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Use of an EMG-controlled game as a therapeutic tool to retrain hand muscle activation patterns following stroke – A pilot study

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Abstract

Background/Purpose: To determine the feasibility of training with electromyographically (EMG)-controlled games to improve control of muscle activation patterns in stroke survivors.

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Methods: Twenty chronic stroke survivors (>6 months) with moderate hand impairment were randomized to train either unilaterally (paretic only) or bilaterally over 9 one-hour training sessions. EMG signals from the unilateral or bilateral limbs controlled a cursor location on a computer screen for gameplay. The EMG muscle activation vector was projected onto the plane defined by the first two principal components of the activation workspace for the non-paretic hand. These principal components formed the x- and y-axes of the computer screen.

Results: The recruitment goal (n=20) was met over 9 months, with no screen failure, no attrition and 97.8% adherence rate. After training, both groups significantly decreased the time to move the cursor to a novel sequence of targets (p=0.006) by reducing normalized path length of the cursor movement (p=0.005), and improved the Wolf Motor Function Test (WMFT) quality score (p=0.01). No significant group difference was observed. No significant change was seen in the WMFT time or Box and Block Test.

Discussion/Conclusion: Stroke survivors could successfully use the EMG-controlled games to train control of muscle activation patterns. While the non-paretic limb EMG was used in this study to create target EMG patterns, the system supports various means for creating target patterns per user desires. Future studies will employ training with the EMG-controlled games in conjunction with functional task practice for a longer intervention duration to improve overall hand function.

Keywords

stroke; motor impairment; neuro-rehabilitation; upper limb; EMG; serious game

1. Introduction

Almost 800,000 Americans experience a stroke each year.[1] While the large majority of these individuals survive the stroke, most face sensorimotor deficits in the upper and lower extremities.[2–4] These impairments have profound implications for performance of a variety of everyday tasks, self-care, and employment opportunities. Regaining motor control is a priority for stroke survivors, but one that is difficult to attain.[3–5]

Current treatment typically focuses on repetitive practice of specific movements or tasks,[6] sometimes with assistance,[7] strengthening,[8] and/or tone reduction.[9] Fundamentally, however, the impairments arising after stroke result from altered muscle activation patterns,[10–12] which are currently only indirectly addressed in rehabilitation practice. Dexterous movement requires proper muscle activation patterns to be implemented across multiple muscles in a coordinated manner.[13,14] For many stroke survivors, achieving proper muscle activation patterns necessary for functional tasks is a challenge.[12] Deficits are often apparent in the abilities to fully activate a muscle,[15] deactivate a muscle,[16] modulate muscle activation with specific tasks,[17] and coordinate muscle activation patterns across multiple muscles.[18] The inability to fully activate muscles voluntarily, as well as to generate and control a variety of task-appropriate muscle activation patterns, severely limits function. In the hand, these deficits result in diminished finger extension[19] and incorrectly directed fingertip forces that preclude stable grip of an object.[20,21]

Direct training of muscle activation patterns holds promise for improving motor control of the paretic limb. The activation patterns represent underlying control better than other variables such as joint movement or torque, as the latter arise from the net contributions of the different muscles without discernment of different conditions.[19,22] For example, lack of movement or torque production at a joint could arise from an inability to activate the agonist muscles, but also could arise from excessive coactivation of agonists and antagonists. Training of activation patterns, such as through the use of electromyography (EMG)-triggered rehabilitation devices like neuromuscular electrical stimulators[23] and arm and hand exoskeletons,[24] has shown efficacy in stroke rehabilitation. One means of implementing this direct training of muscle activation patterns is through “serious” computer games,[25,26] as they can improve participation, motivation, and enjoyment to promote the repetitive practice needed for rehabilitation.[27,28]

Serious games have been increasingly used to address needs in stroke rehabilitation,[29,30] including with utilization of EMG control in an attempt to alleviate excessive coactivation between two proximal arm muscles.[31,32] However, these previous studies did not address control of more than two muscles simultaneously, as is needed for most functional tasks. Therefore, we previously developed a therapy platform in which control of activation of up to 8 muscles may be required to play computer games. EMG signals directly control cursor movement, the user input for the games. Mapping of the EMG activation vector to the cursor location can be customized for each individual according to rehabilitation goals. A pilot study involving healthy adults participating in training sessions with this platform verified that individuals could learn to control activation patterns presented implicitly.[33]

The objective of the present study was to determine the feasibility of training with these EMG-controlled computer games to improve control of the muscle activation patterns in stroke survivors. We focused on muscles of the distal upper extremity, a region commonly impaired after stroke.[4,34,35] As a proof-of-concept, we examined whether stroke survivors could use their paretic limb to create target patterns derived from their non-paretic limb. This was analogous to our pilot study in which neurologically intact individuals used their non-dominant limb to create target patterns derived from their dominant limb.[33] Also in accordance with that study, we examined a unilateral vs. bilateral training paradigm, in which the participant controlled the game only with the paretic limb, or with the control signal derived from a variably weighted combination of the paretic and non-paretic limbs. Bilateral training of the arms has been shown to have an additive effect on unilateral training,[36] possibly due to recruitment of uncrossed corticospinal pathways, bilateral subcortical pathways, or through an interhemispheric mechanism.[37,38] As bilateral activities involving the hands are prevalent in daily living,[39] bilateral training may also prove beneficial for distal upper extremity muscle control. Additionally, bilateral training involving a gradual shift in relative weighting of input from the non-paretic to the paretic limb could better facilitate maintaining an appropriate level of challenge throughout the training[40] than unilateral training. We hypothesized that both groups would improve game performance through better control of muscle activation patterns, but that improvement would be greater for the group using the bilateral paradigm.

2. Methods

Participants

A convenience sample of 20 stroke survivors participated in this pilot study. All participants were recruited from an institutional research database for clinical neuroscience studies that included information about the participant's stroke including the level of upper limb impairment. Inclusionary criteria required that each participant be an adult (minimum age of 18 years old) who incurred a single, unilateral stroke at least 6 months prior to enrollment in the study, as verified by the participant. Participants were required to have moderate hand impairment as indicated by a rating of Stage 4 or 5 on the Stage of Hand section of the Chedoke-McMaster Stroke Assessment (CMSA-H).[41] Stage 4 implies good movement in flexion and some extension; Stage 5 includes movement in flexion, extension, and abduction with slowness. Participants were excluded if they had severe visual deficits that precluded being able to see the game screen or had received botulinum toxin in their upper limb in the past 6 months. This trial was registered on ClinicalTrials.gov (NCT03619772), following the EQUATOR network guidelines for a randomized clinical trial (CONSORT). All participants provided written informed consent as approved by the Northwestern University Institutional Review Board.

Study Design

This study was a single-blind interventional randomized controlled trial. Participants were randomly assigned to either the Unilateral or Bilateral training group (n=10 in each group) by drawling lots, stratified by CMSA-H level. Both groups came to the laboratory (a freestanding rehabilitation hospital) for 11 sessions: a pre-training evaluation, 9 training sessions with the EMG game (approximately 45 minutes each, 3 times per week for 3 weeks), and a post-training evaluation. The Unilateral group played the game with the paretic limb only. The Bilateral group played the game by controlling activation of muscles in both the paretic and non-paretic limbs, gradually shifting from primary control with the non-paretic limb to that of the paretic limb.

EMG Game

For both the Unilateral and Bilateral groups, the purpose of the training with the EMG-controlled games was to improve voluntary control of distal muscles in the paretic hand. For every session, surface active EMG electrodes (19.8 × 5.4 × 35 mm, Bagnoli 2-slot electrode, Delsys, Inc., Natick, MA) were placed on the forearms and hands to record activity from four muscles in each limb for both limbs for both groups. The four muscles were: an extrinsic finger extensor, extensor digitorum communis (EDC), a wrist muscle, extensor carpi ulnaris (ECU), an extrinsic finger flexor, flexor digitorum superficialis (FDS), and an intrinsic muscle, first dorsal interosseous (FDI). The skin was thoroughly cleaned with alcohol swabs before placement of the EMG electrodes. The 8 EMG signals, four from the paretic limb and four from the non-paretic limb, were digitized at 1 kHz (NI-DAQ USB-6443 BNC, National Instruments, Austin TX) and processed in Simulink (Mathworks, Natick MA). Each signal was bandpass filtered between 33 and 439 Hz, then rectified and lowpass filtered with a corner frequency of 1.6 Hz to produce an amplitude envelope of the EMG signal. At the beginning of each training and assessment session, the subject was instructed to produce maximum voluntary contraction (MVC) for each muscle through a variety of guided hand/wrist movements; visual feedback of peak muscle activation was provided to encourage optimum performance. The peak envelope value for each muscle was subsequently used to normalize the processed (rectified and filtered) EMG signal for the corresponding muscle in real time.

The EMG-controlled games translate the muscle activation patterns from multiple surface electrodes onto a two-dimensional game screen.[33] The mapping of the EMG vector to cursor location is determined by the projection of the vector onto the plane formed by target muscle activation vectors defining the horizontal and vertical axes of the screen. For this study, the target vectors for both groups were obtained from the patterns employed in the non-paretic limb. At the start of each session, the participants performed a calibration exercise during which they moved the fingers and wrist of the non-paretic limb to create a variety of postures, as directed with a visual display.[33] Principal component (PC) analysis was performed on these non-paretic EMG data to identify activation vectors describing the EMG space of the non-paretic hand. Two PCs (named PC1 and PC2) were selected as the target EMG vectors and were mapped to x- and y-axes, respectively, on the computer screen.

In addition to target vector direction, the target vector magnitude was also scaled in a custom manner for each subject in order to provide an appropriate level of challenge. Specifically, calibration data were also collected for the paretic hand for both groups. From these calibration data, an outline of the achievable activation region for the paretic hand was projected onto the plane formed by the target PCs. Study personnel selected the extent of the achievable region for the paretic hand to use for training by drawing a rectangle on a custom graphical user interface (GUI).[33] The activation ranges, represented by the lengths of the sides of the rectangle, were mapped to the full ranges of the computer screen. During game play, the EMG vector was projected onto the PC1-PC2 plane through the dot product, and the resulting projection was shown as a cursor on the game screen.

Fundamental cursor control differed for the two groups. For the Unilateral group, the EMG vector from the paretic limb was projected directly onto the PC1-PC2 plane. For the Bilateral group, a linear combination of the EMG vectors for the paretic and non-paretic limbs was projected onto the PC1-PC2 plane for each session. A relative weighting of the two EMG vectors was employed, with weighting of the paretic limb increasing over the 9 sessions in a linear fashion. During the first session, 100% weight was placed on the vector for the non-paretic hand and 0% on the paretic hand. The scaling progressed from 87.5%:12.5% (non-paretic:paretic) for the second session to 75%:25% for the third session, eventually reaching 0% non-paretic and 100% paretic for the final session. In this manner, the challenge of controlling the cursor was systematically increased. The weighting percentage utilized was unknown to the participant.

Cursor movement allowed the participant to play a number of serious computer games, previously described in detail.[33] These include a Picture Reveal game, for which movement of the cursor into one of the 5×5 grids causes the tile to disappear, thereby revealing part of a hidden picture (Fig 1A). In the Maze game, participants guide the cursor around the walls to travel from the Start to the Finish (Fig 1B). For an Asteroids-type game, participants move the cursor to collect coins while avoiding asteroids (Fig 1C). A Volume Exploration game encourages thorough exploration of the muscle activation space by displaying the extent to which the participant accesses the 4-dimensional EMG space (Fig 1D). In this game, the activations of the first two muscles control the position of the cursor in the left grid and the activations of the other two muscles control the position of the cursor in the right grid. The color of the tile in the left grid indicates the extent to which the activation region represented by that tile has been explored within the tiles in the right grid. In this way, the 4-dimensional activation space can be represented on the two-dimensional screen.

Feasibility

We examined time to recruit the target sample size as well as number of screenings needed. Adherence (measured by attendance and participation in the protocol) as well as attrition were obtained. Adverse events were monitored. Any game equipment malfunctioning was also monitored.

Outcomes

We examined the effect of the EMG game on muscle activation pattern control, as determined by performance on a test that the participants did not practice during the training sessions. Specifically, the control of the muscle activation pattern was assessed by recording the time required to move the cursor into each of four predetermined target squares spanning the 5×5 grid (top center, bottom center, center right, and center left). For both groups, the paretic hand EMG signals were used to control the movement of the cursor while the target PCs were from the EMG vectors of the non-paretic hand. Four repetitions of each target were randomly presented, resulting in a total of 16 targets. This assessment was performed before the initiation of training and after the conclusion of the training sessions. The completion time for this assessment was the primary outcome measure of this study. Additionally, we examined the normalized path length traversed by the cursor during this test by dividing the actual curvilinear distance travelled by the minimal distance (the sum of the Euclidean distances) between consecutive targets.

While not anticipated due to the limited duration of the intervention and lack of integration of functional task practice in the study design, possible translation to upper extremity movement was assessed using standardized clinical assessments. Specifically, the Wolf Motor Function Test (WMFT)[42] was administered to assess the duration (time) and quality (score) of prescribed upper limb movements, such as grasping and lifting a pencil. The Box and Blocks Test (BBT)[43] assessed the number of blocks moved over the barrier in 60 s. The same rater, blinded to group assignments, administered these clinical assessments for all participants for both Pre and Post evaluations.

Analysis

Repeated measures analysis of variance (ANOVA) was performed to evaluate the effects of training on the primary outcome measures of completion time and normalized path length. The 2×2 ANOVA had the within-subject factor of Session (Pre/Post) and the between-subject factor of Group (Unilateral/Bilateral). Normality of the data distribution was examined using the Shapiro-Wilk’s test. A Bonferroni correction was implemented for the two tests, such that the overall significance level was set to $\alpha = 0.025$. For the secondary outcomes from the clinical assessments, confidence intervals were created for the change in score from the Pre to Post evaluations, in addition to ANOVA.

3. Results

3.1 Feasibility and Participants

We identified 39 potential participants from the institutional research database. During an initial phone call, 19 declined participation. Twenty potential participants came to a screening visit and all 20 of them met the inclusionary and exclusionary criteria (i.e., no screen fails). The 20 participants were recruited over 9 months with an average accrual rate of 2.2 every month. A consort flow diagram is shown in Fig 2.

Participant characteristics are shown in Table 1. There were no significant differences between the groups for the demographic data. Adherence was 97.8%, as only 4 training sessions were missed out of possible 180 across all participants. The attrition rate was 0%. Across all sessions, there were no reported adverse events or equipment problems.

3.2 Outcomes

The primary outcome measure, related to control of the cursor to perform the test, improved significantly for both groups. Test completion time to reach the 16 targets on the 5×5 grids decreased significantly after the training across both groups (Fig 3A, $p=0.006$ for Session). The time dropped by 59% for the Unilateral group and 26% for the Bilateral group (Table 2). We observed no significant differences in outcomes between the two groups ($p>0.22$ for Group and Group x Session). The normalized path length of the cursor (actual relative to minimum path length) was also significantly reduced from pre-training to post-training (Fig 3B, $p=0.005$ for Session). One participant in the Bilateral group had a path length that was a significant outlier (37 times greater than the group mean); his/her data were not included in path length analysis. Normalized path length decreased by more than 54% for the Bilateral group and 37% for the Unilateral group. Examination of data for individual subjects confirmed that roughly 75% of the participants exhibited a decrease in normalized path length (Fig 3C). No significant differences in normalized path length were observed between groups ($p>0.14$ for Group and Group x Session). No group difference at baseline was found for either test completion time or normalized path length (Table 2).

For the secondary outcome measures, the WMFT Functional Abilities score did increase across both groups: the average score of both groups increased from 3.0 ± 0.3 at Pre to 3.2 ± 0.3 at Post ($p = 0.01$ for Session, Fig 3D). The mean increase was greater than the minimum detectable difference of 0.1[44] but less than the minimum clinically important difference of 1.0–1.2.[45] We did not observe any statistically significant effect of Session or Group on the time to complete the WMFT or BBT ($p > 0.26$ for Session, Group, and Group x Session for both WMFT time and BBT), although there was a group difference at baseline for WMFT time.

4. Discussion

Stroke survivors with moderate hand impairment were able to use the system of EMG-controlled serious games. Twenty participants were successfully recruited, with a 97.8% adherence rate and no attrition. Lack of screen fails is attributable to the research registry that included upper limb impairment information for each participant, thereby allowing for efficient recruitment. Although we did not use satisfaction measures, individuals anecdotally reported that they liked the study, potentially due to the ability within the game to use their muscles to achieve a desired end even when they did not have the capability to use their hand during activities of daily living outside the game.[40] Additionally, the system is customizable to the abilities of the user on the given day. Game challenge can be matched to the user on the GUI through selection of the scaling of the EMG space to be mapped to the screen and adjustment of game parameters, such as number of game tiles or the inclusion of walls to prevent loss of forward progress in the Maze game. It is possible that the high adherence rate and high retention may be related to participants' enjoyment of the challenge inherent in the games. This may have positively affected motivation.[27,28]

After the training, the stroke survivors in both groups improved the ability to control the cursor on the screen through the creation of muscle activation patterns in the paretic limb. Across all participants, Test Completion Time (16 targets) decreased by 5.3 minutes, a 46% reduction. This was achieved primarily by reducing undesired cursor movement. The normalized path length across all of the targets was reduced by 45%. These findings indicate that participants were able to move the cursor and achieve the target muscle activation pattern in a much more efficient manner, as we observed previously with neurologically intact subjects.[33] An improved control of activation patterns might explain these results.

While not anticipated, participants had a significant improvement in the WMFT Functional Abilities score after training. For both groups combined, the WMFT Functional Abilities score increased by 0.23 out of 5. This increase is above the minimum detectable change of 0.1,[44] indicating that this increase is above the level of the measurement error. The WMFT Functional Abilities score assesses proper postural control, the presence of abnormal synergies, the involvement of other body parts to assist task performance, movement precision, fine coordination, and movement fluidity during prescribed tasks.[46] Thus, the training with the EMG game may have a potential to impact *quality of movement*. However, time to complete the WMFT and number of blocks transported in the BBT did not change significantly. Overall, the result is consistent with the previous two-muscle EMG-based training in which impairment was reduced after training.[31]

It should be noted that the target activation patterns for this study were drawn from the EMG signals recorded in the non-paretic limb. It is not clear that this is the optimal choice for stroke rehabilitation, at least for all individuals. The system is sufficiently flexible to allow the selection of other target vectors. For example, PCs can be fit to the EMG space of the paretic hand to work on improving control within and expanding this space. Alternatively, arbitrary desired target vectors can be read into the GUI. The clinician or user can choose the target activation patterns according to their specific therapy goals.

We did not observe any statistical differences in outcomes between the Unilateral and Bilateral groups. For these participants with moderate hand impairment, muscle control may have been adequate at the beginning of the study to directly work with the PCs from the non-paretic activation workspace. For more impaired subjects, it is possible that the bilateral approach may be beneficial. Alternatively, due to the ability to customize the training to the individual, it may be just as effective to immediately focus on unilateral training and incorporate non-paretic only if needed. The influence of motor impairment severity on efficacy of bilateral vs. unilateral training is an area worthy of further study.[47]

Limitations

This initial study of the system with stroke survivors was limited in scope. First, the sample size was small. Thus, the effect should be interpreted with caution. Second, a group receiving usual care or no treatment was not included as a control. While upper limb function is stable in the chronic stage,[48] the effect of psychosocial factors from participating in the study cannot be excluded. Third, no bilateral function was assessed. Thus, the effect of the bilateral training on bilateral function is unknown. Fourth, stroke survivors participated in 3 weeks of training. The effects of longer training periods are unknown. Fifth, as the primary goal of this study was to determine if stroke survivors, particularly in the chronic phase of recovery, could learn to improve control of their muscle activation patterns, no functional task performance was included in the therapy. A future study could implement training with the EMG-controlled game in conjunction with repetitive practice of upper extremity tasks to examine whether this improves control of the muscle activation pattern, quality of movement, and task performance.

Conclusions

In summary, EMG game training for improving control of muscle activation patterns in stroke survivors could be performed and participant compliance was high. Future directions may include investigation of utility of the bilateral approach in persons with greater upper limb impairments and expanding the activation workspace, while including bilateral functional outcome measures. Future studies may also examine the effect of the training with the EMG-controlled games in conjunction with repetitive practice of functional tasks, for a longer intervention duration, against a control group, while monitoring user satisfaction. Incorporation of proximal upper limb muscles may also be explored to target overall upper limb function.[31]

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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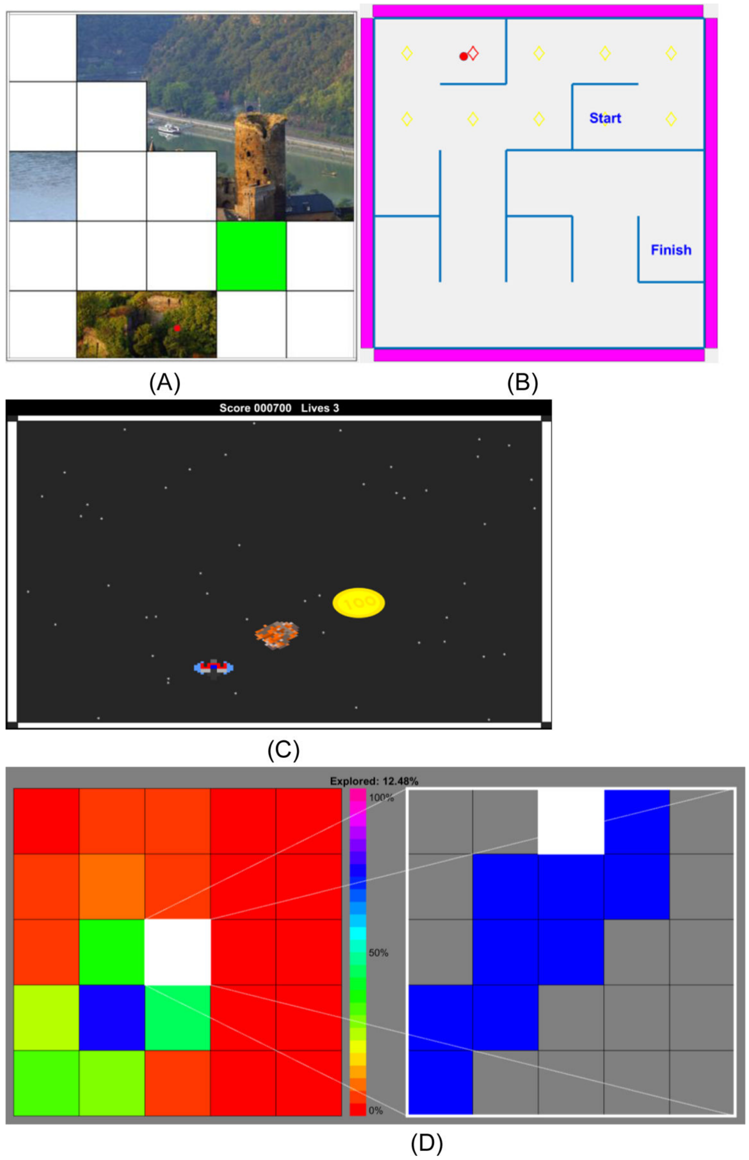

Figure 1.

Examples of games: A) Picture Reveal. User controls the location of the cursor (red dot). Maintaining the red dot within the indicated target (green) tile causes the white tile to be removed, revealing part of the hidden picture B) Maze. User attempts to move the red dot from Start to Finish. The walls are barriers to movement. To make the game easier, the game mode can be set to prevent the user from inadvertently moving the cursor backwards and losing forward progress. C) Asteroids. User tries to gather the gold coins without being struck by the asteroids. As performance improves, more asteroids appear. D) Volume Exploration. Activation for two muscles controls the cursor location (white tile) on the left plane and activation for other two muscles controls the cursor location on the right plane. The color represents the extent to which a certain activation region has been explored.

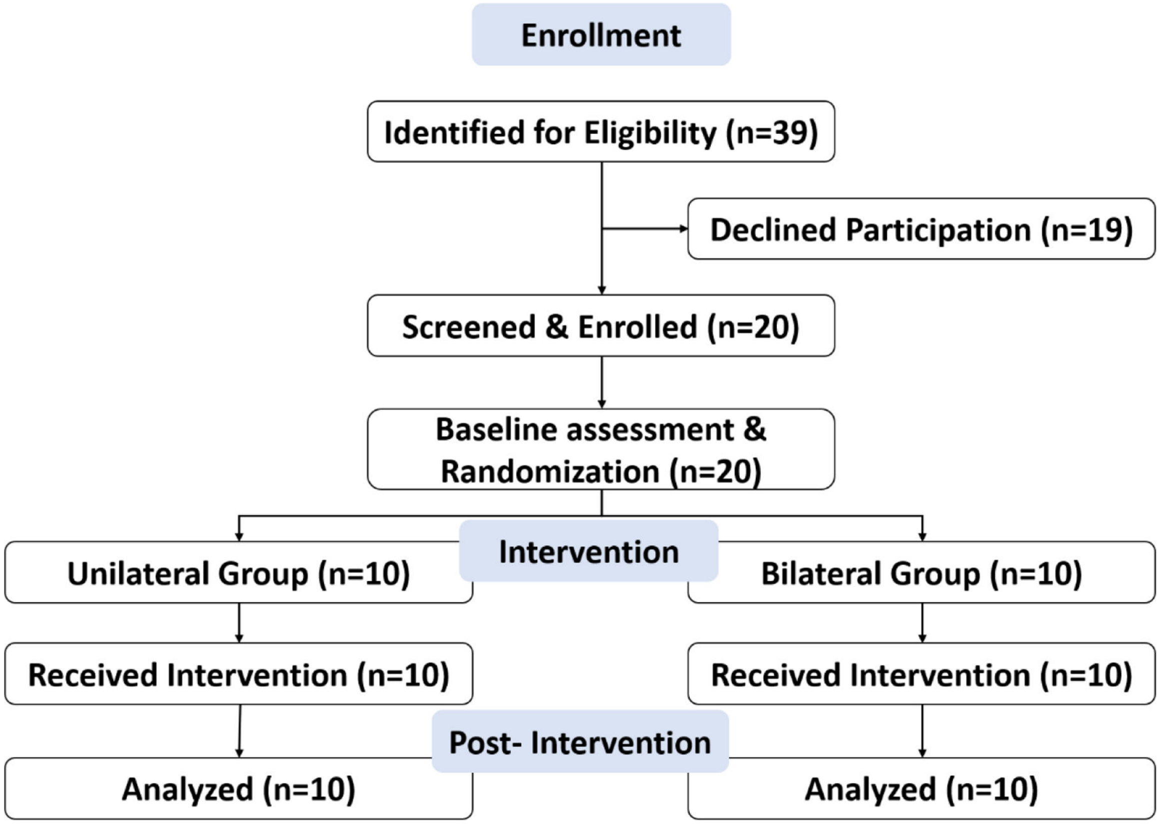

Figure 2.
Consort flow diagram.

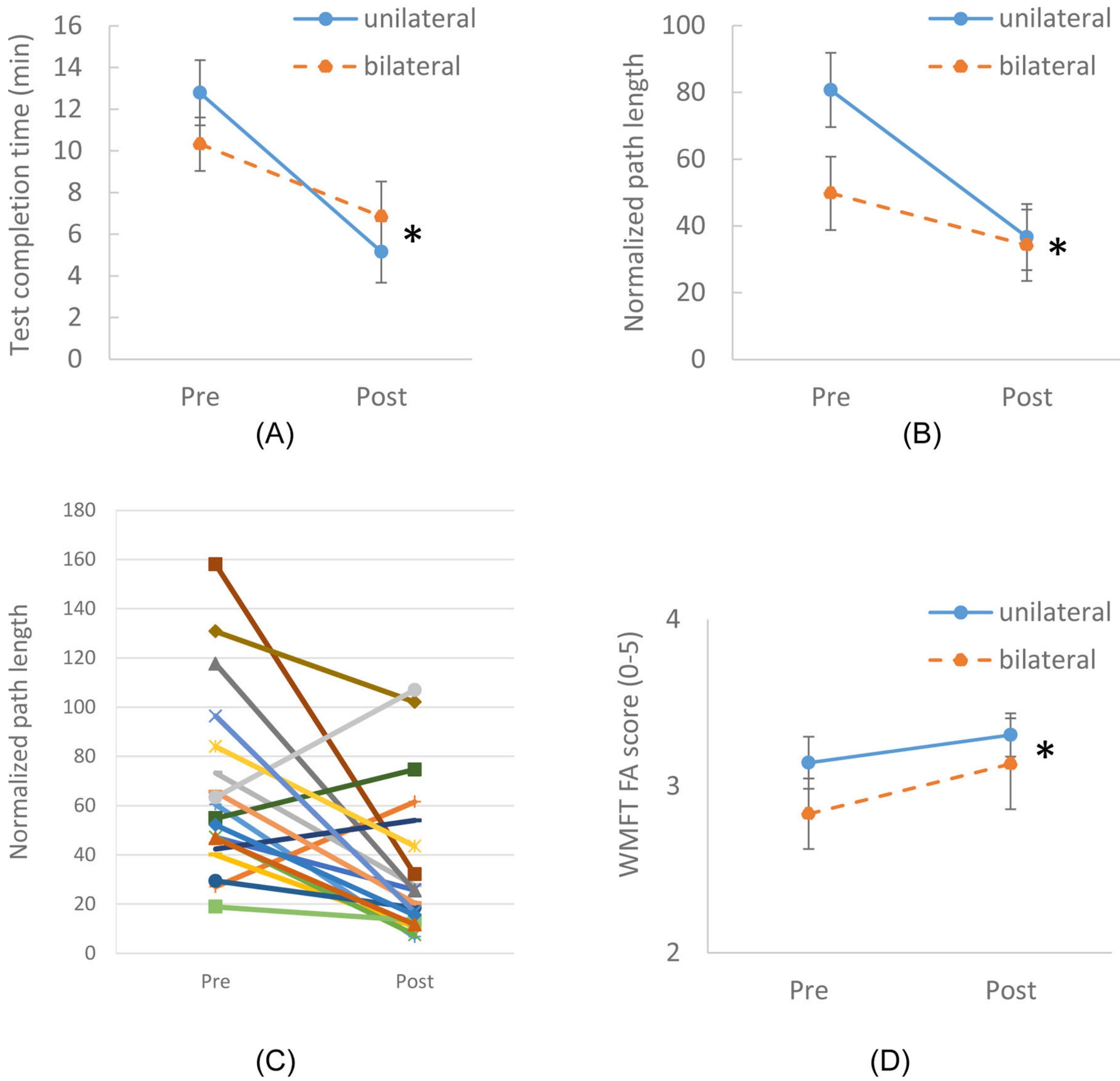

Figure 3.

The effect of the EMG game on the control of the muscle activation patterns as assessed by Test Completion Time (A) and normalized path length (B). Normalized path length during the test for individual subjects (C). The effect of the EMG game on the secondary outcome measure, WMFT score (D). Error bars indicate standard errors. The star signs indicate statistically significant difference between Pre and Post (for both groups).

Table 1.

Demographic information

	Unilateral Group (N=10)	Bilateral Group (N=10)	p-value
Age (Years)	60.4±7.7	59.4±8.5	F(1,18)=0.287, p=0.795
Time Since Stroke (Years)	9.5±5.0	10.5±9.7	F(1,18)=3.599, p=0.768
Gender	8M/2F	4M/6F	χ^2=3.333, p=0.068
Chedoke Hand Score (# of participants in score 4 vs. 5)	7 / 3	8 / 2	χ^2=0.267, p=0.606
Affected Hand	6R/4L	5R/5L	χ^2=0.241, p=0.623
Dominant Hand Before Stroke	9R/1L	9R/1L	χ^2=0.0, p=1.0

Table 2.

Outcome measures at Pre-training and Post-training. Mean ± standard error (95% CI) are shown. P-values are for the change from pre to post (for both groups). No significant group difference was found for any of the outcomes.

Outcome	Unilateral (n=10)		Bilateral (n=10)		F-value	p-value
	Pre	Post	Pre	Post		
Test Completion Time (min)	12.6 ± 1.3 (9.6, 15.6)	5.1 ± 1.3 (2.2, 8)	10.6 ± 1.0 (8.4, 12.8)	7.8 ± 1.9 (3.6, 12)	F(1,17)=9.703	p=0.006
Normalized Path Length	80.7 ± 9.6 (58.9, 102.5)	36.7 ± 8.6 (17.3, 56.1)	55.0 ± 9.6 (33.2, 76.8)	34.2 ± 9.2 (13.3, 55.1)	F(1,17)=10.273	p=0.005
WMFT (time)	17.8 ± 0.5 (16.6, 19.0)	15.5 ± 2.1 (10.7, 20.3)	24.6 ± 1.0 (22.3, 26.9)	26.0 ± 1.0 (23.7, 28.3)	F(1,17)=0.076	p=0.786
WMFT (score)	3.1 ± 0.1 (2.8, 3.4)	3.3 ± 0.1 (3.1, 3.5)	2.8 ± 0.2 (2.4, 3.2)	3.1 ± 0.3 (2.5, 3.7)	F(1,17)=8.429	p=0.010
BBT (blocks)	17.6 ± 1.3 (14.6, 20.6)	17.4 ± 1.7 (13.5, 21.3)	19.0 ± 3.3 (11.5, 26.5)	19.6 ± 3.3 (12.1, 27.1)	F(1,17)=0.007	p=0.935

WMFT: Wolf Motor Function Test, BBT: Box and Block Test