NeuroGame Therapy to improve wrist control in children with cerebral palsy: A case series

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Abstract

Objective: This case series examines the feasibility, specificity, and preliminary effectiveness of NeuroGame Therapy (NGT) for improving wrist control in four children with cerebral palsy (CP). NGT uses surface electromyographic (sEMG) signals routed through motivating computer games to improve motor control.

Methods: Primary outcomes of NGT included feasibility (hours of play) and specificity (changes in sEMG activity during game play). Secondary outcomes included changes in co-contraction, range of motion, segmental alignment, and spontaneous upper extremity function following intervention.

Results: Participants completed a mean of 8.8 hours of NGT over 5–6 weeks. Participants demonstrated dramatic improvement of the sEMG activity during game play. Several participants also showed improvements in range of motion, co-contraction, and spontaneous upper extremity function following NGT.

Conclusion: This case series provides evidence for the feasibility, specificity, and effectiveness of NGT. Future studies will pair NGT with functional practice to improve transfer of learning to daily activities.

Keywords: *Game therapy, pediatrics, cerebral palsy, surface electromyography, biofeedback*

Introduction

Cerebral palsy (CP) results in motor dysfunction that can restrict full participation in typical childhood activities [1]. Common impairments of CP include difficulty with selective muscle activation and muscle weakness or spasticity, which require specialized attention to promote improved function [2]. Though CP is not progressive, children with CP are at risk for developing long-term secondary impairments such as muscles weakness, restricted range of motion, and poor endurance for activity, all of which can lead to decreased participation in family, school, and community-based activities [3, 4].

Targeting specific motor dysfunction with an adequate amount of movement practice is the cornerstone of rehabilitation therapy for children with CP [5]. Salient feedback, high-intensity practice of adequate duration, and motivation to participate in the intervention are necessary to promote neuroplasticity and improve function [6–10]. Neuroplasticity is defined as the "adaptive capacity of the central nervous system (CNS)" and the "mechanism by which the brain encodes experience and learns new behaviors" [8]. These principles for enhancing neuroplasticity are particularly important for children with CP, as rehabilitation often continues in stages throughout life, rather than immediately following a traumatic event or illness.

Surface electromyography (sEMG) has historically been used to provide subjects with enhanced visual feedback in order to activate muscles in appropriate synergies. Related work demonstrates that this strategy can be successful for children with CP by providing salient information for muscle recruitment [11]. Young et al. [12] used sEMG visual feedback for an upper extremity tracking task in children with CP and found reduced co-contraction in antagonist muscles both during and after direct feedback. In addition, Bloom et al. [11] had children wearing a haptic biofeedback device on a specific upper extremity muscle for at least 5 hours

per day and demonstrated improved functional performance in all participants via goal attainment scaling. At present, however, biofeedback of sEMG is not commonly employed in the pediatric clinical environment due to cumbersome set up, antiquated or expensive equipment, and lack of motivating feedback.

NeuroGame Therapy (NGT) utilizes innovative new technology to allow sEMG signals to directly control the movements of popular computer games. This provides children with enhanced visual feedback of sEMG provided through highly-motivating computer games. In NGT, motor control is *shaped* through reinforcement of increased or decreased activity of muscles, including muscle activity that may not produce volitional movement at the joint. NGT provides augmented feedback on appropriate selective muscle control, a key contributor to impaired motor function in children with CP [13, 14]. The demands on the nervous system are automatically increased as the child succeeds at the game levels, and as the threshold for required muscular activation is carefully adjusted as children improve over the course of the intervention. *Repeated practice* is fostered by the engaging nature of the computer games and use within the child's natural home environment.

The present study investigated the feasibility and preliminary benefit of NGT. Our goal was to facilitate practice of selective muscle activation for children with hemiplegic CP in a fun and motivating game environment. The purpose of this case series was to: (1) investigate the feasibility of NGT as a home-based intervention tool, (2) determine the specificity of NGT in improving selective activation and control of wrist flexors and extensors during game play, and (3) to determine whether gains made during NGT transfer to active movement and functional tasks following NGT treatment.

Methods

Study design

This study utilized a multiple case study methodology with a repeated measures design. Two children followed Protocol 1, a lab-and-home-based protocol: $A_1A_2B_1B_2A_4A_5$ (A = Assessment, B_1 = Intervention in Lab, B_2 = Intervention at Home). Once feasibility in the home environment was established, two additional children were enrolled, completing a home-only protocol: $A_1A_2B_2A_3A_4$ ('Protocol 2'). The two protocols are explained in detail below.

Participants

Inclusion criteria for all four children with CP were: aged 8–16 years, diagnosis of CP with unilateral upper extremity involvement, adequate cognitive skill (as evidenced by placement in a mainstream school classroom), and adequate vision and hearing. Exclusion criteria were: co-existence of behavioral or developmental disorders (e.g., Attention Deficit Hyperactivity Disorder (ADHD), or Autism Spectrum Disorders), and visual impairment not correctable by glasses.

None of the children received any anti-spasticity drugs (e.g., Botulinum toxin, Baclofen) or had any surgical procedures on their upper extremities in the 6 months prior to or during their participation. If children were involved in a regular physical and occupational therapy program, they continued their regimen throughout the study. All children and parents provided their assent/consent to participate in the study according to the procedures approved by the University of Washington Human Subjects Division.

The Manual Abilities Classification System (MACS) was used to classify children according to how they used their upper extremities during daily activities via observation and parent interview [15]. This scale describes upper extremity function from Level I-V, ranging from I: "Handles objects easily and successfully" to V: "Does not handle objects and has severely limited ability to perform even simple actions." The MACS has excellent reported interrater reliability and construct validity for children with CP [15]. Table I describes the participants' age, diagnosis, MACS level, concurrent therapies the child was receiving, and outcome measures for each child. Pseudonyms are used for each child.

Intervention

NGT was designed to specifically target independent muscle activation, thereby improving active wrist extension and decreasing inappropriate muscle co-contraction during wrist movement. We used a modified Neurochip circuit [16, 17] to transform bi-polar surface electromyography (sEMG) from two muscle groups into *control* of a computer game. The sEMG activity required for game play was adjusted to the participant's level of impairment.

During NGT, sEMG recorded from the targeted wrist flexor and extensor muscle groups controlled the popular computer game *Peggle*® [1]. To play *Peggle*® via NGT, the mouse's function was disabled, and instead sEMG flexor muscle activity rotated the ball launcher in one direction, and extensor muscle activity rotated the ball launcher in the opposite direction (Figure 1). To promote bi-manual

Table I. Participant characteristics and protocol.

Protocol	Participant (pseudonym)	Age (years; months)	CP diagnosis	Side of UE[a] involvement	MACS level	Concurrent therapies	Secondary outcome measures
1	Alex	13; 8	Spastic diplegia	Right	III[b]	S-B[c] OT S-B PT Outpatient PT Aquatic Therapy	AROM[d] SHUEE[e]
1	Brittany	11; 6	Spastic hemiplegia	Right	II[f]	None	sEMG[g] AROM SHUEE
2	Chris	10; 6	Spastic hemiplegia	Left	II	OT PT Vision Therapy	sEMG[h] AROM SHUEE
2	Danielle	8; 7	Spastic hemiplegia	Left	III	S-B OT S-B PT	sEMG[h] AROM SHUEE

[a]UE = Upper Extremity; [b]Level III = "Handles objects with difficulty; needs help to prepare and/or modify activities"; [c]S-B: School-Based; [d]AROM = Active Range of Motion; [e]SHUEE = Shriner's Hospital Upper Extremity Evaluation; [f]Level II = "Handles most objects but with somewhat reduced quality and/or speed of achievement"; [g]sEMG completed for active wrist extension, ball throw, and pegs; [h]sEMG completed for active wrist extension, ball throw, and can.
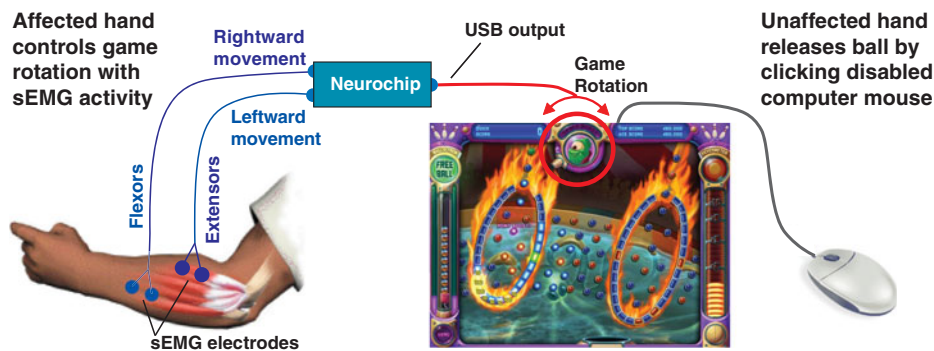

Figure 1. NGT interface. sEMG signals from agonist and antagonist muscle groups of the forearm are transformed using the Neurochip, which produces a USB output to a computer for control of the ball launcher on the top of the screen (circle) in the popular computer game *Peggle*®. Contracting 1 set of muscles moves the launcher to the right, while the other muscles move it to the left. A disabled mouse that cannot control the aim is used to launch the ball when muscle activity has correctly aligned the launcher with the desired target.

coordination, the participant then used the uninvolved hand to click a button to release the ball, while holding the aim of the ball launcher steady via sEMG activity recorded from the affected upper extremity.

The amount of muscle activity necessary to control the game in each direction was manipulated by adjusting the amplifier gain of each muscle group in order to individualize treatment. Amplifier gain for the wrist flexors and extensors was initially set to enable success in game play while retaining some challenge. Once the game was mastered at a certain level, these gain values were changed to facilitate increased selective activation. This was done by a combination of making the flexor gain more sensitive (thereby requiring less activity from spastic flexor muscles) and/or by making the extensor gain less sensitive (requiring more activity from paretic extensor muscles). Gain adjustments occurred at intervals throughout the intervention to challenge the children to practice with greater coordination of antagonist muscles. On-board memory recorded sEMG signals to a microSD memory card during clinic or home game play sessions for offline analysis of muscle coordination patterns.

Intervention Protocol 1. Children completed two pre-test assessments, 1 week apart. Children then played NGT in the laboratory for a total of five sessions over a 2-week period. Following this, each child was asked to play NGT at home at least three times per week for 30 minutes per session, for a total of 3–4 weeks. Two post-test assessments were then conducted, 4 days apart. Figure 2 outlines the study protocol.
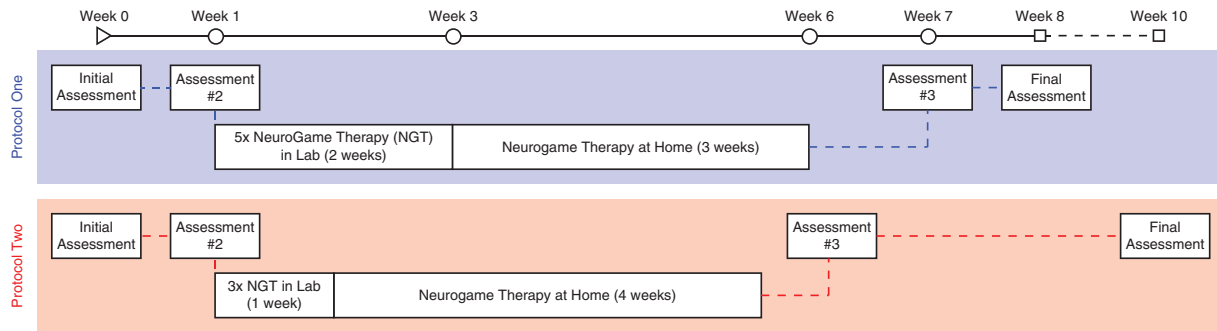
Figure 2. NGT Intervention Protocols. Intervention Protocol 1 involves two pre-tests (1 week apart), 2 weeks of in-lab game play, 3–4 weeks of in-home game play, and two post-tests (4 days apart). Intervention Protocol 2 involves two pre-tests (1 week apart), three training sessions, 4 weeks of in-home game play, and two post-tests (1 month apart).

Intervention Protocol 2. The protocol was subsequently adjusted to better quantify the effect of NGT after observing substantial improvements in the first two subjects, and determining the feasibility of completing NGT in the home environment. For Protocol 2, children again completed pre-tests 1 week apart. Children then received three training sessions in the laboratory to determine the appropriate starting level and to learn how to don/doff the electrodes used in the NGT system. Then the children were asked to play NGT at home three to five times per week for 30 minutes per session, for a total of four weeks. In Protocol 2, post-tests were one month apart to better capture sustained improvements.

Measures

Primary outcomes. The purpose of the primary outcome measures was to examine the feasibility and specificity of NGT.

Dose and adherence of NGT. The total duration of game play sessions were retrieved from the NeuroGame System's on-board memory for each child. These data were calculated for both the full protocol (lab + home) as well as the time played at home, to determine both the total dose as well as home adherence to the intervention.

sEMG during game play. Changes in selective muscle activation and maximum wrist extensor activity during game play were analyzed. sEMG from wrist flexor and extensor muscles was sampled at 2 kHz during all game play sessions and stored on the NeuroGame system for offline analysis of independent antagonist activity and maximum muscle activation.

Secondary outcomes. Secondary measures were used to explore whether gains made during NGT were generalized to movement outside of game play.

Children completed all outcome measures, with the exception of Alex who did not complete the sEMG measures.

sEMG during active movement. sEMG was used to record co-contraction from the targeted arm muscles during several tasks incorporating wrist extension. Each child performed three of the following tasks: active wrist extension against gravity ("active wrist extension"), throwing a tennis ball overhand into a basket ("ball throw"), lifting a can from a table using wrist extension to place it in a vertical slot ("can"), and/or taking pegs from the uninvolved hand and placing them in a vertical pegboard at chest height ("pegs"). Each task was repeated two–five times. Activities were customized for the first two subjects according to their disability, but were standardized for the last two subjects in order to more rigorously compare improvements across subjects.

Although electrodes were placed over the upper trapezius, serratus anterior, biceps, triceps, and wrist extensor/flexor muscle groups, we only report on the results for the wrist extensors and wrist flexors as these were the muscles targeted during the NGT intervention. Initial electrode placement was measured for each child, and the same placement was used for subsequent test sessions. sEMG during Maximum Voluntary Contractions (MVC's) was also recorded for normalization purposes.

Active range of motion (AROM). Active wrist extension was completed one to five times per test session. Starting in a neutral wrist position, the child extended his/her wrist against gravity as much as possible before returning to neutral. For Alex, who was unable to actively achieve a neutral position, he started and ended in his resting flexed wrist position. These trials were videotaped for later analysis.

Shriner's Hospital Upper Extremity Evaluation (SHUEE). The SHUEE was administered to each

child to evaluate active movement and quality of unilateral upper extremity use during functional tasks [16]. For this test, the child was video recorded while completing 16 tasks with their involved arm/hand either as the primary hand or as an assisting hand. Analysis consisted of a rating of spontaneous function on a 5-point scale for nine items (Spontaneous Functional Analysis [SFA]), segmental alignment of the extremity when performing all 16 tasks (Dynamic Positional Analysis [DPA]), and the ability to grasp and release in three different wrist positions (flexion, neutral, and extension). The SHUEE has good psychometric properties for use with children with unilateral CP, including intrarater reliability ($r > 0.98$), interrater reliability ($r > 0.89$), concurrent validity, and construct validity [18].

Data processing

Primary outcomes

Dose and adherence of NGT. Total time using the NGT system at home was calculated and averaged over the number of weeks of home therapy, as the early version of the autonomous NGT system did not permit specific days to be identified. Later versions of the system now stream each home therapy session to the cloud for precise, real-time quantification of home adherence.

sEMG during game play. Maximum muscle activity of the typically weak wrist extensors was calculated during each session by averaging the three largest bursts of the extensor muscle during game play. Values were normalized to the first day of game practice. To examine antagonist independence, all muscle bursts were detected in the extensor muscles. Subsequently, the flexors were examined to determine whether or not a burst occurred simultaneously in the flexors and extensors (i.e., antagonist co-contraction). To examine selective muscle activation, the percentage of wrist extensor muscle bursts occurring *without* co-activation of wrist flexors during game play sessions was calculated. Linear regressions for each subject were then calculated for selective muscle activation and maximum wrist extensor activity to examine trends across game practice sessions. Details of the automated burst detection algorithm are provided in the appendix.

Secondary outcomes. For all of the secondary outcomes, two researchers blinded to test session independently scored 25% of the test sessions. Inter-rater reliability for all outcomes was ≥ 0.95 (ICC (2,1)). One researcher then independently scored the remainder of the test sessions.

sEMG during active movement. We utilized a threshold method (see Appendix for details) to identify muscle activity bursts for each task. The agonist: antagonist ratio for the period of the agonist burst was then calculated, as modified from Damiano et al. [19] (the agonist co-contraction ratio). For the tasks chosen, the agonist was the wrist extensor group and the antagonist was the wrist flexor group. This was normalized to each muscle's activity during Maximum Voluntary Contraction (MVC) for that session to control for electrode placement variations across testing sessions. Higher normalized co-contraction ratios signify greater independence of agonist and antagonist activation.

AROM. A single video frame representing the greatest amount of wrist extension for each trial of active wrist extension was selected. Lines were then digitally drawn to represent the axes by the first author (DR), who was blinded to test session. The axis for the forearm was drawn parallel to the dorsal surface of the forearm; the axis for the hand was drawn along the fifth metacarpal line. The accuracy of these digital lines was verified by the second author (TG) for 25% of the test sessions. The angle on the screen between the two axes was then measured using a standard goniometer. Wrist extension AROM is reported in degrees, with neutral at $0°$ and positive values indicating extension. Negative values for one participant indicate a flexed posture at the wrist.

SHUEE. The primary author (DR) and third author (SWM), both of whom are experienced pediatric therapists, studied the training videos and materials from the test developers. DR and SWM then scored two test sessions independently and discussed scores until consensus was reached. Reliability was then demonstrated for 25% of test sessions, and DR scored the remainder of the test sessions. The grasp/release scores are not reported in this article, as every child achieved a ceiling level at the first pre-test.

Results are presented descriptively for each case on the secondary measures: sEMG, wrist extension AROM, and the SHUEE subtests. Pre-test scores are discussed as a mean $\pm$ SD given that pre-tests occurred a week or less apart. In Protocol 1, post-tests were conducted 4 days apart, thus means $\pm$ SD are also reported for their post-tests. In Protocol 2, post-tests were one month apart to better capture sustained improvements, and are presented separately. The figures, however, include data from all individual pre- and post-tests performed for each subject.

Results: Protocol 1

Alex

Primary outcomes. Alex's total dose of NGT was 10.1 hours. In the home environment, Alex played NGT for a total duration of 5.4 hours, which equaled a mean of 1.8 hours per week.

During game play, Alex's selective muscle activation increased by 30% from the first to the last game training day (Figure 3A). The linear regression over the entire game training period was positive and significant ($r^2 = 0.64$, $p = 0.003$). Maximum wrist extensor EMG activity across game practice sessions showed an increasing trend, but was not significant for this participant ($r^2 = 0.11$, $p = 0.287$; Figure 3B).

Secondary outcomes. Alex showed a dramatic increase in his active wrist extension range of motion (Figure 4). On the first pre-test, he was only able to extend his wrist to $-70°$ (AROM was only measured once at pre-test). His mean AROM at

post-test was $-33.2°$ SD $8.1°$, indicating an improvement of $37°$ from pre-test to post-test. On the SFA subtest of the SHUEE, Alex demonstrated variability in both his pre-test and post-test scores and did not show any consistent changes from pre- to post-test (pre-test 64.5% SD 4.5%; post-test 65.5% SD 5.5%). On the DPA subtest, he increased in mean scores from pre-test to post-test (30% SD 5% to 38.4% SD 3.3%). As seen in Figure 5, however, this change primarily occurred at the second post-test, and there was considerable variability between the two pre-tests.

Brittany

Primary outcomes. Brittany's total dose of NGT was 13.1 hours. In the home environment, Brittany played NGT for a total duration of 10.2 hours, which equaled a mean of 2.6 hours per week.

During game play, Brittany's selective muscle activation was highly variable across game training (Figure 3A), and the linear regression was not
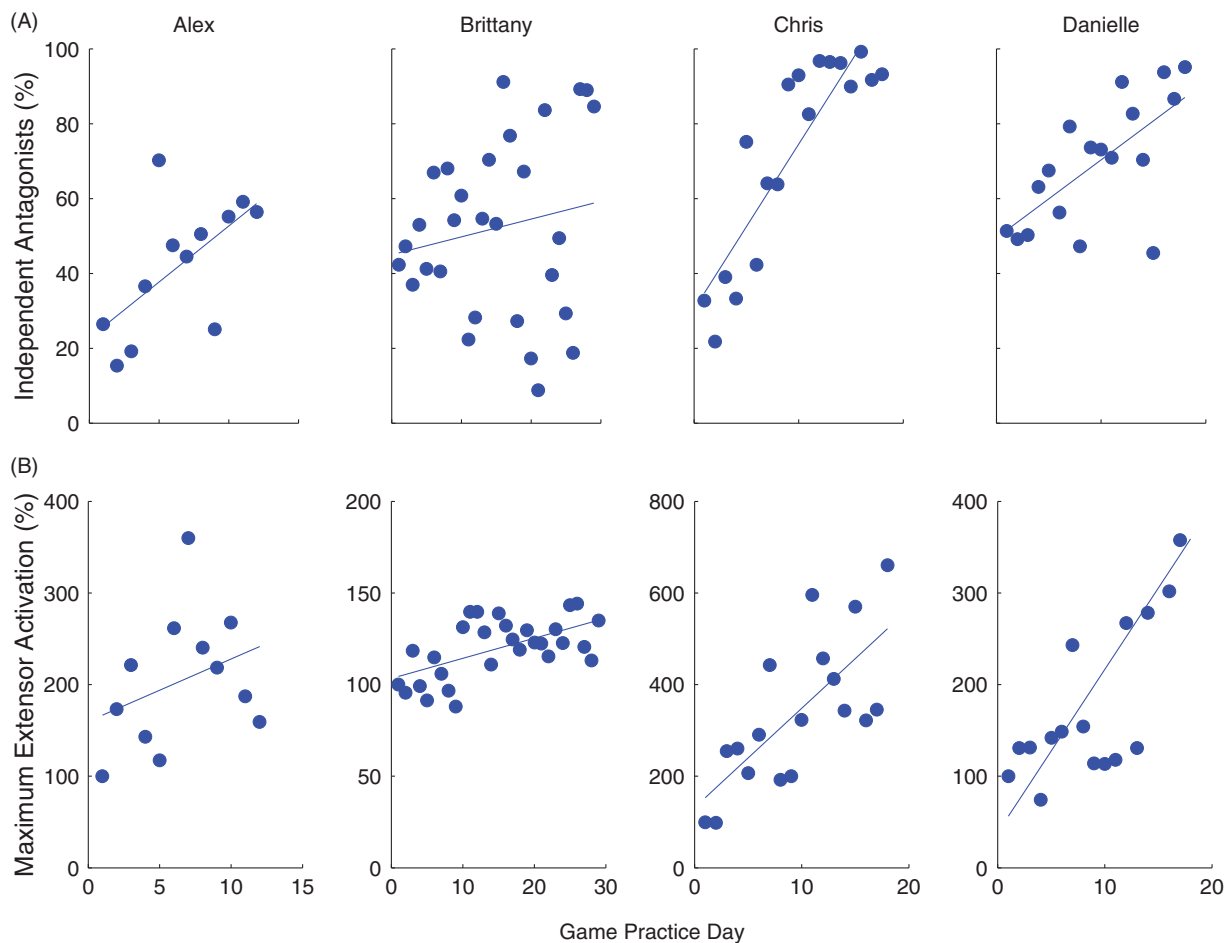

Figure 3. Game Play Data. (A) Percentage of wrist extensor muscle bursts occurring without co-activation of wrist flexors during game play. Three of four subjects improved antagonist independence over the days of game practice. (B) Maximum wrist extensor EMG activity across game practice sessions normalized to the first day of game practice. Three of four subjects increased extensor muscle activity over the days of game practice. Note that the *y*-axis scale in (B) varies between the subjects from 200% to 800%.

significant ($r^2 = 0.15$, $p = 0.278$). This subject, however, did not exhibit spasticity or antagonist co-contraction during assessments. Maximum wrist extensor EMG activity across game practice sessions did show a modest but significant increase of 35% ($r^2 = 0.33$, $p < 0.001$; Figure 3B).

Secondary outcomes. Brittany's AROM demonstrated an increasing trend following intervention (Figure 4). Pre-test mean was 45.7° SD 15.8° and post-test mean was 55.4° SD 5.8°. There was considerable variability at pre-test in AROM. This variability, however, decreased after intervention as evidenced by the smaller standard deviation at post-test. As seen in Figure 5, Brittany's SFA score increased from a mean of 68.9% at pre-test to a mean of 72.2% SD 1.1% at post-test. Brittany's mean DPA also increased from pre- to post-tests (62.5% SD 0.9% to 70.8% SD 2.5%). Her normalized co-contraction ratios were quite variable

between each pre-test and post-test, with no consistent improvement over the NGT intervention (Figure 6).

Results: Protocol 2

Chris

Primary outcomes. Chris's total dose of NGT was 6.8 hours. In the home environment, Chris played NGT for a total duration of 6.1 hours, which equaled a mean of 1.5 hours per week.

During game play, Chris' selective muscle activation increased by 60% from the first to the last game training day (Figure 3A). The linear regression over the entire game training period was positive and highly significant ($r^2 = 0.77$, $p < 0.001$). Maximum wrist extensor EMG activity across game practice sessions also improved by more than 5-fold, with a
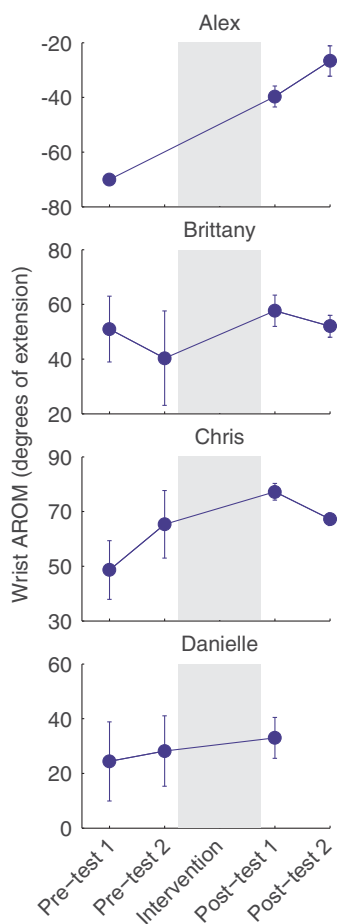

Figure 4. Active range of motion (AROM) in wrist extension across pre- and post-tests surrounding the game intervention (gray shading). All four subjects improved wrist extension AROM during the game intervention. Note that the *y*-axis scale is the same for all subjects but that the range varies. Errors bars are SD.
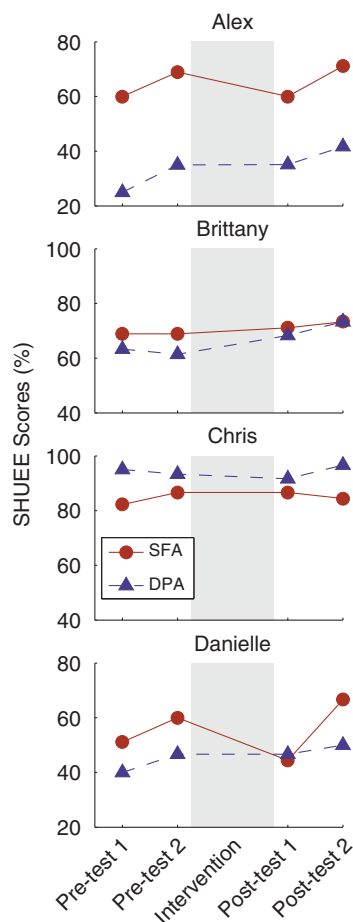

Figure 5. Percentage scores on the Shriner's Hospital Upper Extremity Evaluation (SHUEE) for the Spontaneous Functional Analysis (SFA) and Dynamic Positional Analysis (DPA) subtests. Brittany and Danielle demonstrate increased SFA scores at the second post-test. On the DPA, some participants show a trend toward increasing scores following intervention.
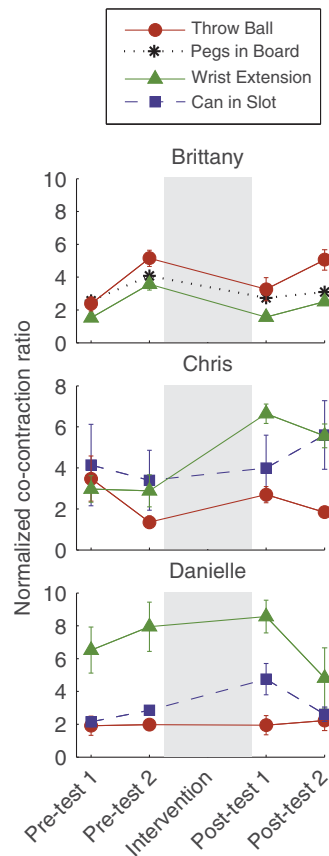
Figure 6. Wrist sEMG co-contraction for Brittany, Chris, and Danielle on three tests each. sEMG data were normalized against maximal voluntary contraction peak activity. Ratios were determined using the total agonist (wrist extensors) contraction over total antagonist (wrist flexors) contraction during agonist burst. The mean and SD of repeated trials during each assessment are reported here for each task performed (of four possible tasks in legend).

significant positive regression ($r^2 = 0.52$, $p < 0.001$; Figure 3B).

Secondary outcomes. Chris improved his active wrist extension AROM immediately following intervention, from 57.7° SD 14.3° at pre-test to 77.2° SD 3.1° at the first post-test (Figure 4). His second post-test showed a slight decrease in the range of active movement (67.2° SD 2.3°). Like Brittany, variability also decreased at post-test as evidenced by the smaller standard deviations at post-test relative to pre-test. As seen in Figure 5, Chris demonstrated no substantial change in SFA or DPA scores on the SHUEE. He did improve muscle isolation during functional tasks evidenced by a higher co-contraction ratio between wrist flexors and extensors – indicating greater independent muscle activation – especially when placing the can in the slot and performing wrist extension (Figure 6).

Danielle

Primary outcomes. Danielle's total dose of NGT was 5.3 hours. In the home environment, Danielle played NGT for a total duration of 3.7 hours, which equaled a mean of 1.2 hours per week. Unfortunately, due to a hardware malfunction, Danielle's final 10 days of game play at home were not available. Assuming a similar rate of game play, Danielle's final dose is likely closer to 6.5 hours.

During game play, Danielle's selective muscle activation increased by 44% from the first to the last game training day (Figure 3A). The linear regression over the entire game training period was positive and significant ($r^2 = 0.45$, $p = 0.002$). Maximum wrist extensor EMG activity across game practice sessions also improved by 2.5-fold with a significant positive regression ($r^2 = 0.59$, $p < 0.001$; Figure 3B).

Secondary outcomes. Danielle's AROM (Figure 4) increased from a mean of 26.3° SD 13.8° at pre-test to 33° SD 7.5° at the first post-test. As with Brittany and Chris, variability decreased at post-test, as shown by the lower standard deviations. Danielle's wrist extension data (for AROM measurements and co-contraction ratios) at the second post-test were omitted due to errors in the testing procedure, which made comparison across test sessions unreliable.

On the SHUEE, Danielle's SFA scores dipped from a pre-test mean of 55.5% (SD 4.5%) to 44.4% at the first post-test. However, at the second post-test her SFA score increased to 66.7%. On the DPA, Danielle's scores steadily increased from a pre-test mean of 43.4% (SD 3.4%) to 46.7% at the first post-test and 50% at the second post-test (Figure 5). Like Alex, however, Danielle's scores at the first pre-test were lower than those at the second pre-test. Finally, Danielle's sEMG results showed a trend toward higher co-contraction ratios at the first post-test for wrist extension and placing the can in the slot (Figure 6). The co-contraction ratios during the ball throw were constant throughout the study.

Discussion

Observations of primary outcomes

The majority of children performed the NGT at home as much or more than requested, based on the adherence data logged on our game system. This is an improvement over typical reports of home adherence, which range from 34% to 67% [20, 21]. This level of compliance is highly encouraging for future clinical applications of NGT as a motivating augmentation to therapy performed either in the clinic or at home. Though participants were not systematically interviewed regarding their

experiences using NGT, all children in our study reported they enjoyed playing NGT and found it motivating. Future studies will collect systematic qualitative data in order to understand participant experiences in using NGT.

Our two protocols provide some example of how NGT might be used in actual therapeutic intervention. In Protocol 1, Alex and Brittany engaged in very structured game play in the laboratory, which may equate to use of NGT in the clinic. Following laboratory training, participants went on to play NGT in the home well beyond the minimum duration requested by the researchers. In contrast, participants in Protocol 2 engaged in NGT in the home about as much as requested by the researchers. Further research is necessary to determine whether adherence to NGT is indeed enhanced by very structured game play in a laboratory or clinic situation.

The data during game play clearly show that the participants improved independent activation of their wrist flexors and extensors, with 3 out of 4 participants demonstrating statistically significant changes. In addition, the maximum voluntary contraction of wrist extensors during game play increased by 35% to over 500%, with 3 out of 4 children showing statistically significant increases over time. These findings demonstrate that NGT provides specific, enhanced feedback at the level of selective muscle activation.

Observations made during game play provide evidence of how motor learning occurred via NGT. Children often struggled initially to control the game, but once they found a strategy, they quickly were able to succeed and progress to more challenging levels. Interestingly, this corresponded to observations of the children initially using a flexor pattern, followed only later by isolated wrist movement. Once this success was achieved, the researchers were able to specifically adjust the system difficulty and require more selective activation, thus continuing to challenge the child. This is a key feature of the NGT system, the ability to adjust the challenge to be "just right" and thus potentially influence neuroplasticity [8].

Observations of secondary outcomes

In addition to the primary outcomes obtained during game play, our pre-test and post-test analysis of sEMG indicated some transfer of learning to wrist movements outside of game play. Our second 2 participants, Chris and Danielle, demonstrated positive trends toward more selective muscle activation as measured by sEMG for the "can in slot" and "active wrist extension" tasks. Brittany did not demonstrate this trend and showed considerable

variability during testing. This is possibly due to her low resting muscle tone, in contrast to the other participants who had high resting muscle tone.

Game play led to substantial increases in active wrist extension for 2 participants, an increase of 32° for Alex and 20° for Chris. Both Brittany and Danielle also demonstrated greater active wrist extension following NGT. Substantial variability at pre-test, however, limits conclusions that can be drawn about this change. Interestingly, the high variability at pre-test was no longer present at post-test. This decreasing variability combined with the trend toward increased active wrist extension suggests that some motor learning likely occurred [22, 23].

The SHUEE reflected improvements in alignment of the involved upper extremity (DPA subtest) and spontaneous upper extremity use (SFA subtest) for three of the participants (Alex, Brittany, and Danielle). Only Brittany, however, had scores that increased immediately post-intervention to a level substantially beyond the pre-test mean. For Alex and Danielle, there was an increasing trend in scores, with most change occurring between either pre-tests or post-tests, and not across the intervention period. It is difficult to determine whether this trend was due to a practice effect of the test, the inherent variability in the children, a delayed change due to the intervention, or some combination thereof.

Limitations

This case series represents an initial step in examining the feasibility and trends associated with NGT. While it proved to be feasible and the trends are promising, our sample size is small. Additionally, two protocols were examined in this study, making it difficult to compare results amongst children. However, we feel this allowed us to examine two "real world" scenarios for the use of NGT.

Unfortunately, the on-board memory in the game system used in this case series was not able to log the number of sessions or average duration of sessions. In response to this limitation, we have since updated the system to cloud-based teletherapy software, which is able to collect real-time adherence data, and even notify the researcher or therapist if subjects are not performing their intervention.

SHUEE pre-test scores were observed to increase for three of the four participants, which may indicate a practice effect. In addition, it is difficult to determine the clinical significance of changes seen in our participants, as there is no information in the SHUEE validation literature on minimal clinically important difference [18]. In the future, additional functional measures will be explored, such as the

Assisting Hand Assessment [24] or the Melbourne Assessment of Upper Limb Function [25].

Conclusions and future directions

The promising results in the primary outcome areas of selective muscle activation and maximum extensor activity during game play are very encouraging for future clinical and research applications of NGT. This study provides "proof of concept" that NGT is effective at the level of selective muscle activation, a key limitation in body function for children with CP [14]. By directly addressing selective muscle activation, NGT provides a foundation for improvement in movement patterns during functional activities.

We are planning several changes to the game play protocol to promote more robust transfer of learning. First, we will expand our intervention to the entire upper extremity, training up to four muscles at a time to improve the complex synergies needed for functional activities [26]. Second, the trends seen in decreasing variability, specifically in AROM, suggest that motor learning outside game play was beginning to occur [22]. We will therefore increase the duration and intensity of practice to further promote transfer of learning, and add more game play scenarios to continue to motivate the child.

Finally, neural plasticity research suggests that greater neurologic change occurs with experience-specific practice and engagement in salient everyday tasks [27, 28]. Future studies will examine the efficacy of NGT in combination with systematic practice of functional activities, including home exercise protocols, occupational therapy, or constraint-induced movement therapy. Control groups receiving each therapy in isolation will permit assignment of improvement to individual or combined therapies. By pairing NGT with skilled therapy, we suggest that observed motor learning will be more readily transferred to functional tasks in order to enhance the child's active participation in everyday activities.

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Appendix

Data processing of sEMG during game play

sEMG data from the game play sessions were down sampled to 500 Hz and low-pass filtered at 200 Hz before rectification and binning into 10 ms windows. Sections of data greater than 3 standard deviations above the mean were removed as likely due to non-physiological signals (e.g., wire movement artifacts). Wavelet analysis was used to establish a reliable baseline level of EMG, which varied in the home due to changes in environmental noise and variations in electrode placement. The Daubechies wavelet family with an order of 44 (Wavelet Toolbox, MatLab release 2011a, The Mathworks, Natick, MA) was used as the mother wavelet function to perform feature extraction from the signal recorded during each game play session [29, 30]. Daily 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 three largest peaks for each muscle. A burst of activity in each muscle was subsequently defined as features in the binned data that exceeded 15% of the maximum activity for at least 0.5 s.

sEMG during active movement

After testing, the sEMG and video data were manually synchronized with the aid of an LED (placed in the view of the camcorder) that indicated the initiation of EMG data capture. Each task was defined by a trained research assistant from the video using the following criteria to identify start and stop frames: *active wrist extension* starting and ending in neutral; *ball throw* starting with arm parallel to the floor and ending when the ball left the hand; *can* starting when the can was lifted from the table

surface and ending when the can left the hand; *pegs* starting when the peg was grasped and ending when the peg left the hand.

The EMG signals were sampled at 1 kHz using a Delsys DS-160 EMG amplifier digitized by a National Instruments USB-6009, 14-bit A/D converter mated to an Apple MacPro running custom LabVIEW data acquisition and analysis software. Signals were rectified and low-pass filtered using a forward/reverse pass 4th order Butterworth filter at a frequency of 20 Hz (per pass).

To determine an EMG contraction event, the signal's onset and termination were determined automatically using a threshold method. A burst of muscle activity was determined for each muscle group (wrist extensors and wrist flexors) and was defined as the EMG signal exceeding the threshold.

The threshold was governed by the mean quiescent EMG value (the lowest value for muscle activity observed), plus five standard deviations of the quiescent signal. This value was multiplied by 5 to identify and isolate only high intensity contractions and reliably identified muscle activity bursts for each task.

The agonist: antagonist ratio for the period of the agonist burst was then calculated (the agonist co-contraction ratio). For the tasks chosen, the agonist was the wrist extensor group and the antagonist was the wrist flexor group. This was normalized to activity during the Maximum Voluntary Contraction (MVC) for that session, to control for variations across sessions. Higher normalized co-contraction ratios signify increased independence of agonist and antagonist.