were 7 females and 13 males in the healthy control group. Table 1 presents the clinical features of the participants.

Table 2 presents the results of the statistical analysis of relative and absolute reliability of the cyclic tracking outcome measures. Following is the summary of thefindings for Total Residual Error (TRE):

1. Test-retest reliability was high (ICC > 0.7) for the cylinder, mug, and soccer ball, and wasmoderate (ICC between 0.5 and 0.7) for the 2-finger fineandthe bilateral tasks.

2. Minimal detectable change as a percentage of group mean value (MDC%) ranged from nine to 16% and was less than 12% in all but one object manipulation task.

The following summarizes the findings for Amplitude Variation (AV):

1. Test-retest reliability was high (ICC > 0.7) for cylinder and 2-finger fine task, andwas moderate (ICC between 0.61 and 0.7) for the soccer ball, mug, and bilateral task.

2. MDC% ranged from 11 to 19%.

Table 2. Results of statistical analysis, ICC scores, group means and standard deviation (SD), Minimal Detectable Change (MDC), and paired t-test p-value for Total Residual Error (% display width/height) and Amplitude Variation. (Coefficient of variation)

Object	ICC	Mean (SD)		MDC (MDC %)	t-test (p-value)
		Test 1	Test 2		
Total Residual Error					
Cylinder	0.81	22.1 (5.1)	22.6 (5.8)	2.6 (11.85)	0.56
Soccer Ball	0.72	24.7 (5.0)	24.2 (4.9)	3.0 (12.26)	0.65
Coffee Mug	0.87	24.0 (5.5)	23.5 (5.7)	2.8 (11.71)	0.57
2- Finger Fine	0.62	22.3 (3.9)	22.4 (5.2)	2.0 (9.09)	0.94
Bimanual- ball	0.56	19.4 (6.2)	21.6 (5.8)	3.2 (16.36)	0.09
Amplitude Variation					
Cylinder	0.76	22.7 (7.0)	23.3 (7.8)	3.6 (15.93)	0.65
Soccer Ball	0.65	28.3 (12.3)	30.3 (12.2)	5.5 (19)	0.61
Coffee Mug	0.61	26.6 (9.74)	28.1 (12.5)	2.9 (11.21)	0.31
2-Finger Fine	0.71	26.6 (8.4)	25.7 (7.6)	4.3 (16.18)	0.54
Bimanual- ball	0.67	23.4 (9.0)	25.8 (9.2)	4.6 (19.66)	0.16

Table 3. Results of statistical analysis, ICC scores, group means and standard deviation (SD), Minimal Detectable Change (MDC), and paired t-test p-value for Success Rate (% of total number of game events); and Movement Onset Time (ms)

Object	ICC	Mean (SD)		MDC (MDC %)	t-test (p-value)
		Test 1	Test 2		
Success Rate					
Cylinder	0.72	84.7 (9.5)	85.6 (87.4)	5.4 (6.4)	0.16
Coffee Mug	0.67	83.6 (6.5)	81.7 (12.1)	6.6 (7.9)	0.34
2- Finger Fine	0.55	81.2 (8.7)	78.7 (15.2)	6.9 (8.5)	0.06
Whole Hand Fine	0.82	79.1 (12.7)	80.1 (13.1)	7.6 (9.6)	0.58
Joystick	0.8	83.5 (7.4)	83.7 (65.6)	4.2 (5.1)	0.85
Movement Onset Time					
Cylinder	0.65	0.80 (0.13)	0.82 (0.14)	0.063 (7.74)	0.69
Coffee Mug	0.61	0.77 (0.14)	0.74 (0.17)	0.071 (9.33)	0.45
2- Finger Fine	0.71	0.77 (0.19)	0.78 (0.19)	0.1 (12.67)	0.79
Whole Hand Fine	0.62	0.75 (0.14)	0.73 (0.18)	0.071 (9.58)	0.48
Joystick	0.6	0.90 (0.22)	0.82 (0.19)	0.113 (12.55)	0.12

Table 3 presents the results of the statistical analysis of relative and absolute reliability for the Motor Skill outcome measures. The following summarizes the findings for Success Rate (SR):

1. Test-retest reliability was high (ICC > 0.7) for cylinder, whole hand fine rotation, and joystick, and was moderate (ICC between 0.55 and 0.7) for mugand finger fine rotation.

2. MDC% was less than 6% for all five-object manipulation tasks.

The following summarizes the findings for Movement Onset Time (MOT):

1. Test-retest reliability was high (ICC > 0.7) for the 2-finger fine rotationtask, andwasmoderate (ICC between 0.6 and 0.7) for the cylinder, mug, whole hand fine rotation, and joystick.

2. MDC% was less than 12% for all five object manipulation tasks.

There was no significant difference in group meansbetween test 1 and test 2 for any performance measure.

Figure 4 presents the group means and standard error of the mean for the CUE performance measures by group, and presents the results of the t-test. With two exceptions, performance of the seven CUE object manipulation tasks wassignificantly better in the healthy able-bodied group as compared to the stroke group. A similar trend, improved performance of the healthy able body group was observed for the two exceptions, Success Rate of the cylinder and whole hand fine motor task (p < 0.06).

Discussion

Test-retest reliability and known group validity of the CUE assessment tool were evaluated using several object manipulation tasks. Moderate to high ICC values, and relatively low MDC scores were observed for the majority of the performance measures.

The seven manipulation tasks tested in the present study were chosen to span a broad range of functional properties and anatomical requirements. All manipulation tasks required finger-thumb or hand palmer surface contacts and involved various combinations of precision wrist, elbow, and shoulder motions. Rolling the cylinder and soccer ball forward and backward were similar and involved a combination of shoulder and elbow flexions and extensions while keeping the hand in contact with the surface and the fingers extended. While the cylinder could only rotate about one axis, the soccer ball can move in multiple directions. Thus, when rolling the ball forward and backward any off-axis rotation or slipping of the hand sideways off the object would need to be prevented, i.e., additional degrees of control and coordination by internal-external rotators and abductors-adductors. Unlike the cylinder and soccer ball which were supported by the table, there was no support for the coffee mug during its manipulation by pronation-supination. Irrespective of the increased degrees of freedom of the soccer ball and coffee mug tasks, the ICC and MDC values were similar. Performance measures of the 2-finger and whole hand fine precision rotation tasks also had high to moderate ICC values. These fine rotation tasks employed a simple crafted object, chosen to eliminate object mass.

There are differences between the Cycle Tracking and Motor Skill tasks. The Cyclic tracking tasks were predictable, several repeated cycles of back-and-forth movements at a fixed frequency and amplitude (user defined). Whereas the Motor Skill game task required precision ramp movements of variable amplitude and directions (random presentation), two performance-based outcome measures were quantified for each game. These performance metrics represent different features of goal-oriented (contextual) movement responses and different aspects of the processing involved. Total residual error and variation in movement amplitude, which were measured over multiple repeated cycles, are measures of the magnitude of movement error and movement consistency or reproducibility. The performance measures of the Motor Skill game quantify; a) success rate, which represents goal attainment, and b) the time to initiate a motor action, which represents information processing and motor planning time. In the present study, the duration of each Motor Skill game event lasted 2 seconds and the game was played for 60 seconds, therefore, thirty contextual movement responses are recorded for analysis of Success Rate and the average Movement Onset Time.

A number of upper extremity function tests are available, such as the Box and Block test [23], the Wolf Motor Function Test [24], and several pegboard test [25]. These tests measure hand function by the time taken to complete several tasks. Time taken to complete

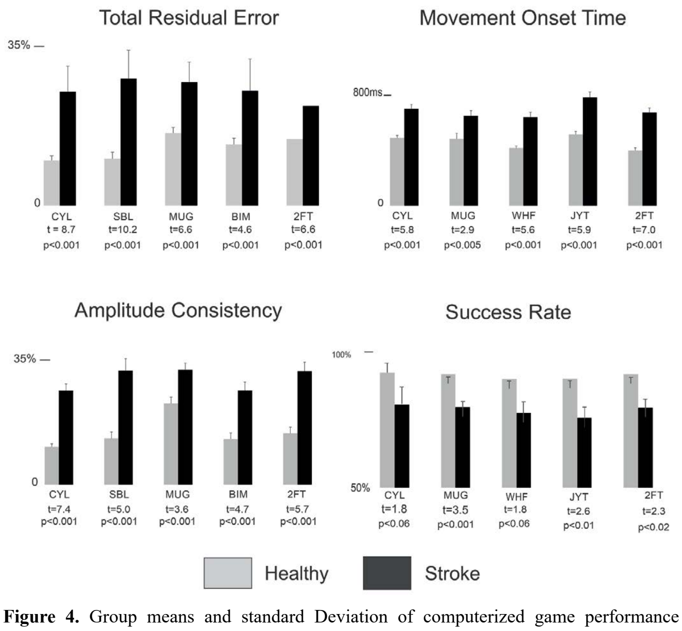

Figure 4. Group means and standard Deviation of computerized game performance measures of object manipulation tasks for a) Tracking task Total Residual Error and Amplitude Consistency and b) Target game, Success Rate, and Response Time. Results of t-test comparisons between the healthy control and the clients with stroke groups are presented for each object manipulation task

a task does not provide performance information about a number of motor control metrics, such as response time, movement errors, and movement variation. Other assessment tools use therapist observation of task completion, such as the Action Research Arm Test [26]. In this test, the client is required to move several objects of different sizes and shapes from one location to another. They are also asked to move their arms to different resting positions, which include the top of their head, behind their head, or to their mouth. Performance is rated on a 4-point scale, ranging from no movement to movement performed normally and without lengthy delays. The above tests [23-25] use average/total time to complete several tasks, or in the case of the Action Research Arm Test, a composite score is computed. These outcome measures do not provide information about performance on any one object manipulation task. In addition, the above-mentioned assessments are limited to a narrow range of objects and tasks, for example, blocks, balls, pegs, coins, pens, and cans.

A number of gaming systems have been used as rehabilitation tools for assessment and treatment. These include commercial entertainment gaming systems like the WII [27] and the Kinect [28], as well as the Leaps 3D depth camera [29] and sensor-equipped gloves [30]. These gaming systems detect and quantify arm segment motions or finger motions. The corresponding segment motion signals are used to interact with virtual avatars/objects or to control a game paddle for play. However, these systems have limitations, in particular, these gaming devices do not target object handling and manipulation. Therefore, there is no sensorimotor processing of skin tactile sensory information regarding the stability and slip of moving objects [31-33]. The present CUE assessment tool targets object handling and manipulation to extend the utility beyond gross reaching or finger movements since the ability to perform manual dexterity skills with the hands is very much an integral part of everyday life, in particular, precise, timely accurate movements. Other assessment systems use inertial motion monitors, in particular linear acceleration [34,35]. Acceleration time series data from a body segment or an object can be used to determine, time to complete a movement or an estimate of movement smoothness. However, this data does not provide information about movement context of precision object manipulation tasks, such as goal attainment, and amount of movement error. In addition, gaming input devices that use linear acceleration, such as the iPhone [36] cannot be used to play common commercial games, the vast majority of commercial games require instantaneous position signals for game interaction, i.e., use of standard optical mouse or IB mouse.

The CUE assessment tool has a number of advantages over the assessments described above. The interactive CUE software provides several different standardized computer-guided activities, time constraints, and analysis procedures to objectively quantify several motor performance metrics. Importantly, the CUE assessment tool allows one to test many objects with varied physical and functional demands. Hundreds of objects of different mass, shape, and size, and surface friction can be changed to function exactly as a computer mouse simply by attaching the miniature motion mouse using Velcro. Objects can be chosen to be handled with 2-finger grip, 3-finger grip, whole hand and both hands, as well as to incorporate a combination of wrist, elbow, and shoulder motion. A thorough knowledge of objects and their geometrical properties, functional and anatomical demands, will help to set specific treatment goals and to obtain objective outcome measures, and monitor progression.

As expected, the group comparison revealed significant differences between healthy adult and stroke groups in all performance measures. As evident from the group means and standard deviations presented in Figure 4, the differences were substantial, for example, the Total residual Error increased by a factor of at least 2 in the stroke group, and average Success rate of the stroke group ranged from 78%-85% as compared to 90%-95% in the control group.

Limitations

One main limitation of the CUE assessment tool is that it requires an inertial-based computer mouse and computer. There are several fine motor skills that cannot be assessed using the CUE assessment tool, such as tying shoelaces, buttoning, and unbuttoning. Another limitation is that the inertial-based mouse detects angular motion, therefore, it is not possible to practice tasks that require only linear motion.Since the CUE assessment toolmeasures participants' motor performance in a given object manipulation task, this fits the ICF model for assessing the level of activity but not the level of participation.

Conclusion

The moderate-to-high ICC values, MDC % values below 20 percent, and lack of systematic errors in the measures indicate that this tool has the ability to repeatedly record reliable data of individuals who have suffered a stroke. The present broadens the range of testing tools that have previously been reported.Hundreds of objects can be instrumented with the IB mouse and used to assess object manipulation tasks required in daily life. In addition, the game activities of the CUE assessment tool have specific goals and time constraints which can be adjusted. The speed of the game objects, paddle size, and movement amplitude can be varied depending on the task requirements and level of impairment.A thorough knowledge of objects and their physical properties and functional demands will help to set specific treatment goals and to obtain objective outcome measures and monitor progression.

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