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ORIGINAL ARTICLE

Preliminary Investigation of an Electromyography-Controlled Video Game as a Home Program for Persons in the Chronic Phase of Stroke Recovery

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Abstract

Objective: To investigate the preliminary effectiveness of surface electromyography (sEMG) biofeedback delivered via interaction with a commercial computer game to improve motor control in chronic stroke survivors.

Design: Single-blinded, 1-group, repeated-measures design: A1, A2, B, A3 (A, assessment; B, intervention).

Setting: Laboratory and participants' homes.

Participants: A convenience sample of persons (N=9) between 40 and 75 years of age with moderate to severe upper extremity motor impairment and at least 6 months poststroke completed the study.

Intervention: The electromyography-controlled video game system targeted the wrist muscle activation with the goal of increasing selective muscle activation. Participants received several laboratory training sessions with the system and then were instructed to use the system at home for 45 minutes, 5 times per week for the following 4 weeks.

Main Outcome Measures: Primary outcome measures included duration of system use, sEMG during home play, and pre/post sEMG measures during active wrist motion. Secondary outcomes included kinematic analysis of movement and functional outcomes, including the Wolf Motor Function Test and the Chedoke Arm and Hand Activity Inventory-9.

Results: One third of participants completed or exceeded the recommended amount of system use. Statistically significant changes were observed on both game play and pre/post sEMG outcomes. Limited carryover, however, was observed on kinematic or functional outcomes.

Conclusions: This preliminary investigation indicates that use of the electromyography-controlled video game impacts muscle activation. Limited changes in kinematic and activity level outcomes, however, suggest that the intervention may benefit from the inclusion of a functional activity component.

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In the United States, approximately 795,000 persons sustain a new stroke each year, and 50% of stroke survivors have difficulty using their impaired upper extremity 6 months poststroke.[1] Persons with poor upper extremity motor function after stroke exhibit a variety of impairments, including hemiparesis and spasticity.[2-4] Voluntary selective muscle activation is often difficult because of excessive co-contraction of agonists and antagonists, leading to an inability to achieve movement using typical activation patterns.[2] Impairments in upper extremity motor function are associated with decreased quality of life and difficulty resuming daily activities.[4,5]

While impairments can be severe, stroke survivors can partially improve motor function with therapy and repetitive practice of specific tasks.[6-8] Rehabilitation therapists use a variety of treatment approaches to address hemiparesis and spasticity. Most current approaches to outpatient therapy, however, provide

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too little practice to produce recovery in the chronic phase of stroke for those who actually receive therapy services.[9,10] While clinical practice guidelines strongly recommend follow-up services for persons with residual impairments after acute rehabilitation, only 30.7% of stroke survivors receive outpatient therapy.[11,12] Even for those receiving outpatient therapy the amount is variable, with a median of 6 outpatient therapy visits (interquartile range, 1−21 visits) in the first year after stroke.[13]

In contrast, the amount of practice needed to induce functional improvements for chronic stroke survivors is extensive. A review article[6] reported that a study by Pang et al[14] found that 57 hours of practice was needed to make functional changes that impact performance in self-care and leisure tasks. With this amount of practice suggested in the literature, typical outpatient therapy provides insufficient practice time for motor recovery during clinical sessions. While practice can be extended through home programs, adherence is generally poor with multiple barriers reported.[15,16]

We sought to address the challenges of providing sufficient and specific practice outside the clinic. We developed a home-based program using surface electromyographic (sEMG) biofeedback interfacing with a computer game. sEMG biofeedback has been used in motor rehabilitation after stroke since the 1960s.[17] While the evidence base for sEMG biofeedback is inconclusive, several small studies[17-19] have found it to benefit upper extremity motor recovery of stroke survivors. We used this biofeedback method with an engaging, commercially available computer game in order to increase practice and subsequent repetitions using the impaired upper extremity at home. The use of sEMG biofeedback provides the participant with specific feedback of muscle activation as an agonist/antagonist pair over multiple repetitions. Specificity and repetition are 2 elements found to induce neural plasticity.[8] We tested the hypothesis that use of the electromyography-controlled video game system improves voluntary muscle activation and functional performance on outcome measures for adults in the chronic stage of recovery from stroke.

Methods

Study design

This preliminary study used a single-blinded, 1-group, repeated-measures design: A1, A2, B, A3 (A, assessment; B, intervention). A1 and A2 were scheduled approximately 4 weeks apart, before system use. A3 occurred immediately after completion of system use in the home. This design was selected because of the heterogeneous nature of stroke survivors and the preliminary nature of this investigation. All procedures were approved by the University of Washington Human Subjects Division, and all participants gave written informed consent before participation in the study.

Participants

Participants were a convenience sample of volunteers more than 6 months poststroke with an average age ± SD of 60±8 years. Participants' level of impairment ranged from no active extension in the digits to full digit extension. Participants had vision and hearing sufficient to play a computer game, and were cognitively able to give informed consent. Participants were excluded if they (1) had a skin condition that would interfere with the sEMG assessment or intervention; (2) reported significant pain in their affected upper extremity; (3) had a secondary neurologic diagnosis such as Parkinson's disease; (4) had a contracture at the wrist that would prevent the wrist from being passively extended to a neutral position; (5) had received neurolytic injections in the previous 4 months; or (6) had variations in dosage of oral antispasticity medication in the previous 3 months.

Twelve participants were enrolled, and 9 completed all 3 assessments and the intervention. Two withdrew because they lacked the time to participate, and 1 was asked to withdraw because of a change in his medical condition unrelated to the study. The characteristics of the 9 participants who completed the study are presented in table 1.

List of abbreviations:

CAHAI-9	**Chedoke Arm and Hand Activity Inventory-9**
MVC	**maximum voluntary contraction**
NGT	**NeuroGame Therapy**
sEMG	**surface electromyography**
WMFT	**Wolf Motor Function Test**

Intervention

The electromyography-controlled video game system, called NeuroGame Therapy (NGT), consists of a laptop computer, NGT console, sEMG leads, and disposable electrodes. The NGT system console uses a custom Neurochip circuit to amplify and digitize bipolar analog sEMG signals from 2 muscle groups and transmit these signals via universal serial bus to the computer.[20,21] Custom software converts muscle activity into movements used to control the computer game. The system's sensitivity can be adjusted to detect very low levels of activation, thus allowing persons with minimal muscle activation to participate. The conversion from sEMG activity to game movement was adjusted as needed during the intervention phase to facilitate challenging but successful game play (ie, the "just-right" challenge). If participants had an Internet connection at home, the investigators could make adjustments to game settings remotely.

Participants used the muscle activity in their affected wrist flexors (ie, flexor carpi radialis) and extensors (ie, extensor digitorum communis) to perform pregame maximum voluntary contractions (MVCs) and then to play the commercially available computer game Peggle.[a] For collection of MVCs, participants were instructed to maximally flex or extend their wrist during a 10-second window, followed by a 10-second relaxation period. This was repeated 3 times for flexion, followed by 3 times for extension. In Peggle, participants attempt to clear the board of orange pegs by identifying the correct angle to launch a ball to eliminate pegs. Participants controlled the aim using their affected upper extremity and launched the ball by clicking a button using the less affected hand. The game could be set up in 2 modes. Mode 1 trained selective muscle activation (ie, quieting 1 muscle group while activating the other). Mode 2 trained activation of a weak muscle group independent of the activity of the antagonist group.

Measures

Home therapy outcome measures

The NGT software captured raw sEMG during each home therapy session. To be included in the analysis, home sessions must have lasted at least 5 minutes and have displayed modulations in recorded signals from both muscles to ensure that the sensors were properly connected to the arm. Outcome variables

Table 1 Participant characteristics

ID	Age (y)	Sex	Hemiplegic Side	Years Poststroke	In Therapy	Full Digit Extension	Self-Reported Location	No. of Home Sessions*	Hours of Home Use†
A	53	M	L	5	Yes	No	Unknown	10	5
B	54	F	L	9	No	No	Parietal/frontal	10	6
C	67	F	R	3	Yes	No	Unknown	8	7
D	54	F	R	1	Yes	No	Brainstem	12	10
E	47	F	R	3	Yes	No	Brainstem	18	11
F	68	M	R	9	No	No	Frontal	19	12
G	58	M	R	6	No	Yes	Unknown	23	15
H	69	M	L	27	No	No	Unknown	27	20
I	69	M	R	2	No	No	Basal ganglia	24	21

Abbreviations: F, female; ID, identification; L, left; M, male; R, right.

* Only included sessions that lasted at least 5 minutes and displayed modulations in recorded signals from both muscles from the day of home setup to the day the system was returned.

† Includes home play that lasted at least 5 minutes and displayed modulations in recorded signals from both muscles.

included number of home game sessions, hours of play, number of usable hours, repetitions per session, independent activity, and MVCs.

Assessment outcome measures

Assessment outcome measures were collected across the impairment and activity levels of the *International Classification of Functioning, Disability and Health*[22] in order to determine the level of impact for NGT. These included sEMG, joint kinematics, and activity tests described below.

Surface electromyography

sEMG electrodes were placed over the motor points for the wrist flexors and extensors of the participants' affected extremity (Delsys Bagnoli EMG System[b]).[23] The electrode placements were measured relative to bony landmarks and were recorded for consistency in future testing. sEMG was collected at 500Hz during laboratory assessments and low-pass filtered at 200Hz.

Joint kinematics

During 2 simple movement tasks, 3-dimensional trajectories were collected using the Qualisys Oqus 300 Camera System[c] with 8 cameras capturing reflective marker data at 100Hz (error residuals <3mm for each camera). Reflective markers were placed on the participant's trunk, forehead, sternal notch, bilateral acromion processes, and throughout the affected upper extremity (lateral epicondyle, ulnar styloid process, radial styloid process, and head of the third metacarpal). In the first movement task, participants were asked to reach out to pick up a cup of water in midline at arm's length away.[24] If the participants were unable to pick up the cup, they were instructed to reach out as if they were going to pick up the cup and make the cup move. The second task evaluated active range of motion at the wrist. Participants' affected upper extremity was supported at the forearm, and they were instructed to move their wrist as far as possible into extension and then flexion. Each of these tasks had a minimum of 5 trials. Joint kinematics were measured to identify changes in upper extremity movement efficiency and compensatory movements.

Activity tests

Participants were video recorded during the Wolf Motor Function Test (WMFT)[25-27] and the Chedoke Arm and Hand Activity Inventory-9 (CAHAI-9)[28-30] as secondary measures. The participants were tested by 1 of 3 trained team members. Scoring was completed by an occupational therapist with 20 years of experience, who was not involved with the study and was blinded to the order of the participants' videos.

Procedures

In the first assessment (A1), participants completed a health history form. Subsequent assessments began with an update on current therapy routines, followed by the WMFT and CAHAI-9. After placement of the sEMG electrodes, participants performed an MVC against a stabilized dynamometer with their forearm resting on a table, first using wrist extension followed by wrist flexion. Kinematic markers were then placed to permit simultaneous kinematic and sEMG data collection during the reach and wrist active range-of-motion tasks.

Participants were trained to use the NGT system after the second assessment (A2). Electrode placement for the wrist extensors varied slightly across participants (ie, proximal vs more distal on the extensor digitorum communis) with the goal of promoting digit extension in the affected extremity when possible. The extensor digitorum communis contributes to both wrist and digit extension. It was also targeted for wrist extension because it is able to produce a greater moment about the wrist compared with other wrist extensors such as the extensor carpi unlaris.[31] Participants received up to 5 training sessions, during which they learned to attach the sEMG electrodes over ink markings applied to the skin, and use the NGT system.

For 8 of the participants, NGT was set up within a suitable space in their homes. Participants were asked to use NGT for 4 weeks, playing the game 5 days a week for up to 45 minutes per day, or a total of 15 hours. One participant determined that her home was unable to accommodate the game system and completed game play at the laboratory 1 to 3 times a week over 8 weeks, unsupervised, in a quiet room. Participants had intermittent contact with the research team during the intervention period to ensure that the system was working and that the level of challenge was appropriate. Participants were able to contact the team at any time should they encounter difficulties. These difficulties were typically solved over the phone but at times required a home visit.

Data analysis

Raw sEMG signals recorded in the home were filtered and wavelet analysis was used to establish a reliable baseline level of sEMG for the detection of bursts in activity. Independent activity was then calculated as the percentage of bursts detected in the agonist muscle when no simultaneous burst was detected in the antagonist. Wavelet analysis allows for the detection of muscle activity against background noise, even when the signal recorded in the home was noisy. The sEMG signal is then iteratively transformed into subsets of coefficients, soft thresholding is applied, and the signal is recovered using the inverse transform.

sEMG data recorded in the laboratory were processed using custom LabView[d] software. The sEMG level during MVC was calculated for wrist flexion and wrist extension as the average of the peak amplitudes over 5 trials per assessment. To calculate the

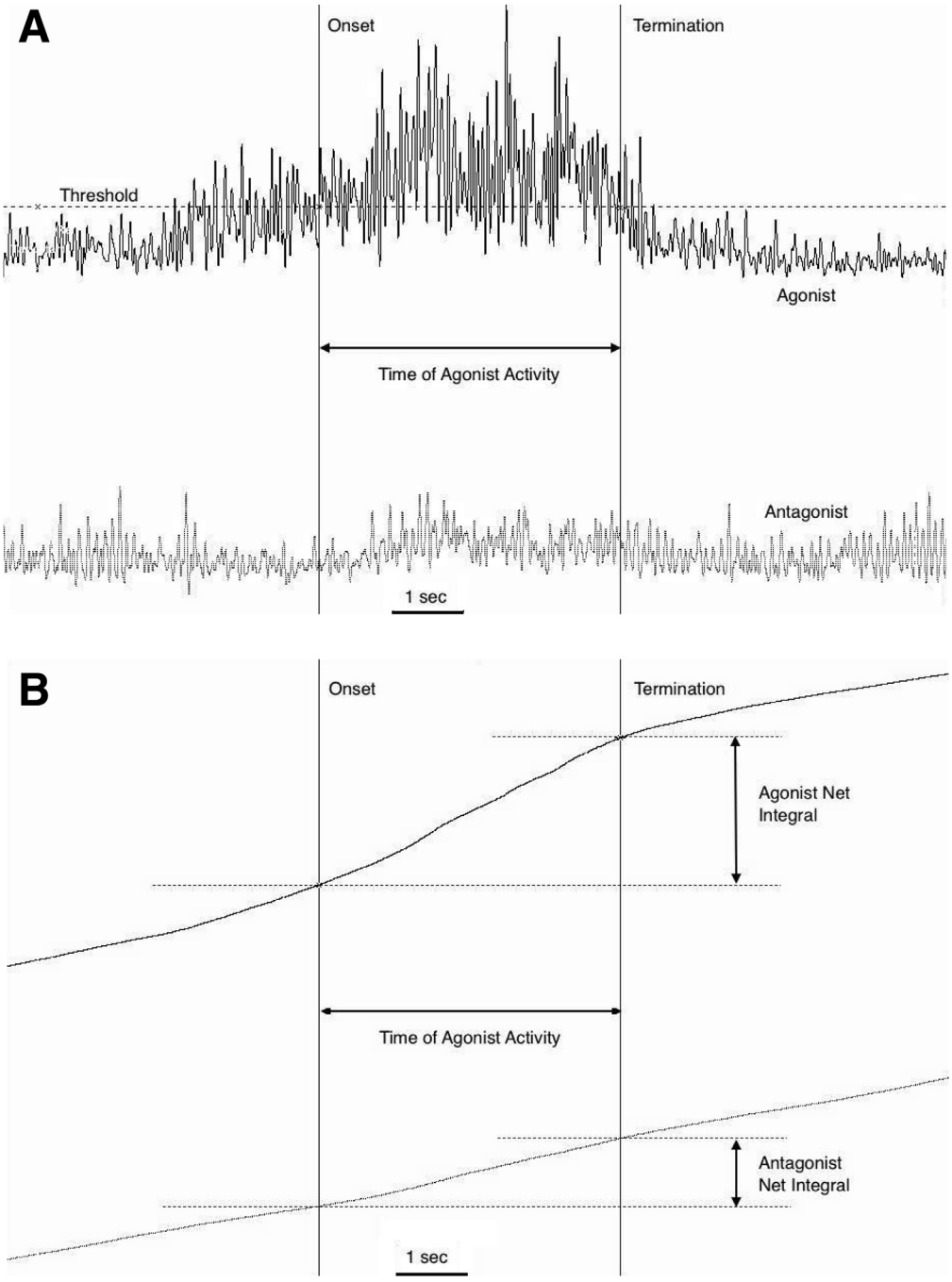

Fig 1 Example electromyography from the agonist extensor muscle (extensor digitorum communis, black traces) and antagonist flexor (flexor carpi radialis, gray traces) during the reach task. The co-contraction ratio is calculated by comparing the relative integrated area under the rectified electromyography of each muscle, during the time of the agonist activity. During the period of the reach movement determined from video records (not shown), the agonist muscle onset and offset (vertical lines) are detected when activity crosses a threshold of 5 SDs above baseline activity (shown in A). The ratio of the resulting cumulative integrals of each muscle (shown in B) were used to calculate the normalized co-contraction ratio.

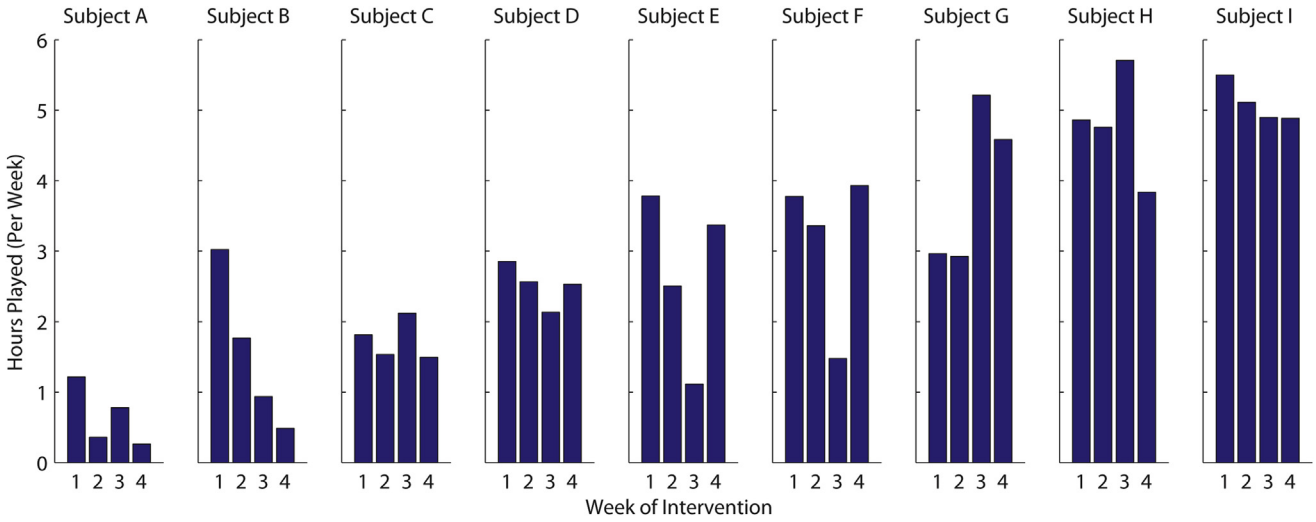

Fig 2 Number of hours of game play across the 4-week intervention for each subject. Subjects are ordered by the amount of time they chose to participate in the NGT intervention in the home. Additional game therapy as part of training was performed in the laboratory before using the system in the home for each subject.

normalized co-contraction ratio over the period of extensor activation, the integrated signal for the wrist extensors was divided by the extensor MVC and then divided by the integrated signal for the wrist flexors over the flexor MVC (fig 1). This was done so that a ratio >1 would indicate greater agonist activation. See appendix 1 for further details.

Kinematic analysis of the 2 tasks determined (1) reach time, (2) number of movement segments, (3) trunk displacement, (4) maximal elbow extension, and (5) overall amount of wrist extension. Details on the calculations used for each of these variables can be found in appendix 1.

Trends in co-contraction and maximal activation for sEMG recorded during home game play were analyzed using linear regressions (Matlab 2011a[e]). For laboratory assessment analysis, variables that contained multiple trials were averaged to create a mean for each variable. Secondary to the small sample size and preliminary nature of the data, the Wilcoxon signed-rank test was used to compare performance across no-treatment (A1 to A2) and treatment (A2 to A3) phases (SPSS version 18[f]). The alpha level for all tests was .05.

Results

Duration of game play

Three participants completed or exceeded the number of 20 recommended home training sessions, and 2 additional participants were close to completing the recommended number of sessions (see table 1). The remaining 4 participants played the game about 2 to 3 times per week. The amount of system use in the home was relatively stable across weeks for most participants (fig 2). Across both training and home use, participants averaged a total of 11.6 hours of system use.

sEMG during game therapy

Five of 9 participants increased independent activation of the wrist extensors and flexors during game therapy. Of the participants who did not increase independence, 3 performed less than 10 hours of game play (fig 3). In addition, 6 of 9 participants increased MVCs for either the flexor or extensor muscles measured during the daily calibration before game therapy (fig 4).

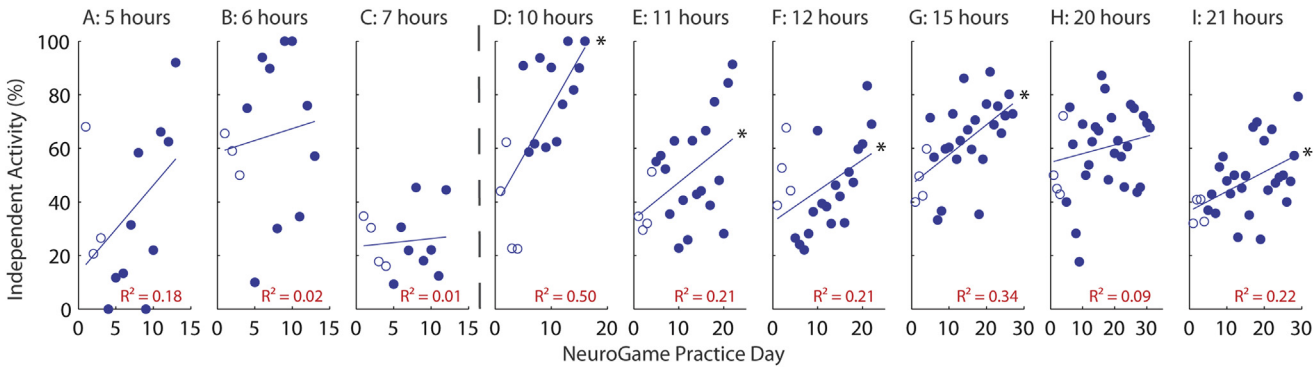

Fig 3 Independent activity across game play sessions. Subjects are ordered by the number of hours of game play suitable for analysis including training and home play. Of subjects who played ≥10 hours (dashed line), 5 of 6 subjects improved muscle independence based on a significant (*$P<.05$) positive regression between independence and game play session. Open circles indicate the practice day occurred during training and closed circle indicate the practice day occurred at home.

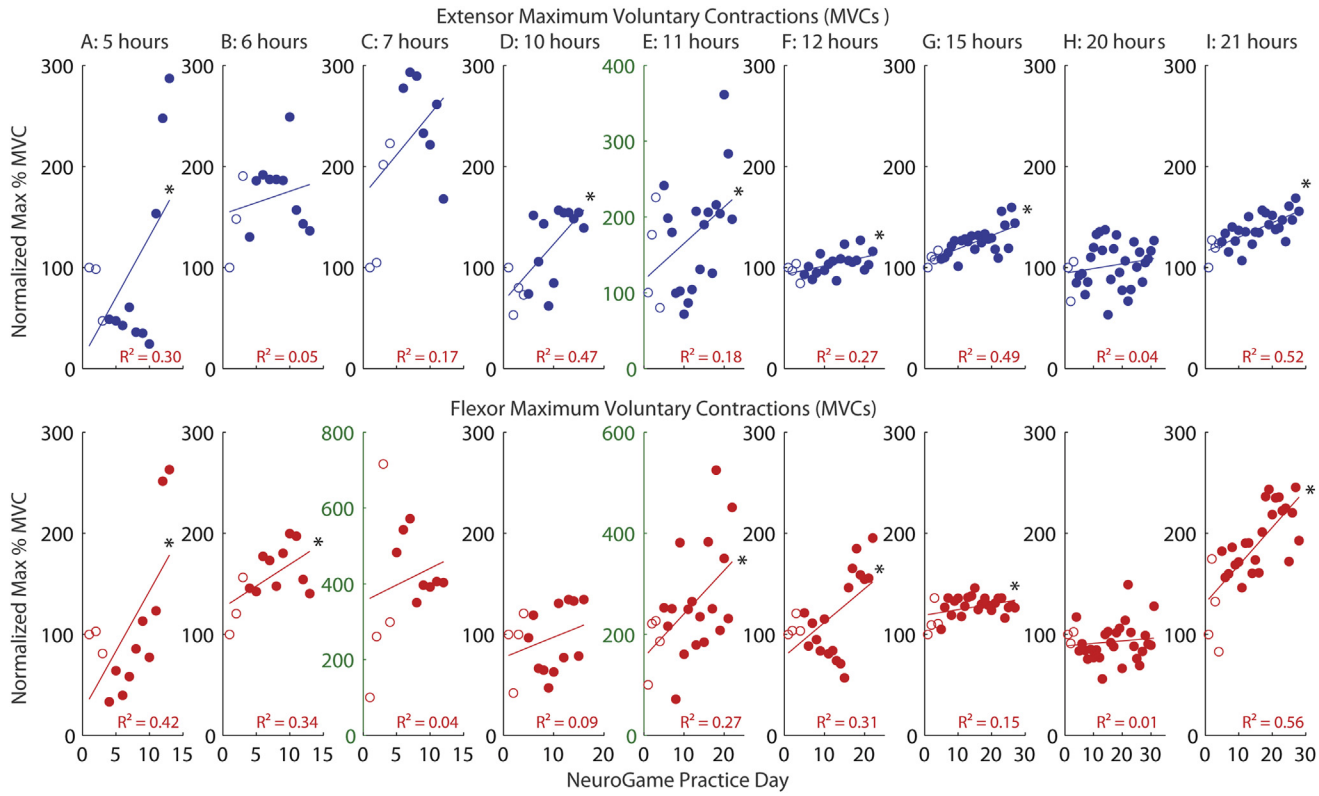

Fig 4 MVC during pregame calibration plotted across game play sessions. Subjects are ordered by the number of hours of game play suitable for analysis including training and home play. Six of 9 subjects improved muscle activation of at least the extensor (top row) or flexor (bottom row) muscles based on a significant (*$P<.05$) positive regression between muscle activity and game play session, while 4 of these subjects improved activation of both muscles. Note that 3 subjects improved their normalized electromyography greater than 300%, requiring greater range on the abscissa, and select axes are thus marked with green text to highlight this difference. Open circles indicate that data were gathered during training; closed circles indicate that the data were gathered during home sessions.

Although there was a trend toward more improvement with greater amounts of game play, linear regressions against the number of hours of game play were not significant for either MVC measures or muscle independence ($R^2 \leq .12$, $P \geq .35$).

Laboratory assessment outcomes

Surface electromyography

During the reach task, 5 of the 6 participants with complete data for analysis demonstrated a change toward increased selective activation of the extensor. This was reflected in a statistically significant difference across the treatment period (A2 to A3) for the normalized co-contraction ratios ($Z=-1.992$, $P=.046$) (table 2). No other statistically significant differences were found for the extensor and flexor MVCs or for normalized co-contraction ratios for extensor active range of motion (see table 2).

Kinematics

Eight participants had usable data for group analysis from the kinematic measures. Of the 4 variables generated from the reach task (reach time, number of movement segments, elbow extension, trunk displacement), a statistically significant difference was found across A1 to A2 for reach time, but no change was found across A2 to A3 (see table 2). No other variables demonstrated statistically significant differences.

Activity measures

No differences were found across time on any of the WMFT subscales or the CAHAI-9 (see table 2).

Discussion

Nine adults at least 6 months poststroke completed this study to evaluate the preliminary effectiveness of NGT as a home program to improve motor control in chronic stroke survivors. Most participants improved maximal activations of at least 1 wrist muscle and independence of antagonist muscles measured during the game therapy sessions. Co-contraction was also reduced in 1 of the functional sEMG tasks after the game intervention. No significant changes were seen on standardized functional activity tests.

There was a statistically significant increase in the amount of extensor activation in comparison with flexor activation present during the simulated reaching task in the laboratory assessment. A similar change in independent activation during game play was observed in most participants who played the game for more than a total of 10 hours. Daily MVC tests before game play showed an increase for some participants. Parallel changes in MVC, however, were not seen in the laboratory assessments. This could be due to the different nature of the test as well as the additional visual feedback provided in the pregame MVC test.

Table 2 Laboratory assessment outcomes

Outcome Measure	n	A1	A2	A3
MVC extensor (μV)*	8	30±29	41±33	37±26
MVC flexor (μV)*	7	38±19	42±25	37±14
CC-extensor AROM*	6	3.14±1.72	4.03±5.62	3.31±3.63
CC-reach*	6	2.92±2.56	3.47±5.84†	5.84±9.78†
Reach time (s)	8	3.97±2.67†	2.52±1.00†	2.54±1.18
Movement segments	8	7±6	4±3	4±3
Elbow extension (deg)*	8	95.3±22.7	96.8±24.7	95.5±22.1
Trunk displacement (mm)	8	121.9±47.2	123.22±65.1	131.7±49.6
AROM (deg)	8	30.4±19.1	31.6±17.7	25.4±17.7
WMFT functional activity score*	9	1.79±.71	1.77±.68	1.79±.66
WMFT mean time (s)	9	67.54±35.09	66.07±33.69	67.85±35.17
WMFT grip strength (kg)*	9	5±6	6±6	7±8
CAHAI percent score*	9	.27±.18	.26±.17	.25±.17

NOTE. Values are mean ± SD or as otherwise indicated.
Abbreviations: A1, assessment 1; A2, assessment 2; A3, assessment 3; AROM, active range of motion; CC, co-contraction ratio.
* Higher number indicates improved performance.
† $P<.05$ via Wilcoxon signed-rank nonparametric test.

The changes in independent activity observed in game play and laboratory assessment suggest that the intervention, which was designed to improve selective muscle activation, was functioning as anticipated. These changes observed at the level of muscle activation are encouraging, as voluntary muscle activation poststroke is the primary source of muscle weakness.[34] A lack of robust findings in voluntary movement activity-based outcomes (eg, range of motion, WMFT, and CAHAI-9), however, suggests that the outcomes are specific to the training provided—consistent with neuroplasticity research.[8] NGT may therefore benefit from combination with active functional movement practice in order to impact functional movement outcomes. Previous research[19] using sEMG biofeedback suggests that a combination of sEMG and more conventional therapy interventions is most successful.

The participants in the study had chronic movement impairment that substantially limited their success completing activities with their upper extremity. This may have contributed to the limited improvements in the present functional outcomes. Chronic movement impairments of this complexity require more time to create functional changes and are accompanied by additional challenges such as spasticity and learned co-contraction patterns.[6] Therefore, it would be beneficial for future studies to investigate the application of NGT during the acute phase of rehabilitation.

Three participants completed or exceeded the number of sessions recommended, and 2 more participants were 1 to 2 sessions away from completing the recommended number of sessions. While this is promising, it does appear that even those participants, who initiated system use at the recommended number of times, did not use the system for the amount of time requested. This suggests that changes to the dosage will need to be considered in future studies. Furthermore, even if the participants achieved perfect adherence, the total intervention duration will likely need to be increased in future studies in order for participants to receive the large amount of practice and repetitions suggested in the literature.[6]

Adherence to NGT was only fair among some participants, suggesting that 5 sessions per week may not be a feasible home therapy frequency. Shorter daily sessions were originally selected to minimize the possibility of overuse injuries; however, no soreness or progressive injuries were reported in interviews accompanying this study. In fact, results from our companion study found that participants on the whole found the game enjoyable and even suggested allowing use for a longer period. Therefore, requiring fewer sessions of longer duration may also provide a greater level of therapeutic intensity.

Study limitations

Limitations of this study include the small convenience sample and the variability in participants' age and time poststroke. Care should also be taken when interpreting the sEMG results, since the maximal sEMG signal can be influenced by a number of factors outside of muscle activation, such as the condition of the participant's skin, electrode placement, electrode contact with the skin, and the nature of the task. Another limitation was the lack of control for confounding factors, such as receiving other motor therapies. However, of the participants who were receiving additional therapy, most were seen just 1 or 2 times a month. Nevertheless, the participants who were not receiving additional therapy had the greatest adherence. This suggests that stroke survivors who are provided with an engaging home therapy program, in the absence of other direct therapy services, may be more apt to follow through with NGT.

Conclusions

NGT is an engaging combination of biofeedback with a commercial computer game, targeting activation of a particular muscle group or co-contraction within an agonist/antagonist pair. In this preliminary study, we found an effect at the level of sEMG showing a decrease in co-contraction but no changes at the level of functional movement. NGT may benefit from a longer intervention time and the inclusion of more functional activity training to assist in the transfer of changes at the muscle activation level to changes in function. Further research is needed to determine the value of this intervention in this clinical population.

Suppliers

a. Peggle; PopCap Games, 2401 4th Ave #300, Seattle, WA 98121.
b. Delsys Bagnoli EMG System; Delsys, PO Box 15734, Boston, MA, 02215.
c. Qualisys Oqus 300 Camera System; Qualisys Motion Capture Systems, Packhusgatan 6S-411 13, Gothenburg, Sweden.
d. SPSS version 18; IBM, 1 New Orchard Rd, Armonk, NY 10504-1722.
e. Matlab 2011a; The MathWorks, Inc, 3 Apple Hill Dr, Natick, MA 01760-2098.
f. LabView; National Instruments, 11500 N Mopac Expwy, Austin, TX 78759-3504.

Keywords

Rehabilitation; Stroke; Technology; Telemedicine; Video games

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Appendix 1 Details of sEMG and Kinematic Data Reduction

Surface electromyography

sEMG data from the game play sessions were down-sampled at 500Hz and low-pass filtered at 200Hz before rectification and binning into 10-millisecond windows. Data greater than 3 SDs above the mean were considered signal outliers likely caused by nonphysiological signals (eg, wire movement artifacts). Wavelet analysis was used to establish a reliable baseline level of electromyography, which varied in the home because of changes in environmental noise and variations in electrode placement. Daubechies order 7 (Matlab Wavelet Toolbox version 2011a[e]) was used as the mother wavelet function to perform feature extraction from the signal recorded during each game play session.[32,33] Daily maximal contraction baseline values were calculated using the mean signal amplitude during all times where features were not detected, and this was subtracted from the rectified signal. The maximum muscle signal for each session was then calculated as the average of the 3 largest peaks for each muscle. For data collected during game play, a burst of activity in each muscle was subsequently defined as features in the binned data that exceeded 15% of the maximum activity that day for at least 0.5 seconds. Independent activity was then calculated as the percentage of bursts detected in the agonist muscle when no simultaneous burst was detected in the antagonist. Independence of muscle activity was calculated for the game play sessions rather than a co-contraction ratio because of an inability to determine whether the subject was attempting to move in flexion or extension during game play.

sEMG during assessments was processed using custom software created in LabView.[d] Because of technical difficulties during testing, some sEMG and kinematic outcome variables have fewer than the 9 participants in the group data analysis. First, the sEMG recording and the video recording were synchronized using a light-emitting diode that flashed when the sEMG recording began. The MVC level was determined by creating an envelope of activity with a very low pass (0.5Hz), eighth-order Butterworth filter applied to the rectified, null-offset sEMG signal during the MVC task. The peak amplitude of the envelope was determined to be the MVC level for each trial. The 5 MVC trials for flexion and for extension were averaged to provide an MVC level for each assessment.

The start and end of each task were identified in video recordings to define the range of data for subsequent analysis (see fig 1). The start of the task was marked as the initiation of movement, and the end of the task was identified when the participant made contact with the cup. Only 2 participants grasped the cup, and they were excluded from this analysis. The sEMG signal for determining timing and amplitude parameters for the reaching task was rectified and 20-Hz low-pass filtered using a forward and reverse pass Butterworth filter with an order of 4 per pass. To determine the amount of sEMG co-contraction, the signal's onset and termination were determined using an automated threshold level. This threshold method was applied after filtering without integration of the signal. The automated threshold of the quiescent data level was set using the following equation: Threshold multiplier $\times$ (Mean + n $\times$ SD of quiescent level). Events less than the quiescent level were not used in determining onset and termination. Events beginning or ending above the threshold were ignored.

To calculate co-contraction, the integrated sEMG signal for the agonist was divided by the integrated signal for the antagonist (over the period of agonist activity). In order to control for potential variability in the placement of electrodes and participants' daily variability in performance, the sEMG signals were normalized using the mean MVC level for wrist flexors and extensors calculated from the MVC task for each participant, and no other weighting was applied. The normalized co-contraction ratio is the integrated agonist value divided by the mean agonist MVC level over the integrated antagonist value divided by the mean antagonist MVC level. For the calculation of co-contraction, the extensor digitorum communis was always considered the agonist, and the flexor carpi radialis was always considered the antagonist. MVC values could not be collected during 1 or more assessments for several participants, and these participants are excluded from the results of this co-contraction analysis.

Kinematics

After data collection, markers were identified and files were exported for analysis using a custom LabView program.[d] The number of repetitions was identified using the third metacarpal marker as the metacarpal of interest. Then each trial's start and finish were visually identified using the Qualisys Track Manager program.[c] At the first movement of the third metacarpal marker the time was noted.

The variables of interest during the reaching task were reach time and number of movement segments during the reach phase. Reach time was calculated as the time from the start of movement at the third metacarpal that was greater than 2% of the maximal

velocity until the cup was moved a minimum of 2mm from its starting position (the average of the first 100 frames of data). The number of movement segments was calculated by first identifying the local minimum and maximum velocity for the hand marker during the reach phase. Velocity peaks were then identified as the difference between a minimum velocity and the next maximum velocity that was ≥20mm/s that occurred at least 150 milliseconds after the prior peak. The number of velocity peaks that met these criteria was considered the number of movement segments.

Maximal trunk displacement was defined as the resultant displacement of the trunk from the starting position in millimeters. The maximal elbow extension was calculated from the vector dot product of 2 line segments formed by the shoulder to the elbow marker and the elbow marker to the average position of the 2 wrist markers. Kinematics were also used to assess active range of motion, specifically extension at the wrist. This was computed using a vector cross-product method to calculate the angle between the 2 planes formed from the elbow marker and 2 wrist markers and the 2 wrist markers and the hand marker, with respect to the axis between the 2 wrist markers (ie, flexion-extension axis). The amount of wrist extension was calculated as the absolute value of the angle of the wrist at the start of the movement minus the maximum angle of wrist extension that was completed during the trial.

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