BrightArm Duo integrative rehabilitation for post-stroke maintenance in Skilled Nursing Facilities

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Abstract*— Purpose: To determine clinical benefits of the BrightArm Duo *bimanual upper extremity (UE) rehabilitation system for maintenance of older hemiplegic residents of Skilled Nursing Facilities (SNFs). Methods: The system underwent a longitudinal controlled study in two SNFs. Seven chronic post-stroke participants trained for 8 weeks of increasingly intensive sessions followed by a 2 week booster period starting 10 weeks later. The sessions involved computer games designed to improve UE motor deficits, function, cognition and emotive state. BrightArm Duo recorded arm reach, arm active movement repetitions, hand grasps, and game performance. The control group (N=3) continued with normal maintenance programs offered in their SNF. Participants' motor function was evaluated pre-therapy, post-therapy, and pre-booster and post-booster using standard clinical measures. Participants' cognition was evaluated pre- and post- initial intervention and post-booster. Outcomes: The experimental group significantly improved in shoulder strength, grasp strength, active range of movement, supported arm reach and depression. The motor function and emotive levels post-booster were much higher than post- initial training. The experimental group motor, emotive, and cognitive outcomes were much better than for the control group. Conclusions: Initial results are promising for the integration of the BrightArm Duo in maintenance programs of SNF residents.

Keywords—BrightArm Duo, Stroke, Skilled Nursing Facility, Virtual Reality, Integrative Rehabilitation, Bimanual Interaction.

I. INTRODUCTION

Close to 800,000 Americans suffer a stroke each year making it the leading cause of disability in the US [1]. Although the mortality rate is declining [2], only 5% of adults post-stroke fully recover their upper extremity (UE) function [3]. Consequently, millions of stroke survivors [4] face a lifetime of disability, impacting quality of life, and sometimes leading to depression [5]. In addition to the personal toll, there are significant direct and indirect costs associated with stroke, currently estimated at $105 billion annually [6].

Physical rehabilitation of the paretic arm typically involves passive and assisted movement, electrical stimulation [7], UE compensatory training, and constraint induced therapy to combat learned non-use of the hemiplegic hand and arm [8]. These uni-manual approaches do not take into account that activities of daily living (ADLs) usually involve both arms.

Bilateral training tends to increase neural cross talk to mirror motor areas associated with the bimanual activities. A meta-analysis of the cumulative effect of bilateral arm training on motor capabilities post-stroke [9] found a significant benefit for repeated bimanual reach movements timed to auditory cues. Another randomized controlled study of stroke patients found that training the healthy arm resulted in a 23% functional improvement in the *non-trained* paretic arm [10]. Researchers also observed improvements in bilateral tasks performance by the experimental group, while the control group showed no significant difference from baseline. These studies underscore the advantages of bilateral training and motivate the study described here.

In the current managed care model, post-stroke therapy typically ends 6 to 9 months from a neural accident. However, neuroscience has shown that UE function can be improved years post-stroke, as long as activities are task-oriented, repeated, and well attended [11]. Naturally, traditional therapy needs to be augmented with computerized therapy systems to accommodate the large number of potential clients.

Repetitions, while necessary to induce brain plasticity, can lead to lack of engagement by the patient and hence can impact the rehabilitation outcome. Performance feedback is key in motor retraining [12] and is a means to keep patients engaged. This feedback can be provided by the therapist, or through graphics in a virtual rehabilitation setting [13].

Stroke survivors who are residents of Skilled Nursing Facilities (SNF) often suffer from a combination of motor, cognitive and emotive disabilities. Current standard of care addresses these domains separately, with therapy provided by different clinicians: physical therapist (PT), occupational therapists (OT), neuro-psychologists, psychiatrists and others. By contrast, integrative rehabilitation addresses the motor, cognitive and emotive deficits in a single-point-of-care approach. Integrative *virtual* rehabilitation uses custom therapeutic games in which the participants solve cognitive problems (such as making image pairs) through physical arm movements and grasping. The emotive domain is addressed by making the integrative rehabilitation games adaptable and winnable and by lavishly congratulating for success.

The *BrightArm Duo* bimanual upper extremity (UE) rehabilitation system [14] embodies many of the properties discussed above. A longitudinal controlled study was started in the summer of 2014 to evaluate its use for maintenance therapy of chronic post-stroke residents at two SNF's. The protocol provided for an experimental group undergoing 8-weeks of initial intensive rehabilitation (16 sessions), followed by periodic 2-week booster sessions starting 10 weeks after initial therapy had been completed. The control

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group continued with their standard of care maintenance programs offered by the SNF. The intensive rehabilitation part of the study completed by the experimental group was discussed in [14]. The results of the BrightArm Duo maintenance program and comparisons between experimental and control groups are the focus of this paper.

II. METHODS

A. BrightArm Duo Rehabilitation System

BrightArm Duo is a computer-controlled rehabilitation table that incorporates electrical actuators. These actuators lift or lower the BrightArm Duo to accommodate different body types [14]. The low-friction table top has an outer contour that accommodates the reach of a 90th-percentile adult male, and an inner contour accommodating the waist circumference of 95th-percentile for men and women in the target age group [15]. The table tilts using 2 quiet electrical linear actuators to allow gravity modulation. Tilting downwards assists weak arms and tilting upwards resists stronger arms when moving away from the trunk (Figure 1).

Participants' forearms are placed on low-friction supports that incorporate grasp sensing. Two overhead cameras with a line of sight perpendicular to the table top track the position of forearm supports, enabling participants to interact with 3D virtual reality simulations through arm movements. Rehabilitation games are rendered by an HP ENVY 17" laptop with a mid-range NVIDIA GeForce graphics card and displayed by a monitor placed across from the participant. The BrightArm Duo transparently stores game performance into an Oracle MySQL database on a secure clinical server.

A major advantage over off-the-shelf games is the ability for BrightArm Duo simulations to adapt to each participant, each day. This adaptation is based on arm reach and grasp strength baselines performed at the start of each rehabilitation session. Arm reach is determined by asking the participant to trace out a region of the table that each arm can comfortably move over. The arm reach is then used to map physical arm movements on the table to virtual movement of avatars in the rehabilitation games.

Figure 1: BrightArm Duo system with participant training both arms when work surface is tilted upward. Laptop screen of the therapist station is seen in front, while the second display showing an identical scene is across the table from the participant. © Bright Cloud International. Reprinted by permission.

Grasp strength is determined by measuring the maximum grasp on the arm support rubber pear. The grasp strength is then used to set the threshold for momentary grasp (25% of the maximum) or sustained grasp (10% of the maximum) used during the games. These values are in line with studies comparing maximum and sustained grasp [16], so to avoid arm discomfort with chronic post-stroke participants [17].

In the current study, the BrightArm Duo therapy sessions consisted of playing up to nine custom games written in Unity 3D [18]. Four games (*Pick-and-Place, Card Island, Treasure Island* and *Breakout 3D*) were bimanual versions of the uni-manual games previously developed for the original uni-manual BrightArm system [19]. Three games (*Remember that Card*, *Musical Drums,* and *Xylophone*) are BrightArm Duo adaptations of games previously developed for the BrightBrainer portable system [20, 21]. Two games (*Arm Slalom* and *Avalanche*) were created primarily for the BrightArm Duo and have been previously described in [14].

BrightArm Duo systems were installed at two SNF's in Edison NJ (Roosevelt Care Center and JKF Hartwyck at Edison Estates) and pre-tested with older healthy volunteers.

B. Participants

The study enrolled 10 residents of these two SNFs. The inclusion criteria were Hemiplegia due to stroke, more than 12 months since stroke, being older than 60, and a SNF resident. Good mental awareness and speaking English were required to understand the consent form, cognitive evaluation questions, and the exercise simulations. Additional criteria included UE motor involvement with a score of 5 to 45 in the Fugl-Meyer UE Assessment (FMA) [22]; some ability to actively move the UE (~15° of total active range or better for shoulder and elbow flexion/extension); and at least 4 months after casting procedures or Botox injections. Exclusion criteria were total lack of active movement in the hemiplegic arm, blindness, severe cognitive dysfunction and dementia, a history of violence in the 6 months prior to enrollment, receptive aphasia and uncontrolled hypertension (>190/100 mmHg).

The demographic and medical history information for the experimental group (N=7) and control group (N=3) are summarized in Table 1. This includes vital statistics, months since stroke, affected side, UE functional level, depression level, cognitive impairment, ambulation, co-morbidities, language primarily spoken, and years of formal education.

The experimental group was comprised of 5 male and 2 female subjects with a mean (standard deviation) age of 69.7 (13) years. The group ethnicity was White (4), Hispanic (2) and African American (1). The primary languages spoken were English (4), Spanish (2) and French (1). The mean education level was 11.7 years (high school) as three participants finished in 8th or 9th grade, three completed high school, and one having a graduate degree.

Similarly, the control group consisted of 2 male and 1 female subject with a mean age of 70.1 (SD=16.4) years.

Table 1. Participant statistics and medical history pre-intervention for experimental (N=7) and control (N=3) groups of chronic post-stroke SNF residents. © Bright Cloud International Corp. Reprinted by permission

Variable	Experimental (N=7)	Control Group (N=3)
Age	69.7 (13.3) years	70.1 (16.4) years
Gender	5 Male, 2 Female	2 Male, 1 Female
Race	4 White, 2 Hispanic, 1 Afr. American	2 Afr. American, 1 Hispanic
Primary Language	4 English, 2 Spanish, 1 French	3 English
Formal education	11.7 (3.8) years	10.7 (1.5) years
Time since stroke	98 (42) months	100 (28) months
Affected side	4 Left, 3 Right	1 Left, 2 Right
UE Funct. Level	3 Severe, 4 Moderate	1 Severe, 2 Moderate
Depression Level	6 Minimal, 1 Moderate	3 Minimal
Co-morbidities	Diabetes Mellitus (4), Heart condition (4), Hypertension (3), Anemia (2)	Diabetes Mellitus (2), Hypertension (2)
Ambulation	6 Wheelchair bound, 1 Independent	2 Wheelchair bound, 1 bed bound

Races included African American (2) and Hispanic (1) and the primary language spoken was English (3). The mean formal education level was 10.7 years of school ranging from 9th grade through high school graduate.

For the experimental group the mean time since stroke was 98 (SD=45) months and the affected side was split: 4 left and 3 right. Their UE motor function was rated severely impaired for 3 participants and moderately impaired for 4 participants based on the initial UE FMA score. Depression levels were minimal with one participant having moderate depressive symptoms according to Beck's Depression Inventory II (BDI-II) [23] scores. Cognitively, 4 participants initially exhibited severe impairment in attention or memory (or both), while one participant had less severe cognitive impairments. All participants had multiple medical co-morbidities, with 4 having Diabetes Mellitus, 4 having a heart condition, 3 having hypertension, and 2 having had a history of anemia. Six participants ambulated in wheelchairs within their SNF and 1 ambulated independently.

Similarly for the control group the mean time since stroke was 100 (SD=28) months and the affected side was split: 1 left and 2 right. The UE motor impairment was rated moderate for 3 control participants based on their initial UE FMA score. The three control participants had minimal depression levels according to BDI-II and were severely impaired in both attention and memory. Their primary comorbidities were Diabetes Mellitus (2) and Hypertension (2). One control participant was bed bound while two were wheelchair bound.

C. Data Collection Instruments

The study protocol was ABAABA, with data being collected pre-training (A) for both groups, during 8 weeks of intensive training (B) for the experimental group, post-training (A) for the experimental group, pre-booster (A) and during the 2-weeks booster for the experimental group (B), and post-booster (A) for both groups.

BrightArm Duo initial intervention for the experimental group consisted of 16 sessions of intensive training followed at 10 weeks by 4 sessions of booster training (2 sessions/week). Data captured during each rehabilitation session included the arm reach and grasp strength baselines, active/assisted arm repetitions, game performance data and participant's blood pressure and pulse.

Technology acceptance by the experimental group was measured at the end of 8-week initial intensive training and after the 2-week booster training. Participants completed a 10 question subjective evaluation questionnaire. Ratings used a 5-point Likert scale, from 1 (least desirable outcome) to 5 (most desirable outcome). The control group did not receive the virtual reality intervention and thus did not fill any rating forms for the BrightArm Duo.

Table 2. Range of motion of affected and unaffected arms for experimental chronic post-stroke participants versus control group. T1 pre-training, T2 post-training (week 9), and T3 post-booster (week 18). Bold differences are statistically significant or trending; * indicates improvement over time; underline denotes T3 better than T2 or T3-T1 better for experimental than control. © Bright Cloud International Corp. Reprinted by permission.

Variable	Experimental group (N=7)				Control group (N=3)		
	T1	T2	T3	T3-T1	T1	T3	T3-T1
Affected Arm	**Shoulder Range of Motion**						
Flexion	42.4	46.0	37.0	-5.4	64.3	65.0	0.7*
Extension	18.7	31.7	34.4	**15.7***	19.1	34.1	13.3*
Abduction	68.0	71.4	76.4	8.4*	78.3	89.0	10.7*
Adduction	6.3	5.0	6.6	0.3*	5.0	3.3	-1.7
Internal rot.	49.3	49.9	45.3	-4.0	64.0	25.0	-39.0
External rot	12.1	11.1	8.6	-3.6	20.0	23.3	3.3*
Unaffected Arm							
Flexion	141.0	136.1	129.7	-11.3	106	117	10.7*
Extension	65.6	71.0	64.7	-0.9	51.3	52.7	1.3*
Abduction	151.6	146.3	143.9	-5.7	129	137	8.0*
Adduction	34.6	38.7	33.1	-1.4	27.7	20.7	-7.0
Internal rot.	49.3	53.4	54.0	9.6*	34.0	33.3	-0.7
External rot	59.6	67.7	68.3	8.7*	64.0	56.7	-7.3
Affected Arm	**Elbow Range of Motion**						
Flexion	130.1	136.0	132.4	2.3*	132	139	7.3*
Extension	68.7	65.1	60.6	**-8.1***	25.7	39.0	13.3
Pronation	40.0	39.4	43.6	3.6*	90.0	90.0	0.0
Supination	17.9	14.3	16.9	-1.0	41.0	58.3	17.3*
Unaffected Arm							
Flexion	144.6	148.7	149.4	**4.9***	144	148	4.3*
Extension	3.6	2.9	3.7	0.1	0.0	0.0	0.0
Pronation	82.6	82.0	88.0	5.4*	86.0	91.0	5.0*
Supination	72.0	80.7	81.4	**9.4***	51.0	72.7	21.7*
Affected Arm	**Finger Ranger of Motion**						
Thumb	7.1	17.9	20.0	12.9*	36.7	38.3	1.7*
Index	25.7	22.3	29.7	4.0*	53.3	39.0	-14.3
Middle	22.9	22.3	20.0	-2.9	34.3	20.0	-14.3
Ring	28.1	21.4	28.1	0.0	43.3	23.3	-20.0
Pinkie	27.9	21.3	29.3	1.4*	48.5	25.0	-23.3

The motor function and impairment clinical evaluations were conducted by a senior OT pre-training, post-training, pre-booster and post-booster. The UE motor impairment evaluations included measuring the affected and unaffected arm shoulder strength (using wrist weights), grasp strength (with a mechanical Jamar dynamometer), and finger pinch strength (with a mechanical pinch gauge). The active range of motion for shoulder, elbow and fingers were determined using of a mechanical goniometer. The arm and hand function were measured with the Jebsen test of hand function [24], the Chedoke Arm and Hand Inventory (CAHAI-9) [25], and the UE subset of the FMA test (for the affected arm).

A graduate student in neurology evaluated cognition and depression using neuropsychological measures. These were administered pre-training, post-training and post-booster for the experimental group, while the control group was evaluated at times corresponding to the pre-training and post-booster of the experimental group. The emotive and cognitive evaluations included standardized measures: BDI-II; the Hopkins Verbal Learning Test, Revised (HVLT-R) [26] to assess verbal learning and memory; the Brief Visuospatial Memory Test, Revised (BVMT-R) [27] to assess visual learning and memory; Neuropsychological Assessment Battery (NAB[28]) Attention Module (verbal and visual attention) and Executive Functioning Module (verbal fluency); and the Trail Making Test A and B (TMT-A & TMT-B) [29] to assess speed. Alternate test forms were used whenever possible to minimize test-taking practice effect.

Both clinicians were blinded to research methodology and study scope. The cognitive evaluations were supervised by a board certified neuropsychologist who was familiar with the BrightArm Duo technology and is a co-author of this article.

D. Experimental Protocol

Each session was assisted by an OT and a system technician. Participants' blood pressure and pulse were measured by the OT before and after each session. Subsequently the OT stretched the participant's affected arm and fingers and when needed assisted arm movements during game play. The OT also made sure the arms were positioned properly on the forearm supports. The initial participant's preparation was followed by baseline measurements of reach and grasp strength of the arm(s) being exercised in that session.

During 8 weeks of initial training, the duration of actual game play increased from 20 to 50 minutes per session. Training intensity was increased by gradating the BrightArm Duo table tilt angle from 0° (horizontal) to a 20° upward tilt and adding up to 2 lb. wrist weights on each arm. Exercise difficulty increased during 8 weeks of training by migrating from easier games with no required grasping to more difficult ones requiring sustained grasping.

Each session the participants played a sequence of up to 9 games, in a set order. The game sequence was repeated as needed to achieve the prescribed session duration specified for that week. The OT had the authority to deviate from the set game level progression in case it proved too difficult, or not challenging enough for a given participant.

The four booster sessions followed a similar protocol to that used during the later sessions of initial training. This included session length of 50 minutes, 20° upward tilt for BrightArm Duo table, sustained grasp within games and a sequence of nine games similar to that used in week 8 of the initial training.

E. Statistical Analysis

Pre-training, Post-training and Post-booster comparisons of continuous variables were implemented by paired t-tests. Two-sided P-values less than 0.05 were deemed to be statistically significant, and p-values from 0.05 to 0.1 were deemed trending to statistical significance. Although negative statements were less reliable due to low statistical power (small N), positive statistically significant findings implied that the results were robust and not obscured by the small sample size.

The results for multiple measures were analyzed together to overcome low statistical power. Cognitive and physical domain tests were grouped and observations were made of how many variables were in the direction of improvement. A binomial sign test was then used to evaluate the hypothesis that there were no more differences between pre- and post- in the improved direction than in the reverse.

III. OUTCOMES

A. Arm Range of Motion

Training on the BrightArm Duo resulted in an increase in movement for both the affected and unaffected arms. In Table 2, about 60% of the range of motion metrics improved between pre-therapy (T1) to post-booster (T3). By the same measure, 15 of 25 range of motion metrics were better post-booster (T3) than post-training (T2). Similarly, 15 of 25 differences from T1 and T3 were better for the experimental group than the control group, although the control group started less impaired in the motor domain.

The greatest improvement in shoulder movement was in extension of the affected arm, with mean pre-training (T1) angle of 18.7° and post-booster (T3) angle of 33.3°. The 15.7° range increase was statistically significant ($p=0.04$). Shoulder abduction increased on average 8.4° from 68.0° at T1 to 76.4° at T3. The greatest post-booster improvement of shoulder movement for the unaffected arm was internal and external rotation, with mean angles increase of 9.6° and 8.7°, respectively. This exceeded the 9.0° and 8.1° range improvements measured post-training (T2) vs. baseline (T1).

For the elbow of the affected arm post-booster, there were improvements in flexion (2.3°), elbow extension (8.1°), and pronation (3.6°) between T1 and T3. Elbow extension was trending towards statistical significance ($p=0.06$). For the elbow of the unaffected arm post-booster, there were statistically significant increases in flexion range of 4.9° ($p=0.01$) and supination of 9.6° ($p=0.001$) between T1 and T3.

The range of motion for fingers of the unaffected arm was found to be within normal limits for both the experimental and control participants. For the affected hand of the experimental group, the thumb showed the largest mean improvement in

range of motion, 12.9° post-booster (T3) and 10.7° post-training (T2) relative to pre-training (T1). The difference of all five hand movement metrics between T1 and T3 were better for the experimental group than the control group.

B. Arm Strength

The experimental group made steady progress in the strengthening of both arms. 80% of the shoulder and hand strength metrics in Table 3 improved for the experimental group post-booster (T3) relative to pre-therapy (T1). The delta for all ten strength measures between T1 and T3 were better for the experimental group than for the control group.

The largest change for the affected arm was in grasp strength, from a mean of 7.6 N pre-therapy to 23.5 N post-booster. The improvement of 15.9 N (210%) is above the repeatability threshold of the Jamar dynamometer [30]. By comparison, the grasp strength of the control group increased from 106.2N (T1) to 117.6N (T3), a smaller difference of 11.4N that is only 10% of the pre-study value.

The largest gain for the unaffected arm was Shoulder Anterior and Lateral Deltoid strength. The 23.8N (112%) and 22.6N (106%) improvements were both statistically significant (p=0.01). Affected arm shoulder Anterior and Lateral Deltoid strength increased by margins of 4.8N (72%) and 8.0N (120%). The Lateral Deltoid results was statistically significant (p=0.01). For the control group, Anterior and Lateral Deltoid strength was less at 3.7N and 1.5N for affected arm, and 5.9N and 5.9N for the unaffected arm.

Table 3. UE function and strength of affected and unaffected arms for experimental chronic post-stroke participants versus control group. T1 pre-training, T2 post-training (week 9), and T3 post-booster (week 18). Bold differences are statistically significant or trending; * indicates improvement over time; underline denotes T3 better than T2 or T3-T1 better for experimental than control group. © Bright Cloud International Corp. Reprinted by permission.

Variable	Experimental group (N=7)				Control group (N=3)		
	T1	T2	T3	T3-T1	T1	T3	T3-T1
Affected Arm	**Shoulder and Hand Strength (N)**						
Ant. Deltoid	6.7	7.0	11.4	4.8*	5.2	8.9	3.7*
Lat. Deltoid	6.7	7.9	14.6	**8.0***	5.9	7.4	1.5*
Hand Grip	7.6	17.2	23.5	15.9*	106.2	117.6	11.4*
3-Finger Grip	0.0	0.0	0.1	0.1*	10.1	5.2	-3.9
2-Finger Grip	1.0	0.9	0.3	-0.7	22.9	19.0	-3.9
Unaffected Arm							
Ant. Deltoid	21.3	32.1	45.1	**23.8***	22.2	28.2	5.9*
Lat. Deltoid	21.3	30.8	43.8	**22.6***	22.2	28.2	5.9*
Hand Grip	247	265	249	2.7*	225	218	-6.4
3-Finger Grip	54.6	49.9	52.6	-2.1	30.7	26.7	-4.0
2-Finger Grip	43.5	41.2	44.5	1.0*	36.9	34.1	-2.8
	UE Function						
FMA	15.6	16.9	17.4	1.9*	27.7	27.0	-0.7
CAHAI-9	11.9	14.0	18.6	**6.7***	30.0	30.0	0.0
	Jebsen						
Affected Arm	1260	1260	1260	0.0	1260	1260	0.0
Unaffected	148	129	104	-43.6*	299	257	-42*

C. Arm Functional Outcomes

The greater shoulder and hand strength translated in higher scores for CAHAI, FMA and Jebsen tests. As indicated in Table 3, the CAHAI increased 6.7 points for the experimental group from 11.9 to 18.6 between pre-training (T1) and post-booster (T3), which is statistically significant (p=0.01). This is an improvement over the 2.1 point change between pre-training (T1) and post-training (T2) for the experimental group, and no change in the control group between T1 and T3.

The FMA increased 1.9 points from 15.6 points pre-training (T1) to 17.4 points post-booster (T3). This is slightly better than the 1.3 points between T1 and T2 for the experimental group, and -0.7 change between T1 and T3 for the control group.

None of the participants were able to complete the timed tasks of the Jebsen test using the affected arm due to elbow and finger spasticity. The Jebsen time for the unaffected arm improved by 43.6 seconds from a mean of 148 seconds (T1) to 104 seconds (T3) (less is better). This was better than the 18.3 second improvement between (T1) and (T2), and slightly better than the mean 42 second improvement for the control group between (T1) and (T3).

The binomial sign test was performed on the experimental group (N=7) data in Table 3. In total, 12 of the 13 metrics improved between pre-training (T1) and post-booster (T3). The rejection of the null hypothesis of no difference between T1 and T3 scores is statistically significant (p=0.003). 11 of 13 of the metrics for experimental group from pre-training (T1) were better post-booster (T3) than post-training (T2). Rejection of null hypothesis of no difference between T3 and T2 scores is also statistically significant (p=0.02).

For the control group, only half of the metrics differences in Table 3 between T1 and T3 were improvements. All 13 differentials between T1 and T3 were better for the experimental group than the control group. Rejection of null hypothesis that there is no difference between experimental and control changes is statistically significant (p=0.0002).

D. Arm Baselines and Repetition Outcomes

The baseline area traced by each arm for the experimental group was measured pre-training, post-training, and post-booster on the table at 0° tilt. The area for the affected arm increased from a pre-therapy mean of 187 cm^2 (SD 186 cm^2) to a post-booster mean of 554 cm^2 (sd. 518 cm^2). The mean increase of almost 200%, is on the threshold of statistical significance (p=0.05). The unaffected arm reach area improved by a more modest 107%, from a mean of 584 cm^2 (SD 316 cm^2) pre-training to 1,211 cm^2 (SD 796 cm^2) post-booster. In comparison, the mean post-training reach areas for affected and unaffected arms were 682 cm^2 (SD 826 cm^2) and 1,897 cm^2 (SD 936 cm^2), respectively. Hence the post-booster results for affected and unaffected arms represent an 18% and 36% decline, respectively in baseline areas relative to the end of 8 weeks of intensive training.

Figure 2 illustrates arm movement repetition by session number for both arms. The affected arm repetitions increased over the 16 sessions of intensive training, as session time

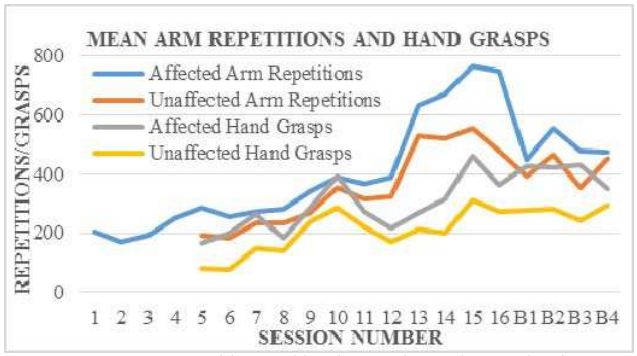

Figure 2: Mean arm repetitions and hand grasps by session number for affected and unaffected arms of the seven experimental chronic post-stroke participants. © Bright Cloud International. Reprinted by permission.

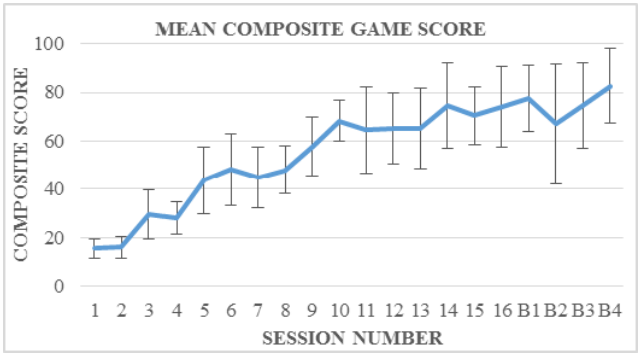

Figure 3: Mean composite game score by session number for the seven experiment chronic post-stroke participants. © Bright Cloud International. Reprinted by permission.

progressed from 25 to 50 minutes. The unaffected arm repetitions tended to track affected arm repetitions starting with bimanual play in session 5. The combined arm repetitions averaged 650 over the 16 training sessions and 1200 during sessions 13 through 16. By comparison, arm repetitions during the four booster sessions (B1 to B4) had a mean of 900. This is 40% greater than the mean for the 16 training sessions, but about 25% lower than sessions 13 to 16. Over all 20 sessions of the study, participants averaged a total of 10,390 arm repetition, 6,200 for the affected arm and 4,180 for the unaffected arm.

Figure 2 also shows hand grasps by session number. Affected and unaffected hand grasps started at 164 and 80 in session 5, and generally increased to session 15, where grasps plateaued to means of 410 and 270, respectively during boosters. The mean total grasps of 680 during the four booster sessions was about 13% higher than 600 mean grasps of training sessions 13 to 16, and 42% higher than 480 mean grasps for sessions 5 to 16. Over the 16 sessions training hand grasp in the study, participants averaged a total of 5,750 hand grasps, 3,390 for the affected hand and 2,360 for the unaffected one. The large number of grasps may explain the 15.9N (210%) improvement in hand grasp strength for the affected arm seen in Table 3.

Table 4. Emotive and cognitive outcomes for experimental chronic post-stroke participants versus control group. T1 pre-training, T2 post-training (week 9), and T3 post-booster (week 18). Bold differences are statistically significant or trending; * indicates improvement over time; underline denotes T3 better than T2 or T3-T1 better for experimental than control. © Bright Cloud International Corp. Reprinted by permission.

.Variable	Experimental group (N=7)				Control group(N=3)		
	T1	T2	T3	T3-T1	T1	T2	T3-T1
BDI-II	8.0	4.9	3.1	**-4.9***	2.7	0.7	-2.0*
NAB Person	12.3	12.1	13.3	1.0*	6.3	4.3	-2.0
NAB Time	7.7	7.7	8.9	1.1*	1.0	1.7	0.7*
NAB Place	3.3	3.4	3.4	0.1*	2.0	0.7	-1.3
Digits Forw	4.6	4.3	4.1	-0.4	2.7	3.0	0.3*
Digits Back	1.3	2.9	1.6	0.3*	2.3	0.7	-1.7
NAB Dots	2.1	2.7	2.0	-0.1	2.3	0.7	-1.7
TMT-A	90.9	94.6	94.7	3.9	120	120	0.0
HVLT-R	15.1	14.9	15.3	0.1*	2.7	0.0	-2.7
BVMT-R	5.9	10.1	7.0	1.1*	1.0	0.3	-0.7
TMT-B	255	229	237	-18*	300	300	0.0
Word Gen	3.9	3.0	4.7	0.9*	2.9	3.7	0.7*

E. Cognitive and emotive outcomes.

Table 4 presents the group statistical analysis for the emotive and cognitive measures taken pre-training (T1) and post-booster (T3), times where both groups were measured. Overall, 9 of 12 cognitive metrics improved for the experimental group between T1 and T3. The mood generally became better for participants, with the mean depression scores decreasing by 4.9 points, a statistically significant result (p=0.04). The mean experimental group change between T1 and T3 was higher than for the control group for 10 of 12 cognitive measures in Table 4. The binomial sign test rejected the null hypothesis of no difference in the improvement between experimental and control group (p=0.04).

F. Game performance outcomes.

The composite game score for a session was computed as the mean of the individual game scores played that session. *Xylophone* was excluded from the calculation due the low number of sessions (2 to 4) the game was played during the 8 weeks of intensive training. The protocol increased game difficulty over the first 16 sessions, resulting in a general increase of the composite game scores in Figure 3. There is a drop in score (B2) during the first week of boosters, but the score rebounds to a maximum of 83 by session B4. The mean score of 75 over the four booster sessions (B1 to B4) is comparable to the 71 mean score the last four training sessions (13 to 16). This is an indicator that cognitive level was largely maintained from post-training to post-booster.

G. Blood Pressure and Pulse

The participants' blood pressure and pulse were checked at the start and end of each session. Figure 4 shows a steady decline of the experimental group mean blood pressure (Systolic/Diastolic) over the duration of the intervention. The drop between sessions 1 to 4 of training (136/78 mmHg) and sessions 12 to 16 (124/72 mmHg) was 12/6 mmHg. The Systolic blood pressure change is trending to statistical

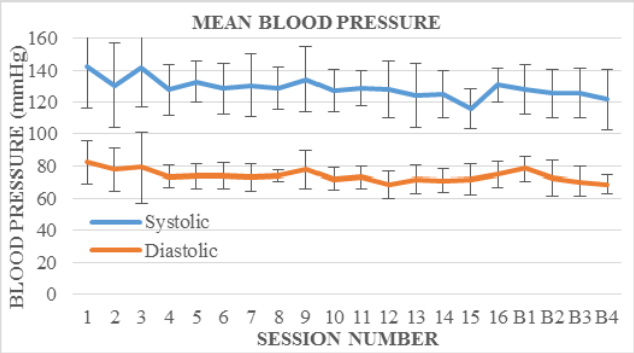

Figure 4: Mean systolic and diastolic blood pressure by session number for the seven experiment chronic post-stroke participants. © Bright Cloud International. Reprinted by permission.

significance (p=0.06). The mean blood pressure (125/72 mmHg) during the four booster sessions (B1 to B4) largely maintained the values at the end of initial training. Pulse fluctuated around a mean of 70 bpm over the 20 sessions.

H. Technology acceptance.

Experimental group participants provided their subjective evaluation of the system by answering ten questions after initial training (week 8) and booster (week 20). The mean response was 3.5 (SD 1.1) post-booster sessions, slightly lower than the mean post-training of 3.7 (SD 1.0). On the booster evaluation form, the response was 4.0 or better for the following questions: *Like system overall (4.0); Would encourage others to use it (4.0); Not bored while exercising (4.0); Length of exercising appropriate (4.0); Instructions useful (4.6).* Only two of the questions scored below 3.0: *Playing games with affected was arm easy (2.6)* and *Playing games with both arms was easy (2.6).*

IV. DISCUSSION

A. Impairment and function improvements

The booster sessions with the BrightArm Duo improved affected arm strength for the experimental group well beyond the post-training assessments (T2) and the control group for the same time period. The post-booster results were also better than a prior study using the original BrightArm system [19]. Previously reported differences between pre-study and post-study follow up for Grasp Strength, Shoulder Lateral and Anterior Deltoid strength for the affected arm were 12N, 3.8N and 4.6N, respectively. By comparison, the BrightArm Duo post-booster strength increases for the affected arm were 15.9N, 8.0N (p=0.01) and 4.8N, respectively. Unlike its predecessor, the current system trained both arms simultaneously. Consequently, the BrightArm Duo training also induced increased strength in Anterior and Lateral Deltoid for the unaffected arm. The 23.8N and 22.6N improvements were both statistically significant (p=0.01).

In another study ten multiple sclerosis participants trained 30 minutes on the Armeo Spring (Hocoma AG) three times a week for eight weeks [31]. The study demonstrated improved in arm function but, unlike the BrightArm Duo, there was no significant increase in muscle strength.

The greatest range of motion post-booster improvement of the affected arm for the BrightArm Duo study was 15.7° in shoulder extension and 8.1° (p=0.06) in elbow extension. This is significantly better than the prior BrightArm study where a mean increase of 9° in shoulder extension and 5° in elbow extension were reported at the follow up assessment. The range of motion gains are a reflection of the 200% increase (p=0.05) in affected arm supported reach baseline areas from the first training session to the last booster session.

In the current BrightArm Duo study, the CAHAI improved by 6.7 points or 56% post-booster relative to the pre-therapy levels. This is comparable to another study where two chronic post-stroke subjects trained in virtual reality executing bimanual tasks using the YouGrabber system [32]. The affected arm performed 5,478 and 9,835 grasps, which resulted in CAHAI score improvements of 4 and 13 points. The mean of 8.5 points is in line with the BrightArm Duo result with a combined mean of 5,750 hand grasps for both arms. The YouGrabber training did not provide strength training, but the researchers reported ADL improvements that were maintained at 12 weeks post-therapy.

FMA post-booster scores improvement was fairly modest at 1.9 points. The prior BrightArm study reported a mean improvement of 4.4 points at post-therapy follow up for five chronic post-stroke survivors.

Interestingly, there were improvements in shoulder and grip strength in the control group that had not trained. These may be the result of increased attention these subjects had received, by participating in the longitudinal study which entailed periodic examinations. These results are similar to those found by Van Haitsma and colleagues [33] with residents of SNFs.

B. Emotive and cognitive gains

The booster sessions with the BrightArm Duo improved cognitive and emotive metrics for the experimental group beyond both its post-training assessments (T2) and those of the control group (T4). The mean BDI-II score dropped by 60% overall, which translated in a 4.9 point improvement (p=0.04) in depression. By comparison, the mean BDI-II score in the prior BrightArm study improved by 30%, or 2.6 points reduction on the BDI-II test at follow up.

For the participants in the BrightArm Duo intervention, verbal attention and working memory improved a mean of 0.3 points (25%) and visual attention by 0.6 points (30%). These results are in line with a study showing statistically significant improvements for the group playing video games which trained in 3D over popular 2D brain training games in the areas of spatial perception and skill persistence [34].

V. CONCLUSIONS

The longitudinal controlled study of the BrightArm Duo rehabilitation system with chronic post-stroke residents of two SNF has yielded promising results. The experimental group significantly improved in the motor and emotive domains over

levels immediately after initial 8 weeks training. There is continued good acceptance of the technology by participants. Also, for the same time period, the experimental group significantly improved relative to the control group in motor, emotive and cognitive domains.

A limitation of this study is the small sample size (n=10), owing to recruitment difficulty in SNFs. Another limitation is the lack of imaging studies to determine if brain reorganization was induced by the experimental training.

Nevertheless, results bode well for the use of BrightArm Duo as a maintenance system in SNFs. As the longitudinal study continues, the control group will be clinically evaluated at set periods of time and compared with the experimental group that will have two more periodic booster sessions on the BrightArm Duo.

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