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Reaching, Swinging, and Punching: Kinematic Change after Video Gaming Intervention in an Individual with Chronic Stroke

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Abstract

Residual upper extremity impairment can limit function post stroke. The purpose of this study is to examine kinematic changes after participation in the ENGAGE video gaming protocol in order to clarify why and how functional change occurs as a result of this intervention. This case describes a 51 year-old male six years post stroke with right hemiparesis and an initial Fugl-Meyer upper extremity motor score of 20/66. He received twelve hours of individualized video gaming as an adjunct to physical therapy over twelve weeks following the established ENGAGE protocol. Three activities of increasing difficulty were analyzed before and after the intervention: reaching from hand in lap to table top, swinging a Wii golf club, and punching a hanging eight inch ball. Motion capture and analysis were used to calculate hemiparetic shoulderand wristdisplacement, time, velocity, and jerk index. After intervention, the Fugl-Meyer score increased five points. Movement time, excursion, and mean/peak velocities decreased in all conditions except for increased shoulder motion in golf and punching where the trunk is an integral part of normal motion. Also, the movement strategy changed completely for punching, from a one-motion circular swing to a posterior set-up followed by a straight plane anterior punch after the intervention. This is the only task in which mean movement velocity and jerkiness increased, suggesting that learning had not consolidated as well for this new movement pattern. Movement smoothness, as measured by the jerk index, decreased for reaching and golf.Trunk and arm motion became better coordinated in the golf swing and punching.

Background and Purpose

Fifty percent of the 795,000 individuals who suffer stroke yearly in the United States have some residual hemiparesis after six months [1]. Residual upper extremity hemiparesis in turn limits function [2]. Commercial video gaming is a more recently developed intervention that has been shown to improve arm function post-stroke [3-5]. Gaming's effectiveness is theorized to be related to the virtual reality nature of video gaming in conjunction with its ability to provide massed practice.

Several mechanisms help explain the effectiveness of virtual reality as an intervention promoting motor recovery. The on-screen avatar, portraying the player's movements in real time, and which the player sees while performing the tasks, is hypothesized to engage the mirror neuron system [5], which has been shown to promote motor learning post stroke [6-8]. The virtual reality experience is typically engaging, realistic, and transfers to real life experience [9]: a form of immersion into the experience occurs during gaming, often called "presence" in the virtual reality literature [10]. Video gaming, as a form of virtual reality, is a unique type of therapeutic training because there are so many varied personal, task, and environmental factors that can be incorporated into treatment as compared to more traditional forms of exercise [11]. The virtual gaming environment presents many cognitive and perceptual elements in conjunction with the motor task, offering a wider array of activity demands than traditional therapy activities. For example, in addition to motor demands, a driving video game requires perceptual and cognitive skills in a variably fast paced and moving environment. The task demands in these multiple domains are typically quite flexible, permitting gaming to be highly individualized to meet a specific patient's rehabilitation needs post stroke.

In addition to its virtual reality nature, commercial video gaming is well suited to mass motor practice in order to drive functional recovery through exercise-dependent neuroplasticity [12]. Post stroke, hundreds to thousands of repetitions of specific task practice are required for motor relearning [12]; however, Lang and colleagues [13] found that individuals post stroke are not obtaining nearly enough upper extremity practice in typical therapy sessions, with an average of less than two active assisted or purposeful upper extremity movements per minute of therapy time. Gaming provides much more practice [4], in part because it is less boring and more engaging [14-16]. In a summary of systematic reviews of therapeutic exercise, Taylor and colleagues found that therapeutic exercise was more effective if it was relatively intense, targeted, and individualized [17]. Gaming is an effective means of obtaining this intensity while still having the flexibility to be very specifically targeted to a given task and individualized to the needs of a specific patient.

During motor recovery post stroke, movement typically becomes less fragmented and smoother [18]. While clinical measures assess whether change has occurred during recovery, kinematic analysis permits quantification of these changes. Further, biomechanical analysis allows speculation as to the mechanisms involved in motor recovery post stroke [19]. TheENGAGE video gaming protocol: *Enhanced Neurorehabilitation: Guided, Activity-based, Gaming Exercise*, [4] was designed to provide intense, massed, immersive, and highly individualized video gaming interventions for individuals post stroke. ENGAGE uses commercial video games as an adjunct to concurrent therapy sessions. ENGAGE provides graded massed

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practice of motor tasks that is individualized to address the unique cluster of each individual's neurologic impairments post stroke. The patient and clinician first develop a collaborative functional goal. Next the clinician completes analysis of the task along with an assessment of the patient's impairments in body structure and function that are hypothesized to be limiting this functional activity. In addition to motor demands, other non-motor factors such as attention and perceptual demands are included in this analysis process. Finally, using the game selection framework, a group of games are selected that will address the disparity between the patient's current abilities and those required to complete the functional goal. Thus both the gaming and/or the concurrent therapy sessions typically focus on foundational impairments and required task components as well as providing actual task practice. However, during the video gaming, this movement practice is always part of ameaningful activity even though it might be addressing an underlying impairment, thus differing from many conventional therapy movement activities.

Bimanual task training is another critical aspect of the ENGAGE protocol. Bimanual upper extremity functional tasks are very diverse and are used in more than 54% of hand activities [20], in addition to being an effective rehabilitation tool [21-24]. Bimanual skills are further subdivided into five categories: bimanual assisted or "yoked" (i.e. golf swing); symmetrical; reciprocal; and asymmetrical. Games are chosen from the accelerometer based Wii system (Nintendo), the motion capture Play Station 2 with EyeToy (Sony), or Rock Band (Harmonix Music Systems, Inc.) in order to provide a wide number of gaming alternatives, while limiting gaming options enough for the clinician to be familiar with all choices. In addition, these games are typically modified and use various props in order to further individualize and grade game difficulty for a given individual.

The purpose of this study was to examine the functional movement recovery, particularly the underlying kinematic changes in an individual's hemiparetic arm movements after participation in the ENGAGE protocol. Since little is known about recovery of proximal arm function in individuals with poorer arm function post stroke [19, 25-27], this case report, focusing on shoulder and wrist kinematics, allows speculation about both proximal and distal motor learning occurring as a result of the ENGAGE training protocol.

Methods

Case description and outcome measures

This study was approved by the Cleveland State University Institutional Review Board for Human Subjects in Research. The case describes a 51 year-old male six years post stroke with right hemiparesis. Although this individual lived alone and used public transportation, he was not able to return to work after his stroke. He was a community ambulator, using a right ankle foot orthosis and no other assistive device, although he had occasional falls. He had an initial Fugl Meyer upper extremity motor score of 20/66. In addition, a full physical therapy examination was completed. The following non-motor impairments in body structure and function were deemed significant factors in this individual's ability to use his hemiparetic arm. First, he had decreased passive range of motion in his right shoulder, forearm and hand, with significant functional limitations in forearm supination as well as flexor tendon tightness limiting finger and wrist extension. His right elbow flexion had a Modified Ashworth Scale score of two, however, this was not deemed to be a significant limitation in his function as compared to the passive components of his right arm stiffness. Finally, while not aphasic, he did have higher-level cognitive processing difficulties making it hard for him to learn new tasks with complex movement demands, especially when timing and speed were required.

Three activities of increasing difficulty were analyzedbefore and after the intervention: reaching up and forward from a hand in lap position to a table top location 15 cm ahead of the initial hand position, swinging a Wii Sports (Nintendo) golf club on the first hole of the beginner golf course in the video game (with hemiparetic hand grasp secured on golf club using an elastic bandage strap when required), and punching a midline hanging 8" ball positioned at shoulder height. Motion analyses were completed using three-dimensional motion capture (Motion Analysis Corporation, Santa Rosa, CA) at 120 frames/second using the UETrak (Motion Analysis Corporation, Santa Rosa, CA) marker set. Four trials were collected in each condition and motion data were used to calculate the following kinematics for his hemiparetic shoulder and wrist movements: excursion, movement duration, mean velocity, and peak velocity [19,28]. The jerk index was also calculated as a measure of change in movement smoothness [29,30]. Hemiparetic arm function was reassessed clinically post-intervention with theFugl-Meyer. The same kinematic variables for the same tasks were calculated for a 21 year-old female with no neurological involvement as a comparison.

Intervention

The participant received 720 minutes of individualized video gaming along with concurrent physical therapy over a 12 week period following the established ENGAGE protocol [4]. In this case, the participant completed eight one-hour PT sessions focused on: 1) manual therapy, stretching, and splinting to increase passive range of the flexor tendon complex and forearm supination; 2) electrical stimulation and active exercise focused on active wrist and finger extension in functional tasks; and 3) learning how to elevate the shoulder against gravity without concurrently activating upper trapezius in active assisted bilateral functional tasks, using therapist, mirror and biofeedback cuing. During the 720 minutes of ENGAGE gaming, the participant played ten different video games, using both hands together in active assisted tasks 93% of the time and the hemiparetic hand alone the other 7% of the gaming time. The games played are summarized in table 1. While bilateral arm use was required for the games involving driving, golfing, and wakeboarding, both hands were "yoked" together in an active assisted fashion for other games such as bowling and table tennis. Actual movement repetitions were not counted. Rest periods and time spent changing discs were not counted in the practice time. Of the games played, 68% were continuous tasks (i.e. driving), 15% were discrete (i.e. bowling), and 17% were mixed, with periods of discrete motion followed by more continuous motion (i.e. serving followed by rapid volleys in table tennis).

Data analysis

Kinematic data were tracked using Cortex 2.5 (Motion Analysis Corporation, Santa Rosa, CA). Beginning and end frames for each analyzed component of motion were established through visual analysis of x-y-z coordinate graphsusing the following process.First, all trials in a given condition (hand to table, golf swing, or punching) were viewed to develop a definition of movement initiation and termination. For example, the golf swing was broken down into three parts: preparatory backswing, forward swing (component used in this analysis), and return to rest. For the forward swing component, the beginning motion frame was defined as the first motion of the right

Game	Hand use	System/ game disc	% of time	Task description	Modifications
Wakeboarding (water skiing)	Bilateral reciprocal	Wii Resort	31%	Continuous	Increased controller width to ↑ shoulder external rotation/ forearm supination
Cow Ride (driving game)	Bilateral reciprocal	Wii Play	23%	Continuous	Increased controller width to ↑ shoulder external rotation/ forearm supination
Table tennis	Bilateral asymmetrical	Wii Resort	11%	Mixed	Hands “yoked”
Bowling	Bilateral asymmetrical	Wii Resort	10%	Discrete	Hands “yoked”
Drumming	Unilateral	Rock Band	7%	Continuous	Strap supporting hand on drumstick
Golf	Bilateral asymmetrical	Wii Resort	5%	Discrete	Hands “yoked”
Four other games (<5% each)	All bimanual	Varied	13%	7% Continuous 6% mixed	Various

Table 1: Summary of games played.

	Reach	Golf	Punch
Pre	1.22 (0.18)	0.61 (0.90)	0.85 (0.24)
Post	1.12 (0.19)	0.53 (0.50)	0.35 (0.07)
Normal	0.71 (0.18)	0.68 (0.18)	0.35 (0.01)

Table 2: Movement duration (sec) and standard deviation.

Figure 1: Participant playing Play Station2 with EyeToy game Bubblepop with active-assisted “yoked” bimanual bilateral asymmetrical upper extremities.

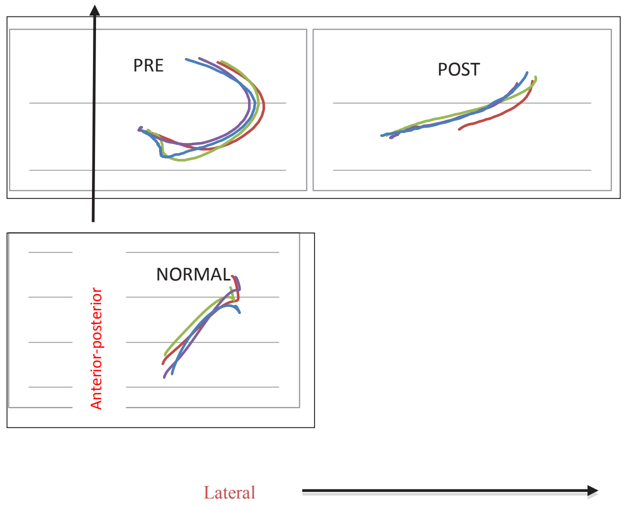

Figure 2: Transverse plane view of lateral and anterior/posterior wrist linear displacement during punching, superimposing individual trials (each trial represented in a different color) in each condition (pre-intervention, post-intervention, and normal).

ulnar wrist marker in either the y or x-axis of motion, while the end motion frame was defined as the last motion of the same marker in the z-axis. After start and stop frame definitions were established, each trial was reviewed and the starting and ending frames were determined.

Analysis data were then obtained across this defined movement periodfor the hemiparetic/right shoulder (acromion process) and wrist (ulnar styloid process) marker x-y-zcoordinatelocations and velocities. Movement duration, excursion, mean velocity, and peak velocity were calculated from these time/position/velocity data. Movement duration time was calculated from the defined first to last frame, with these data being collected at 120 frames/second. Movement excursion was calculated for the same defined range of frames for the shoulder and wrist markers. For each location, the distance moved between each frame was calculated and these distances were summed to give overall movement excursion for each trial at each marker location. Finally, mean and peak velocities were calculated during this defined time period at the shoulder and wrist.

The jerk index is defined in terms of the time derivative of acceleration [29, 30]. It quantifies movement smoothness and has been calculated in multiple ways [30]. The jerk index in this case was calculated as follows. Suppose $s(t)$ is the speed data for values of t from 0 to T (at a sampling frequency of N Hz, 120 Hz in this work). First, the data are segmented into time intervals of τ seconds: the initial segment is from 0 to τ, the second is from $1/N$ to $\tau+1/N$, the third is from $2/N$ to $\tau+2/N$, and so on. Next, the first finite difference $a(t)$ of $s(t)$ is calculated, and the number of local extreme values Mj of $a(t)$ in segment j are computed. The jerk index is the maximum over all the segments. The interval τ is chosen so that each task performed lasts for at least τ seconds.

Results

After intervention, the Fugl-Meyer score increased from 20/66 to 25/66. Mean movement duration decreased in all conditions (Table 2). The most substantial decrease in movement time was in punching, where a totally different strategy was adopted post intervention as illustrated by the wrist x-y coordinate plots in figure 2. Before the intervention, the participant used a circular hook pattern to punch the hanging ball. After the intervention, he moved using a two part motion, raising his hand to shoulder height and then punching straight forwardin a fashion similar to the pattern used by the control subject.

Excursion decreased except for shoulder movement during golfing and punching, where the motion almost doubled (Table 3). Substantial increases in shoulder excursion in conjunction with decreases in wrist excursion occurred in both golfing and punching, where trunk

	Shoulder	Wrist				
	Reach	Golf	Punch	Reach	Golf	Punch
Pre	60.2 (10.5)	138.2 (19.8)	74.1 (37.0)	454.5 (51.6)	3910.3 (453.7)	767.8 (54.6)
Post	49.7 (5.3)	249.3 (30.8)	144.8 (49.6)	340.6 (18.0)	3493.1 (185.6)	223.9 (136.2)
Normal	40.8 (5.8)	400.9 (38.3)	168.8 (14.1)	308.7 (4.6)	1687.1 (656.6)	735.0 (55.7)

Table 3: Movement excursion (mm) and standard deviation.

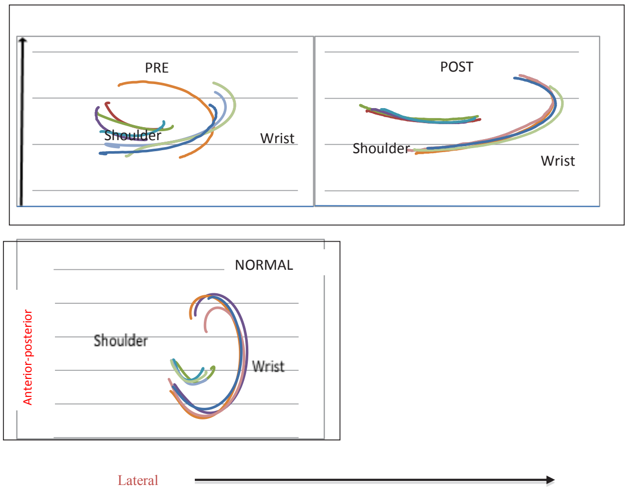

Figure 3: Transverse plane view of lateral andanterior/posterior shoulder and wrist linear displacement during golfing, superimposing individual trials (each trial represented in a different color) in each condition (pre-intervention, post-intervention, and normal).

	Shoulder			Wrist		
	Reach	Golf	Punch	Reach	Golf	Punch
Pre	353.7 (124.0)	1614.8 (262.8)	660.5 (70.7)	1123.9 (175.1)	3910.3 (454.7)	3620.5 (339.8)
Post	301.3 (68.5)	1570.5 (231.2)	1106.0 (121.1)	822.8 (171.2)	3493.1 (185.6)	3455.1 (1213.1)
Normal	212.2 (47.8)	1230.1 (142.6)	880.9 (78.7)	1185.7 (69.3)	4866.4 (282.1)	4545.9 (295.9)

Table 4: Peak velocity (mm/sec) and standard deviation.

motion is an integral component of the normal movement pattern. In addition, coordination between trunk and arm motion became more organized following training. This can be seen in figure 3 which illustrates the overlying shoulder and wrist x-y coordinate plots pre and post intervention.

Peak movement velocity (Table 4) decreased in all conditions (5-49%) except at the shoulder in punching where it increased 40%. Mean movement velocity (Table 5) decreased slightly for reaching and golfing (3-7%), but increased for punching (56% at the shoulder; 10% at the wrist).

Qualitatively, the speed vs. time curves became smoother following the intervention, as shown in the example of the shoulder in golfing (Figure 4). While the number of smooth trials increased after training, there were still some very jerky trials post intervention across joints and conditions. The change in movement smoothness was quantified using the jerk index (Table 6). Shoulder and wrist motion became less jerky in golfing and reaching, except for remaining unchanged at the wrist in reaching. However, these changes were larger at the shoulder as compared to the wrist. In punching, both shoulder and wrist motion increased in jerkiness post intervention, with the participant using a different movement strategy.

	Shoulder			Wrist		
	Reach	Golf	Punch	Reach	Golf	Punch
Pre	217.5 (49.5)	861.5 (93.4)	331.6 (65.4)	563.2 (144.0)	2103.7 (281.3)	1727.0 (441.3)
Post	209.7 (64.2)	815.5 (104.7)	711.7 (150.8)	525.8 (148.6)	2005.7 (197.2)	1904.4 (167.5)
Normal	91.9 (21.2)	590.9 (82.0)	481.1 (34.7)	1014.8 (441.1)	2474.9 (245.8)	2068.7 (130.8)

Table 5: Mean velocity (mm/sec) and standard deviation.

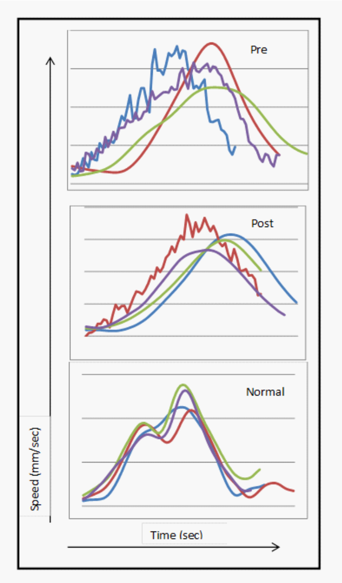

Figure 4: Example of speed vs. time profile: Golfing at the shoulder.

	Shoulder			Wrist		
	Reach	Golf	Punch	Reach	Golf	Punch
Pre	7.8	9.3	7.3	5.3	7.3	7.5
Post	5.3	5.3	11.8	5.3	5.0	11.3
Normal	15.0	4.0	9.8	7	3.5	3.0

Table 6: Movement smoothness as measured by the jerk index.

Discussion and Conclusions

Varied kinematic changes occurred in all three movements. The hand to table reaching task was the least complex motion, with no force demands. Also, it required minimal coordination between trunk and hand motion since it could be successfully completed with arm motion on a stable trunk. In this activity, movement time decreased (Table 2) and reaching became more efficient following the gaming intervention with the wrist/hand unit following a more direct, straighter movement path to the table top, as seen by the 25% decrease in the movement excursion (Table 3). The excursion also became less variable between trials, with the standard deviation decreasing by more than 50%.

In the golf swing, shoulder excursion increased by 45% while wrist displacement decreased slightly by 11% after training (Table 3), resulting in a more normal swing pattern in this bilateral task with force demands as well as trunk-hand coordination requirements. Figure 3 shows x (medial-lateral) and y (anterior-posterior) axis shoulder and wrist motion. After intervention, motion is much less variable and more closely approximates the normal movement pattern. The motion also became less jerky, especially at the shoulder, as illustrated by the velocity curves of individual trials in figure 4. Jerk index values decreased by 43% at the shoulder and 22% at the wrist (Table 6).

We introduce this new version of the jerk index for several reasons. Primarily, this index allows for comparison not only across various subjects, but also across the various tasks performed. Also, it is clear that it is not influenced by changes in movement duration (the three measured tasks have different movement durations). Moreover, if a particular part of the motion is jerky, while the rest of it is smooth, the index will detect it.Our interpretation of jerk index values is that a value below five indicates that the motion is quite smooth, and a value of above 15 indicates that the motion is jerky. Thus the shoulder and wrist approximate a smooth motion with values of 5.3 and 5.0 respectively after the intervention. This is an indication of improved motor control since during motor recovery post stroke, motion typically becomes less fragmented and smoother [18]. The changes in golfing are especially striking since the participant played golf only 5% of his gaming time. However, while the number of smooth trials, as shown in Figure 4, increased after training, there were still some very jerky trials post intervention, suggesting that learning the golf swing had not fully consolidated in the 720 minutes of gaming time.

Punching, the most demanding task, required unilateral, forceful, and target specific motion. The movement strategy changed dramatically after the intervention, as illustrated by the x-y coordinate plot of wrist motion in figure 3, from a one-motion circular swing to a posterior set-up followed by a straight plane anterior punch. This is the only task where jerk index values increased, suggesting that learning had not consolidated as well for this new movement pattern as compared to reaching and golfing. It should be noted that the participant never played a boxing game during the intervention sessions, and that he only trained unilaterally 9% of the ENGAGE gaming time (Table 1). However, he developed the ability to use a different motor control strategy when punching the ball during post testing, suggesting transfer of learning from other tasks.

Finally, after the intervention, shoulder excursion (Table 3) increased and became more coordinated with distal extremity motion in the golfing and punching conditions where the trunk is an integral part of the normal movement pattern. The more normal increased shoulder movement in golfing and punching after the intervention suggests less excessive and unnecessary trunk co-contraction as movement quality improved. Also, shoulder and wrist motion became less jerky (Table 6) in golfing and reaching, except for remaining unchanged at the wrist in reaching. However, these changes were largest at the shoulder as compared to the wrist, reflecting a relatively greater degree proximal motor control improvement. The lower peak velocities (Table 4) in reaching and golf, but not the newly learned punching pattern, are probably another reflection of smoother movement and improved motor control. However, to punch more effectively, one would expect the observed increased peak and mean velocity with recovery due to the specific task demands of punching the ball with greater force.

It should be noted that none of the measured tasks were practiced specifically in a gaming context during the intervention except for 37 minutes of time playing Wii Golf. This raises the issue of task transfer. The virtual gaming environment incorporates many cognitive and perceptual elements in conjunction with the motor task practice which may allow more effective transfer of the activity to function [9]. This may clarify the recent discussion about the effectiveness of upper extremity task-specific practice [31-34]. We hypothesize that perhaps the critical component is meaningful and engaged task practice rather than just task specificity. With upper extremity tasks being highly varied, an understanding of how to facilitate transfer of learning to a variety of functional activities is essential as we grapple with the dosage of exercise necessary to facilitate motor return in the stroke population.

In this case, the participant gamed for 720 minutes, a number determined from the original ENGAGE trial where gaming dosage was correlated with functional outcomes [4]. He completed continuous tasks 868% of the time, suggesting he obtained a large number of practice repetitions in this trial. However, the kinematic changes suggest a longer gaming time would have been beneficial in order to consolidate the new punching strategy demonstrated on post-testing and to develop more consistent, smooth motion in the other conditions. A limitation of this study is the lack of follow-up testing several months after completion of the intervention to see whether improvements had reached a level that could be maintained through daily activities. Critical issues related to dosage of exercise and maintenance of motor gains will require additional examination.

In conclusion, the participant in this case study completed the ENGAGE protocol, playing individually tailored commercial video games for 720 minutes in conjunction with eight hours of physical therapy. Clinically, his upper extremity Fugl-Meyer score increased by five points from 20/66 to 25/66. Kinematic data show general improvements in movement excursion, task completion time, velocity, and jerkiness, with the exception of the punching activity where the participant adopted a new, higher level movement strategy by the end of the intervention, albeit with increased movement jerkiness.

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