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Novel Therapeutic Game Controller for Telerehabilitation of Spastic Hands: Two Case Studies

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***Abstract*—Spasticity or increase in muscle tone presents challenges during post-stroke rehabilitation. The use of off-the-shelf game controllers is problematic for individuals with hand spasticity. The novel BrightBrainer Grasp (BBG) controller was designed to overcome these barriers when used in virtual rehabilitation of individuals post-stroke. The custom controller measures power grasp, finger extension, wrist position and orientation, as well as 3D hand position. It is designed to minimize friction when used by those with no gravity bearing. Two controllers were used in bilateral training. This paper presents a detailed description of the BBG controllers and their interaction with the BrightBrainer™ gaming system. Two case reports of individuals chronic post-stroke who participated in a 4-week telerehabilitation intervention are included.**

Keywords—BrightBrainer Grasp, stroke, telerehabilitation, game controller, spastic hand, power grasp, finger extension

I. Introduction

Movement impairment is a common sequela post-stroke with upper extremity (UE) disability severely impacting independence in daily life activities [1]. More than 80% of stroke survivors present with UE impairments [2]. Increase in muscle tone or spasticity complicates post-stroke movement recovery especially in those who reach the chronic phase [3].

Spastic UEs present unique challenges for game-based rehabilitation [4]. Spasticity can create involuntary forces that cause flexion at the elbow and wrist. This makes using off-the-shelf controllers extremely difficult and occasionally counter-productive due to increased spastic activity. To overcome these forces, the controllers need to have proper positioning with strong materials, strapping and be light weight. Game-controllers developed to date are not able to provide freedom of movement while providing adequate position control [5]. Additionally, spastic muscles are weaker than muscles with normal muscle tone [6]. The game controllers need to provide adequate forearm support over a surface for arms that cannot move against gravity. As UEs start developing movement control, the controller also needs to be able to allow the arm to lift off the supporting surface, so to improve reach. The controllers thus need to be lightweight and cause minimal friction when dragged on a table. Commercially-available controllers do not provide this level of functionality [5].

Distal UE control and hand dexterity are much delayed compared to proximal control during recovery [7]. As hand control develops, functional movements that can be meaningful in daily life include grasping, releasing objects (as in finger extension), and arm/wrist rotation. These movements, while essential to meaningful recovery of the hand, are not easily mediated by current off-the-shelf game controllers.

Developing virtual reality (VR) gaming technology which can be used with spastic hands, and also done at home without a therapist present, is even more challenging. In such settings game controllers need to be simple to don/doff with minimal assistance, need to be adaptable to spastic fingers, have few buttons, and need to be integrated with a computer to upload gaming performance to the cloud.

Bright Cloud International Corp. had developed the BrightArm Duo robotic table for training grasp under gravity modulation on a low friction table. It was used for training sub-acute and chronic stroke survivors [8, 9]. Research presented here details the novel *BrightBrainer Grasp* (BBG) therapeutic game controller [10], and case reports of two individuals who used it in a home telerehabilitation intervention.

II. Methods

A. BrightBrainer Grasp Therapeutic Game Controller

The BBG forearm attached game controller (Fig. 1a) measured power grasp, finger extension and wrist position and orientation, as well as 3D hand position. In order to facilitate supported arm movement (needed for weak arms) while also

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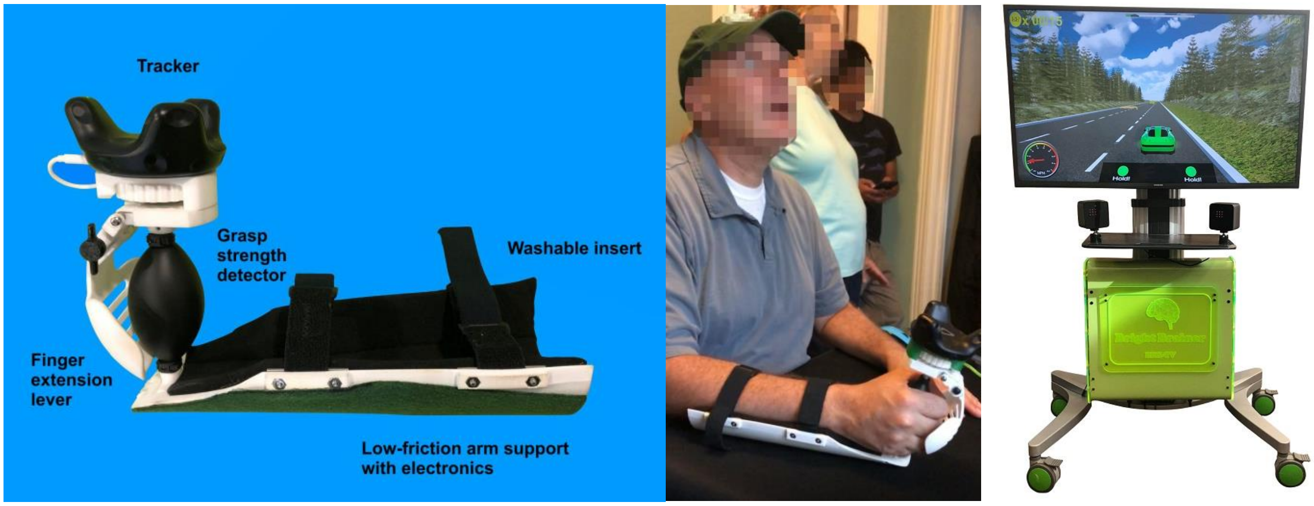


a) b) c)

Fig 1. Telerehabilitation setup: a) BBG therapeutic controller [10]; b) Case 2 training at home while resting his affected arm on a low-friction mat; c) the BrightBrainer System © Bright Cloud International. Reprinted by Permission.

allowing forearm pronation/supination, the BBG had a rounded sled. Position tracking was provided by an embedded HTC VIVE Wireless Tracker (HTC Model# 99HANL002-00). It had a compact form factor (320 grams) and was powered via a micro USB cable connected to the controller electronics block.

The tracker was mounted with a regular DSLR camera mount (1/4-20 tripod) screw on top of a custom support. This support integrated a finger extension detection mechanism and a stainless hollow central tube mounted to its underside. The other end of the tube connected to the forearm curved sled through a one-degree-of-freedom rotary joint. This design accommodate varying wrist yaw angles present in spastic hands.

The finger extension detection mechanism was a custom lever with a curved surface matching the outer shape of a fist. This lever was designed to be moved by any extending finger. Thus global finger extension was detected, without specific finger information. A rotary sensor embedded in the joint of the lever measured the degree of lever movement away from the fist. Small return springs embedded in the structure ensured positive contact with the back of the fist, so to detect small extensions. Closed hand fingers wrapped around a central rubber pair mounted coaxially with the supporting tube. This created an air chamber with a pressure sensor inside the forearm sled.

The supporting forearm sled has three major components: 1) a rounded plastic shell which attaches to the user's forearm using Velcro strips; 2) an electronics board with rechargeable batteries and wireless transmitter; and 3) a detachable pad that provided comfort to the user's forearm. The total weight of the BBG was about 570 grams, which did not hinder movement for those with higher motor function. Those with diminished or no gravity bearing could still use the BBG, as long as it was supported by a low-friction table or a low friction mat. More details on the BBG therapeutic controller may be found in [11].

Two BBG controllers (one for each arm) were interfaced with a BrightBrainer™ rehabilitation system (Fig. 1c) which included a medical grade computer, a large 40" display and a cart for mobility. BrightBrainer communicated with each controller wirelessly, receiving data on finger grasp force and extension angle. The BrightBrainer used in this feasibility study was a BBX ("BrightBrainer Exerciser") version which replaced the Razer Hydra [12] used in earlier models with an HTC VIVE system. Two VIVE "lighthouse" cubes illuminated the HTC Trackers embedded in the BBG controllers, and tracking information was received by a VIVE Head Mounter Display (HMD) placed inside the computer enclosure. The HMD, in turn transmitted the information to the PC, where it was combined with finger extension and power grasp information so to control avatar objects in the therapeutic games.

B. Serious games to train grasp strength and finger extension

BrightBrainer software had an artificial intelligence (AI) component that adjusted games based on each individual's motor and cognitive abilities. Before each session, a motor baseline was completed to determine each arm reach horizontally and vertically, as well as arm pronation/supination.

BrightBrainer baselines, when used with the BBG controllers, incorporated grasp and finger extension baselines. The grasp baseline was designed so to remove residual pressure due to involuntary finger pressure on the rubber pair. An average pressure reading was performed for three voluntary grasps, counting only pressure above the residual value. A percentage of this average was used by the game software to detect finger extension for that particular user.

For finger extension baseline, the initial position was determined when the user was told to close the fist. Subsequently, three readings were taken during maximum voluntary extension, and then averaged. A percentage of this average was then used by the game software to detect finger extension for that particular user.

The above baselines were meant to adapt games to each user, no matter the degree of motor impairment. This ensured that BrightBrainer games were winnable even by individuals with severe motor deficits. Additionally, the AI read previous game performance data and adjusted game difficulty to provide winnable game settings for users with different cognitive capabilities. When a user had repeatedly succeeded and passed benchmarks for a particular game, the AI increased that game difficulty, so the user was always challenged. Conversely, had a user failed two times in a row at a particular difficulty setting, the AI lowered the difficulty so to increase chances of success.

The library of BrightBrainer therapeutic games that used the Hydra had been previously described [13]. However, the addition of grasp detection and finger extension functionality required that the software be modified. With BBG control, object avatar activation now required grasping (Fig. 2a). Conversely, resetting an activated object now required finger extension. What follows is a sub-sample of games used in the study and their modification for BBG control.

Car Race (Fig. 2b) trained arm pronation/supination, grasping, finger extension and reaction time. The player drove a car avatar through a race course while avoiding different obstacles. Obstacles included roadblocks that stopped the car, sand pits that slowed it down, oil spills that caused loss of control until both hands pronated/supinated to regain control, and traffic intersections that required a stop at the red light. To accelerate, users extended their fingers, while braking required that the user grasp the rubber bulb. Changing lanes was done when both arms pronated or supinated. Difficulty was modulated through obstacles number/type, as well as car speed.

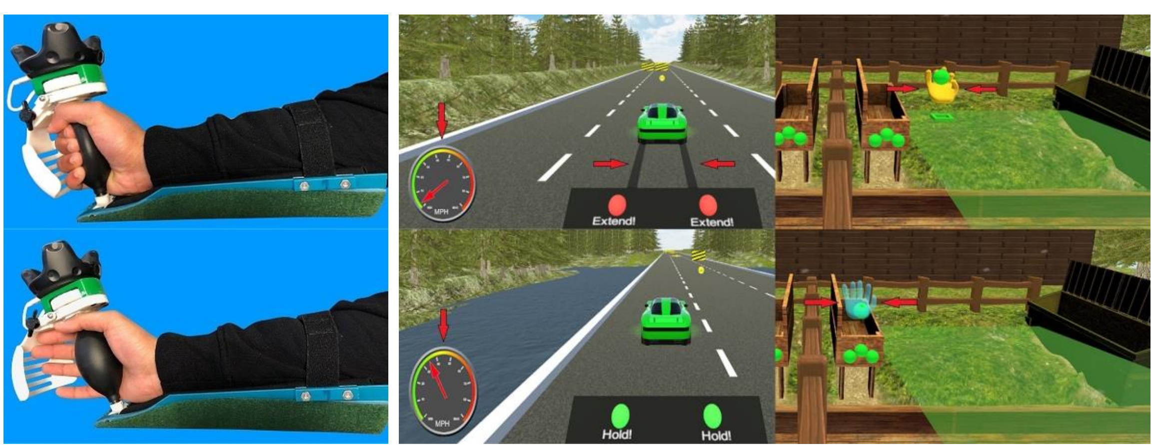
Catch3D (Fig. 2c) was a sorting game that trained grasping, finger extension, executive functions and reaction time. The user controlled hand avatars to catch falling objects. Objects had different shape and color combinations. Bins with associated specific shape and color combinations were used in sorting of objects with the same shape and color as the bin. Objects that did not match had to be placed in a garbage bin. At higher difficulty levels, wind made objects drift from vertical. Users had to predict where falling objects would land and catch them in time before falling to the ground. Additionally, users needed to squeeze the bulb right as the object touched the hand avatar, so to catch it. To drop a caught object, users had to move their hand over a bin and then extend their fingers.

C. Cases

The two cases described here were part of a group of n=8 individuals chronic post-stroke living at home who took part in a telerehabilitation feasibility study. The two cases were the only two who trained with the BBG controllers and their characteristics at baseline are shown in Table I.

Case 1 was a 56 year old female with dominant right hand affected by a stroke which occurred 6 years prior to enrollment. She presented with severe spasticity in her right hand, and her neutral position had the affected arm pronated. As a consequence of the limited active range of her hand, her initial Fugl-Meyer UE [14] score was 25/66, indicating severe impairment [15]. This participant also complained of weakness in her affected hand, and her fingers were flexed in relaxed position. She ambulated with a brace for improved stability and complained of cognitive issues following stroke. At screening, her score on the Montreal Cognitive Assessment test (MOCA) [16] was 24/30, indicative of mild cognitive impairment.

Case 2 was a 48 year old male with dominant right hand affected by a stroke which occurred more than 17 years prior to enrollment. He was higher functioning in the motor domain than Case 1, with an initial Fugl-Meyer score of 43/66, indicative of mild impairment [15]. He was in good physical shape, attended gym regularly, and did not think he would benefit from the telerehabilitation intervention. Case 2 presented with circulatory problems in the lung for which he had a filter to prevent embolism. Furthermore, his stroke resulted in a vision cut in the left field, for which he was wearing special corrective glasses. His baseline MOCA score was 22/30, indicative of mild cognitive impairment as well.



a) b) c)

Fig 2. BBG game control: a) Grasping and extending to change avatar states; b) *Car Race* braking (when grasping) and accelerating (when extending); c) *Catch 3D* catching a falling object (grasping) and releasing in a matching bin (extending). © Bright Cloud International. Reprinted by Permission.

TABLE I. CASE DEMOGRAPHICS AND MEDICAL HISTORY AT ENROLLMENT. © BRIGHT CLOUD INTERNATIONAL. REPRINTED BY PERMISSION

Case	***Age***	***Gender***	***Race***	***Education*** (years in school)	***Dominant Arm***	***Affected Arm***	***Years post stroke***	***Fugl-Meyer score*** (more is better)	**MoCA Score** (more is better)
1	56	F	Caucasian	14	Right	Right	6	25/66	24/30
2	48	M	Caucasian	19	Right	Right	17	43/66	22/30

D. Data Collection Instruments

This feasibility study followed an ABA protocol, where data were collected at baseline (A), during training sessions (B), and post telerehabilitation intervention (A).

Each clinical evaluation session consisted of standardized measures of motor impairment, motor function, cognitive measures, language assessments and depression severity.

Motor impairments were assessed using goniometers for active arm and fingers range of movement, a mechanical Jamar dynamometer for grasp strength, Jamar pinch gauge for pinch strength and calibrated wrist weights for shoulder strength.

Motor UE function was measured with Jebsen Test of Hand Function [17], the UE subset of the Fugl-Meyer test, Chedoke Arm and Hand Inventory [18], for bimanual activities, and the Upper Extremity Functional Index [19] for self-reported independence in activities of daily living (ADL).

Emotive and Cognitive measures were the Beck Depression Inventory II [20], the Brief Visuo-spatial Memory Test, Revised [21] for delayed recall, the Hopkins Verbal Learning Test, Revised [22] for memory, Neuropsychological Assessment Battery (NAB) Word Generation subtest of the Executive Functioning Module [23]; and Trail Making Test A and B [24] for set shifting. Language was assessed with the Boston Naming Test [25] and the Verbal Fluency Test [26].

Subsequent to approval from Kessler Institutional Review Board, potential participants were screened for chronic stroke diagnosis, and cognitive impairments with MoCA test. Participants living in Central/Northern NJ were recruited together with their caregivers. This was done so that caregivers could assist in the home rehabilitation sessions, as well as provide valuable feedback on the BBG technology feasibility for home use. Subsequent to consenting, the two participants allowed the research team to inspect their homes, to gauge best equipment location, and to test the quality of home Internet.

Game Performance Data was automatically sampled at each telerehabilitation session. These data consisted of objective measures of performance in the motor and cognitive domains. Game motor variables measured during therapeutic game play were arm repetitions, grasp and finger extension repetitions, intensity of training (as in arm repetitions/minute, grasp repetitions/minute and hand extensions/minute). Game cognitive variable were session game average difficulty level, game average duration, as well as total cognitive exercise time.

A project portal was developed as well as remote graphing capability. This allowed researchers to log in, and remotely review individual's performance, by entering the participant-assigned code. Each session (once completed) was documented in a session report, which was also available for remote viewing by the clinical and engineering project staff.

Subjective evaluations used a 10-question subjective evaluation questionnaire. Questions ranged from enjoyment and clarity of game instructions to technical problems and arm pain while playing, to whether they would recommend the system to others. Each answer rated the system and experience on a 5-point Likert scale (1- least desirable, 5 -most desirable outcomes). Participants were asked to fill the form at the end of every telerehabilitation week, so to determine evaluation changes with harder games and recurring technical issues.

E. Experimental Protocol

Each home received a BrightBrainer system, a pair of BBG controllers, a large low-friction rubber mat and (for Case 2) a 6-foot wide table for support during training. Each participant and caregiver were instructed in the system use and their first session was assisted on-site by the team that installed the systems. Subsequent telerehabilitation sessions were either assisted remotely by a researcher, or done independently.

Each participant performed 5 sessions/week over one month, consisting of integrative games for motor, cognitive and emotive functions. Each session was started by measurement of blood pressure and pulse, something that was repeated mid-session and when the session ended. Readings were logged on the computer and on a paper binder. Sessions were set to increase in duration from 20 minutes of actual play per session (week 1), to 25 minutes (week 2), to 30 minutes in (week 3) and 40 minutes in the last week of training.

Sessions consisted of a combination of 4 different games played in week 1, 5 games in week 2, 7 in week 3 and 8 different games in week 4. Depending on the session duration, the sequence was repeated as needed. Each game difficulty progressed from easier games in weeks 1 to hardest levels in week 4. Difficulty was increased further when participants switched from uni-manual play in week 1 to bimanual interactions for weeks 2-4. Playing bimanually increased physical and cognitive effort, requiring split attention, task sequencing, and better hand-eye coordination.

At the completion of each game, its performance data parameters were uploaded on a Microsoft Azure cloud server under code. Subsequently, researchers occasionally called the home when graphs showed abnormal values.

III. OUTCOMES

The changes in the participant's motor impairments, motor function and degree of independence in activities of daily living

(ADLs), following the experimental intervention are summarized in Table II. The progression in the participants' game performance over the 4 weeks of training is shown in Table III. Finally, Table IV gives the subjective evaluation scores the participants gave the system using only 1 form for Case 1 and 4 forms for Case 2. Case 1 and her caregiver had either forgotten or refused to fill the first 3 evaluation forms.

A. *Case I*

Motor impairments Case 1 affected hand grasp strength progressed from 138 N pre-training to 172 N post (25% gain). Her pulp-to-pulp thumb-index pinch strength went from 18 N pre- to 21 N post- (17% improvement). The difference between active range of motion pre-to-post training was a 20° increase in thumb metacarpophalangeal (MP) flexion and 25° increase in middle finger flexion. There was no increase in index finger flexion, nor in the extension of thumb, index or middle fingers.

Motor UE function Case 1 UE function remained unchanged for her Fugl-Meyer score (25 pre and post), and she was unable to perform the Jebsen Test of hand Function due to her hand spasticity. There was however a gain in the ability to perform bimanual tasks, with an increase in the Chedoke score from 9 pre- to 11-post, a 33% gain. Furthermore, on the standardized subjective UEFI questionnaire she reported pre-training having no difficulty with only 3 out of the 20 ADL activities. At post- training evaluation she reported having no difficulty with 14 of the 20 tasks.

Emotive and Cognitive Pre-intervention Case 1 Beck Depression Inventory (BDI – II) score of 15 was indicative of mild depression. Post-training her BDI-II raw score was 11, showing a reduction in depression severity to minimal range.

The Neuro-cognitive evaluation showed a small gain in her executive function (NAB word generation raw score increased from 3 pre- to 4 post). While Case 1 set shifting was substantially worse post-training with an increase in the time needed for the Trail Making Test B from 107 seconds pre- to 133 seconds post-, her language abilities improved. Her Boston Naming Test increased slightly from T=8 pre- to T=9 post, and her Verbal Fluency Test showed an improvement from the impaired range (T=14) to borderline normal (T=17).

Game Performance Data in Table III shows that Case 1 progressed from about 275 arm repetitions in her first BrightBrainer uni-manual session to about 1900 bimanual repetitions in session 20. Her grasp repetitions went from 22 in session 1 to a maximum of 310 per session, while her finger extension counts went from 3 in the first session to a maximum of 342 combined left and right extensions per session. This increase in repetitions was not due only to the longer sessions, or to the fact that training went from uni-manual in week 1 to bimanual for the rest of the training. Case 1 ability to sustain a higher intensity of training is shown by the fact that her arm movement intensity went from 12 repetitions/minute in session 1 to 99 repetitions per minute. Grasping training intensity went from 1 grasp/minute to 8 grasps/minute, while finger extension frequency increased from less than 1/minute at start to a maximum of 8 extensions/minute. Her average game difficulty reached 3.5 (out of a possible 10 or 16 levels depending on game), indicative of challenges she faced in play.

TABLE II. CHANGES IN AFFECTED UPPER EXTREMITY IMPAIRMENTS, FUNCTION AND INDEPENDENCE IN ACTIVITIES OF DAILY LIVING OVER 4 WEEKS OF TRAINING WITH THE BBG THERAPEUTIC GAME CONTROLLER. © BRIGHT CLOUD INTERNATIONAL CORP. REPRINTED BY PERMISSION.

	Case 1		**Case 2**	
Outcomes	**PRE**	**POST**	**PRE**	**POST**
Motor Impairments				
Grasp strength	138 N	172 N (+ 25%)	208 N	196 N (-6%)
Pulp-to-pulp pinch strength	18 N	21 N (+ 17%)	25 N	28 N (+12%)
Thumb metacarpophalangeal (MP) flexion	0-30°	0-50° (+20°)	0-50°	0-60° (+10°)
Thumb MP extension	0	0 (+0°)	0-20°	0-30° (+10°)
Index MP flexion	15-60°	15-60° (+0°)	0-70°	0-75° (+5°)
Index MP extension	0	0 (+0°)	0-25°	0-30° (+5°)
Middle MP flexion	20-60°	20-85° (+25°)	0-80°	0-85° (+5°)
Middle MP extension	0	0 (+0°)`	0-25°	0-25° (+0°)
Motor Upper Extremity (UE) Function				
Jebsen Test of Hand Function	Unable	Unable	186 seconds	120 (-35%)* seconds
Fugl Myer UE score (66 max)	25	25 (+0%)	43	45 (+5%)
Chedoke Arm and Hand Activity Inventory score (63 max) bimanual	9	11 (+ 33%)	52	55 (+6%)
Upper Extremity Functional Index				
Tasks Unable to perform	7	5	0	0
Tasks present some difficulty	10	1	10	0
Tasks present no difficulty	3	14	10	20

*Reduction in Jebsen cumulative time is an improvement reflective of faster ADLs

Subjective evaluations Table IV shows Case 1 technology acceptance rating at the end of the training (week 4 was her only returned form). She disagreed that the system was easy to use, or that it was easy for her to play with both arms, and she disagreed that the games improved her stroke symptoms. She did not agree that there were few technical problems. Despite these negative ratings, she agreed that she was not bored while exercising, she agreed that she liked the system overall, and that in fact she would encourage other patients to use it (scores of 4). Her overall evaluation was 3.2 (slightly above neutral).

In her exit interview Case 1 was more positive, but thought the allowed 1 month of training was too short. She stated: *"This training was a very good thing ...In my opinion I liked it a lot, but you need more time to work with it."* Her caregiver echoed this opinion, stating *"You need like 6 months to a year."* The caregiver added that *"...she was able to think and move the right hand at the right time."*

B. Case II

Motor impairments Case 2 had a slight decrease in his affected hand grasp strength from 208 N pre- to 196 N post (-6%). His pulp-to-pulp pinch strength increased 12% from 25 N pre to 28 N after training. Case 2 had an increase in active range of motion for the affected hand fingers. Thumb flexion and thumb extension increased 10° each, index extension and flexion active range increase 5° each, and there was a 5° increase in middle finger flexion post-training.

Motor UE function The most remarkable improvement was in Case 2 affected hand dexterity as reflected in 35% faster performance on the Jebsen test (total execution time decreased from 186 seconds pre- to 120 seconds post-training. His Fugl-Meyer score increased 2 points (43 pre- to 45 post), while his Chedoke score improved also, from 52 to 55 (a 6% gain in biannual ADLs). This improvement in his affected arm function translated in his self-reported UEFI score. While pre-telerehabilitation intervention he reported having some difficulty with 10 out of 20 ADLs listed in the form, post-training he reported having no difficulty in any of these tasks.

Emotive and Cognitive Case 2 improvements in motor impairments and function were mirrored by improvements in his emotive state and cognition. Specifically, he started minimally depressed (Beck Depression Inventory score of 13) and improved in the minimal range to a score of 9 points (a 31% reduction in depression severity). Case 2 executive function on the NAB Word Generation test score increased from a T=6 pre-training to T=10 post (a 67% improvement). His score on Trail Making Test B improved from 100 seconds pre- to 94 seconds post (a 6% improvement in set shifting and processing speed). In the Language domain Case 2 had a remarkable improvement in his verbal fluency, within the normal range. His raw score went from T=20 to T=32, a 60% improvement.

Game Performance Case 2 progressed in his game performance as well, from 344 arm repetitions in his first session to a maximum of 1,563 combined left and right arm repetitions/session. His grasp counts went from 20 to 487 grasps/session, while his finger extensions increased from 22 to a high of 463 extensions/session. Grasp training intensity improved from 1 grasp/minute to as high as 14 grasps/minute. Finger extension frequency increased from 1 extension/minute (first session) to 11 extensions every minute. His game average difficulty per session was close to 6 on his last session, with a cognitive training time which went from 20 minutes to as high as 45 minutes/session.

Table IV shows a progression of the subjective evaluation Case 2 gave the BBG technology. His lowest scores were for technology problems (2.8/5) and perceived usefulness in improvement of stroke symptoms. He mostly agreed that playing the therapeutic games with both arms was easy, and liked the system overall (score of 4/5). Similar to Case 1, he agreed that he would encourage other patients to use the system (score of 4), and his overall evaluation was 3.7.

On his exit interview Case 2, who was 17 years post-stroke, suggested that this experimental treatment be tried earlier, even in the hospital:

> "*What I would suggest is do it to people who are five years and under (from stroke), only because you get more… and another thing .. go and put it in the hospital .. maybe that would be better with what they can do and what they can't do*." He was ready to participate in follow-on studies

TABLE III. GAME PERFORMANCE OUTCOMES TWO CASES OVER 4 WEEKS OF TRAINING WITH THE BBG THERAPEUTIC GAME CONTROLLER.

	Case 1		Case 2	
Outcomes	**Session 1**	**Highest**	**Session 1**	**Highest**
Motor domain				
Session Arm Repetitions	275	1931	344	1563
Repetitions/min	12	99	17	39
Session Grasps	22	310	20	487
Grasps/min	1	8	1	14
Finger Extensions	3	342	22	463
Extensions/min	<1	8	1	11
Cognitive domain				
Game average difficulty	1	3.5	1	5.7
Game average duration (min)	2.3	3.5	1	2.8
Cognitive exercise time/session (min)	23	44	21	45

saying "*If you have any new thing that comes up please give me a call*."

IV. DISCUSSION

BrightBrainer Grasp therapeutic game controller development was targeted at overcoming virtual rehabilitation challenges for individuals chronic post-stroke. The controller, when integrated with the BrightBrainer rehabilitation system, was able to deliver high intensity remotely-monitored virtual rehabilitation. For the two cases reported here, repetition rates ranged from 12 to 99 arm repetitions/minute, 1 to 8 grasps/minute, and 3 to 342 finger extensions/minute. There are currently no comparable systems training and tracking grasp and finger extension for telerehabilitation [5].

The use of BBG controllers enabled large therapeutic gains for both participants and they enjoyed the experience as indicated by their rating on subjective evaluation of 3.2 and 3.7 out of 5. Case 1, who had severe UE impairments on the dominant right side, showed remarkable improvement in grasp and pulp-to-pulp pinch strength, finger metacarpophalangeal flexion, and a 33% improvement in the test of bimanual UE performance. More research needs to be done to find out whether in a larger representative group, this change would reach criteria for minimal clinically important difference [27]. The participant's greatest gain was noted in self-reported daily upper extremity tasks with a 'no difficulty' rating indicating ease of self-perceived use of the UE during daily tasks (see Table II). The increase in strength and range to be able to grasp various objects could have contributed to this effect. Another contribution to this discrepancy between self-reported and performance-based measures could be the reduction in depression by 4 points. This finding is consistent with prior studies by this group [9], which also indicated reduced depression among individuals with stroke taking part in virtual rehabilitation. There were no changes in extension for any of the fingers for Case 1 and she reported in the exit interview that one month was too short for training. The severity of her stroke and spasticity could explain this effect. However, it is important to note that there was no decrease in finger extension range for the fingers, indicating that spasticity did not increase in this individual. A detailed measurement of spasticity using a standardized test, such as the Modified Ashworth Scale [28], would have provided better support for this result and should be included in future trials.

Case 2, with mild UE impairments, showed much greater improvements in flexion and extension than Case 1, even though he was 17 years post-stroke. In addition, Case 2 made particular gains in speed of movement (35% improvement in Jebsen test). His visual field cut did not interfere with the games since BrightBrainer used a large TV display instead of HMD. Researchers found that the mild nature of this participant's impairments were more amenable for training finger extension, similar to other reports [29]. There is clearly greater benefit with BBG training on finger flexion and extension for mild UE impairments, as it assumes an ability to actively generate finger movement. The larger gain for mild impairments has been erroneously translated into stringent inclusion criteria wherein researchers have systematically excluded individuals with severe impairment to maximize their study gains. The use of BBG controllers can not only benefit individuals with mild impairment, but help design better rehabilitation protocols. Such protocols should have substantially longer duration, frequency, or higher intensity to provide an opportunity for individuals with severe impairments to engage in telerehabilitation.

One intriguing finding in the present study was improved speech output on a verbal fluency task in both stroke survivors. Changes in verbal fluency with arm motor rehabilitation require further evaluation in large-scale research studies because this may be a feasible and practical co-treatment approach for communication disorders [30].

The BBG impact was enhanced by an evidence-based gaming system, the BrightBrainer, which has shown benefits for individuals post-stroke, post-TBI and with dementia. Both Cases had mild cognitive impairments and the improvements noted in cognition for both can be attributed to the integrative nature of this gaming system [31]. Adaptive games posing

TABLE IV. SUBJECTIVE EVALUATION SCORES COMPLETED BY THE CASES OVER FOUR WEEKS OF TELEREHABILITATION (1 LEAST DESIRABLE, AND 5 MOST DESIRABLE).

		Participant 1				Participant 2				Question Avg. Score
Number	**Questions**	Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4	
1.	The system was easy to use				2	4	4	4	4	3.6
2.	Playing games with both arms was easy				2	4	4	4	3	3.4
3.	I had no muscle pain or discomfort				4	4	4	4	4	4
4.	The instructions given to me were useful				4	4	4	4	4	4
5.	Playing games improved my stroke symptoms				2	3	3	3	3	2.8
6.	I was not bored while exercising				4	4	4	2	4	3.6
7.	The length of exercising in a day was appropriate				4	4	4	4	4	4
8.	There were few technical problems				2	3	3	4	2	2.8
9.	I would encourage another patient to use it				4	4	4	4	4	4
10.	I liked the system overall				4	4	4	4	4	4
11.	Average score per participant	3.2				3.725				3.46
12.	Average score for all participants	3.62								

appropriate cognitive challenges, when combined with BBG controllers which accommodate users with hand spasticity, could drive the next generation of virtual rehabilitation systems.

Telerehabilitation is better suited for those unable to make outpatient visits [32]. The use of BBG-type controllers could make telerehabilitation feasible for engaging protocols. Although gains may not be dramatic for these individuals, engagement in meaningful rehabilitation programs can prevent secondary complications, such as reduced strength, reduced range of motion, or increased depression severity.

The BBG controller fitted to the hand was used to manipulate avatars such as car, hand, play card, rather than tools. This approach may be easier for people with limb apraxia to use purposively. Because this disorder occurs in as many as 50% of stroke survivors, especially with left brain injury [32], (Foundas, 2013), further studies examining whether this design makes the system particularly effective in people with this cognitive-motor disorder, are needed.

The generalization of findings presented here is limited by the small sample of two individuals. They were part of a feasibility study with a larger sample (n=8 but different controllers). Analysis of the entire cohort will provide further evidence to inform the efficacy of the approach. Although improvements were observed, the findings need to be studied with a control group to determine comparative effectiveness over conventional treatments and off-the-shelf game controllers. Translation of the findings to participation in daily activities needs to determine the real impact of this approach.

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