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▶ **To cite this version:**

Maxime Térémetz, Alicia Garcia Alvarez, Sylvain Hanneton, Agnès Roby-Brami, Nicolas Roche, et al.. Improving upper-limb and trunk kinematics by interactive gaming in individuals with chronic stroke: a single-blinded RCT. Annals of Physical and Rehabilitation Medicine, 2021, Online ahead of print. 10.1016/j.rehab.2021.101622 . inserm-03520880

HAL Id: inserm-03520880

https://inserm.hal.science/inserm-03520880

Submitted on 11 Jan 2022

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Improving upper-limb and trunk kinematics by interactive gaming in individuals with chronic stroke: a single-blinded RCT

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Abstract

Background. Commercial gaming systems are increasingly being used for stroke rehabilitation; however, their effect on upper-limb recovery versus compensation is unknown.

Objectives. We aimed to compare the effect of upper-limb rehabilitation using interactive gaming (Nintendo Wii) with dose-matched conventional therapy on elbow extension (recovery) and forward trunk motion (compensation) in individuals with chronic stroke. Secondary aims were to compare the effect on 1) clinical tests of impairment and activity, pain and effort, and 2) trajectory kinematics. We also explored arm and trunk motion (acceleration) during Wii sessions to understand how participants performed movements during Wii gaming.

Methods. This single-centre, randomized controlled trial compared 12 hourly sessions over 4 weeks of upper-limb Wii therapy to conventional therapy. Outcomes were evaluated at baseline and 4 weeks. The change in elbow extension and trunk motion during a reaching task was evaluated by electromagnetic sensors. Secondary outcomes were change in Fugl-Meyer assessment, Box and Block test, Action Research Arm Test, Motor Activity Log, and Stroke Impact Scale scores. Arm and trunk acceleration during Wii therapy was evaluated by using inertial sensors. A healthy control group was included for reference data.

Results. Nineteen participants completed Wii therapy and 21 conventional therapy (mean [SD] time post-stroke 66.4 [57.2] months). The intervention and control groups did not differ in mean change in elbow extension angle (Wii: +4.5°, 95% confidence interval [CI] 0.1; 9.1; conventional therapy: +6.4°, 95%CI 0.6; 12.2) and forward trunk position (Wii: -3.3 cm, 95%CI -6.2;-0.4]; conventional therapy: -4.1 cm, 95%CI -6.6; -1.6) (effect size: elbow, d=0.16, p=0.61; trunk, d=0.13, p=0.65). Clinical scores improved similarly but to a small extent in both groups. The amount of arm but not trunk acceleration produced during Wii sessions increased with training.

Conclusions. Supervised upper-limb gaming therapy induced similar recovery of elbow extension as conventional therapy and did not enhance the development of compensatory forward trunk movement in individuals with chronic stroke. More sessions may be necessary to induce greater improvements.

Key words. stroke; compensatory strategies; elbow extension; trunk movement; gaming; wii-therapy

ClinicalTrials.gov: NCT01806883

Highlights

Interactive gaming induced similar changes in elbow extension as conventional therapy.

Physiotherapist supervised interactive gaming did not enhance forward trunk movement.

Arm, but not trunk, acceleration increased across gaming sessions.

The number of sessions may have been too low to induce clinically important changes.

Introduction

Commercial gaming systems are increasingly being used for stroke rehabilitation [1]. These systems are attractive because they are fun, low cost, simple to use and provide meaningful activity and facilitate large numbers of repeated movements. They are of clinical interest because they can be used to increase rehabilitation time by promoting self-rehabilitation in the hospital or the patient's home [2] and have been shown to improve upper-limb motor function [3].

However, an important issue is whether the use of gaming systems to improve upper-limb motor function leads to increased development of compensatory trunk movements [4]. Compensation refers to the substitution of impaired functions, whereas recovery refers to the restoration of a function back to a more normal, pre-injured state [5,6]. During reaching tasks, individuals with stroke often compensate for reduced elbow extension by flexing the trunk [7], which may lead to reduced training of impaired movements (e.g., elbow extension). This issue is of clinical importance since Michaelsen et al. [8] reported that patients with moderate motor impairment who developed compensatory trunk movement when training reaching without trunk restraint had a reduced functional recovery potential. It would seem reasonable to expect that individuals with stroke would use the most effective movement strategies available to them [9] to win points during gaming therapy, thus "training" compensatory movement patterns. This could potentially have a deleterious effect on their functional recovery [8].

Therefore, we designed a study that would evaluate the effect of Wii therapy on all dimensions of motor recovery, from impairment (including movement quality), through function, to quality of life, in accordance with the International Classification of Functioning, Disability and Health [6]. Our purpose was to determine whether any improvements were mediated via recovery or compensation [10].

The primary aim of this study was to evaluate the effect of supervised upper-limb therapy using a gaming system, the Nintendo Wii, on upper-limb recovery and compensation (elbow extension and forward trunk motion) and to compare with time-matched conventional upper-limb therapy.

Secondary aims were to compare the effect of Wii and conventional therapy on the different dimensions of upper-limb function [6]: 1) clinical tests of upper limb motor impairment and activity, pain and perceived effort and 2) kinematic parameters relating to hand transport during reach (velocity, smoothness and curvature). We also explored relative motion of the arm and trunk during Wii sessions and compared with a healthy control group, to gain knowledge of how patients with stroke perform movements during Wii gaming.

We hypothesised that games therapy would induce less recovery of elbow extension and more compensatory trunk motion than conventional therapy in individuals with chronic stroke.

Methods

Design

This was a single blind, randomized controlled, single-centre (university hospital, France) trial comparing Wii and conventional upper-limb therapy in individuals with chronic stroke-related hemiparesis (ClinicalTrials.gov: NCT01806883). Recruitment began in March 2013 and closed in June 2016. Ethical approval was received (CPP Ile de France XI # 12071) and all participants provided written informed consent. The study is reported according to the CONSORT guidelines.

Blocked, stratified randomization was carried out by the physiotherapist using a web server with a random list, pre-generated by the software. Patients were stratified according to Fugl-Meyer score < or ≥ 50 and the side of the hemispheric lesions (similar to Michaelsen et al. [8]). Evaluating therapists were blinded to group allocation.

Participants

Participants with chronic hemiparesis (≥ 6 months) after a single hemisphere stroke were recruited from our hospital outpatient clinics. Inclusion criteria were age 18 to 75 years, right-handed, not regular users of Nintendo Wii, not having received any injections of botulinum toxin within the previous 3 months, able to bring the hemiparetic hand to the mouth (to ensure that some movement was possible), no major cognitive or perceptual impairments that would limit participation in therapy sessions (determined by the enrolling physician) and providing written informed consent. Exclusion criteria were cerebellar stroke, epilepsy during the previous year, pacemaker (contraindication to use of the Wii), and uncorrected visual deficits. Participants were asked not to participate in any other upper-limb rehabilitation for the duration of the protocol. All participants were out-patients.

A reference group of age- and sex-matched healthy control participants were recruited among hospital staff and family (spouses) and friends of the participants with stroke. The purpose of the healthy control group was to record reference kinematic data for the pointing tasks and to be able to compare arm/trunk patterns during Wii therapy between healthy and stroke participants because "normal" patterns for such games were unknown. The inclusion criteria for the healthy controls were age 18 to 75 years, right-handed, not regular users of the Nintendo Wii and with no pathology affecting upper limb movements. Fourteen individuals were recruited (6 females, mean age 51.6 years, 95%CI 45.3; 58.7): 10 underwent the same kinematic evaluation as the participants with stroke, and 10 underwent the same inertial evaluation during a Wii session (see below for evaluations) (i.e., not all 14 participated in both the kinematic analysis and Wii sessions).

Interventions

Patients participated in 12, 1-hr therapy sessions, 3 days/week for 4 weeks. Missed sessions were performed during a fifth week. The same physiotherapist (AG) performed both Wii- and conventional-therapy sessions.

Wii therapy

Wii therapy (Nintendo, 2006) consisted of 3 games — tennis, golf and boxing (from the Wii Sports pack) — chosen because each involved arm movements in different planes. Participants performed 15 min of each sitting on a stool (to avoid balance issues). At the beginning of each session, patients were instructed to try to win as many points as possible without causing themselves pain. The game order was changed each session. If necessary, the Wii remote was fixed to the patient's hand using a bandage. Only Wii therapy was performed during the session, and no other techniques were performed (e.g., no stretching or mobilization). The other hand could be used to assist if the movement was very difficult. The therapist simply stood beside the participant and encouraged them to score points and produce large arm movements; she verbally discouraged compensatory movements.

Conventional therapy

Upper-limb and hand exercises were determined for each participant by the physiotherapist (AG), with a main focus on functional exercises. After each conventional therapy session, the therapist completed a form [11] to provide a record of the content of the sessions (supplemental file). In summary, sessions consisted of passive and active movements of impaired joints and functional, task-oriented reaching and grasping exercises, the proportion depending on the participant's capacity and needs, as is the case in usual conventional therapy [12]. Compensations were verbally or physically discouraged (e.g., by the physiotherapist placing her hand on the participant's sternum). Use of restraints such as constraint-induced movement therapy (CIMT) or trunk restraint was not allowed; any other techniques could be used as the physiotherapist felt appropriate.

Baseline and outcome measures

All outcomes were measured during the week before the beginning of the intervention (pre) and the week after the final session (post) by a blinded evaluator.

Baseline measures

A comprehensive battery of clinical tests was used to characterize participants (see supplementary file and Table 1).

Primary outcome: change in elbow extension and forward trunk motion during an active reaching task (see Kinematic evaluation below) from pre- to post-intervention.

Secondary outcomes:

Clinical (see supplemental file for more details)*:*

Pain, and its location, was rated at the beginning and end of each session on a 10-cm visual analog scale. Perceived effort was rated at the end of each session using the 10-point Borg scale [13].

Change from pre- to post-intervention was analysed for the upper-extremity Fugl-Meyer Assessment (FMA-UE, Minimal Clinically Important Difference [MCID] = 6 points [14]), the Box and Block test (BBT, MCID = 5.5 blocks/min [15]); the Action Research Arm Test (ARAT, MCID = 5.7 points [16]), the Motor Activity Log (MAL, MCID = 1.0–1.1 points [17]) and the Stroke Impact scale (SIS, no MCID) [18].

Satisfaction was evaluated at the end of the intervention on a 10-cm visual analog scale.

Kinematic evaluation

Set-up (see supplemental file for more details)

An electromagnetic, 6 degrees-of-freedom motion tracking device, the Polhemus Fastrak system (SPACE FASTRAK, Colchester, VT, USA) with 4 electromagnetic sensors was used to record kinematic data (sampling rate: 33 Hz). The sensors were fixed on the manubrium, deltoid insertion, forearm and dorsum of the hand. The 3D position of the radial and ulnar styloids, medial and lateral epicondyles was digitized as described [19]. The position of the glenohumeral rotation centre was calibrated from passive circumduction movements of the upper arm [20]. Then the position of those anatomical points was calculated in the local reference frame of the corresponding sensor, and the 3D positions of the anatomical points were computed by using a local-to-global transformation [19]. The Polhemus magnetic source was fixed to the underside of the table, so the sternal sensor was behind the source, which is why values presented for trunk motion are negative.

Task

Participants were seated at a table, with their back against the back rest, the hand in a fist positioned on a cross marked on a table, upper arm vertical, elbow at 90°, shoulder not abducted and forearm in neutral pro-supination (as far as possible).

The target was a circle of red tape (1-cm diameter) on a thin post positioned in 3 locations (short-range, long-range and high) (Fig. 1). To standardise conditions and to account for participants who had difficulty pointing with the index finger, participants were instructed to touch the target with the knuckle of their hemiparetic hand (or right hand for control individuals), at their own speed, and then return their hand to the starting position. The experimenter carefully verified the starting position before each trial and gave a verbal signal to begin the movement. The order of the targets was not randomised. A practice trial was allowed for each target, then 3 trials were recorded for each target.

Data analysis

A custom-made program was developed using Labview software (National Instruments, Austin, TX, USA) to process the data. Only the movement toward the target was analysed (not the return). The tangential velocity of the hand sensor was calculated by derivation of the displacement data. Then the beginning and end (i.e., when the participant touched the target) of the movements were automatically detected (with a threshold of 0.05 m/s), then visually checked and validated by using an interactive display.

The following variables were calculated:

Elbow angle (in degrees): calculated as the angle between a vector from the radial styloid to the lateral epicondyle of the elbow and a vector from the lateral epicondyle of the elbow to the centre of glenohumeral joint. Larger angles denote greater extension. The elbow angle when the movement stopped (i.e., the participant had reached the target) was used for analysis. This variable has been shown to have high inter- and intra-rater reliability for pointing movements in patients with stroke, using a similar measurement technique [21,22].

Trunk position (in centimetres): calculated as the position of the sternal sensor relative to the Polhemus magnetic source in the sagittal plane (to measure forward trunk motion) when the movement stopped.

Peak hand velocity: the maximum hand velocity attained during the movement.

Curve index: the curvature of the hand trajectory was calculated by the ratio of actual distance travelled/direct distance [23].

Number of peaks: the number of peaks in the hand velocity curve during the movement (with a velocity > 10% of the maximum velocity of the trial and with duration > 100 ms).

Movement duration: time from the start to the end of the movement.

Inertial evaluation

An inertial evaluation was performed to determine the extent to which participants in the Wii group used their trunk versus upper limb to perform movements during Wii therapy. During the second (so that participants had time to become familiar with the Wii games) and final Wii therapy sessions, participants were equipped with 2 wireless, 6 degrees-of-freedom accelerometers, on the back of the hand and the sternum. Those sessions were also filmed.

Data analysis

Data recorded from the inertial units were used to quantify the "amount" of movement the participants with stroke made and the control participants. Details of the method are provided in the supplemental file. Two variables were calculated: amount of arm and trunk acceleration.

Statistical analysis

Sample size calculation was based on Michaelsen et al. [8], who reported a 6-degree increase in elbow extension after trunk restraint therapy. We expected a similar increase in the conventional-therapy group and 30% smaller increase in the Wii group (i.e., a mean [SD] increase of 4 [2] degrees). A two-sample inference test comparing 2 means, assuming a normal distribution, two-tailed alpha =0.05 and power=0.8 indicated that we would need 16 patients in each group.

IBM SPSS Statistics 23 for Windows (SPSS Inc., Chicago, IL, USA) was used for analysis. Mean (95% confidence interval [CI] or SD) and median (interquartile range [IQR]) were calculated. Normality was tested with a Shapiro-Wilk test. Change (pre to post) was compared between groups by Mann-Whitney test for clinical scores (except BBT) and for perceived pain and effort during sessions and by Student *t* test for the BBT and kinematic variables. Cohen's d was calculated to indicate effect sizes.

A session had to involve at least 30 min of active therapy to be considered and participants had to have participated in at least 10 sessions for their data to be analysed.

We found no between-group differences for any of the 3 targets for the primary or secondary outcomes and no time*group*target interaction for elbow angle (p=0.846) or trunk position (p=0.856), so data for the 3 targets were pooled. The resulting 9 trials (3 trials per target) were averaged for the analyses.

Changes in movement patterns (arm and trunk acceleration) from the start (second session) to the end (final session) of the Wii therapy (inertial evaluation) were compared within and between groups (Wii group and healthy control group) by using repeated measures ANOVA (multivariate approach [24,25]). A Mann-Whitney test was used to analyse group differences between stroke and healthy participants in the 3 Wii games (boxing, golf, and tennis).

Results

We included 43 individuals with stroke (mean age 56 years, 95%CI 52.1; 59.9; 42% females) and 14 healthy control individuals (mean age 52 years, 95%CI 45.3; 58.7; 43% females). Of those with stroke, 21 were allocated to Wii therapy and 22 to conventional therapy (Fig. 2). Three individuals did not complete the study (2 in the Wii-therapy group and 1 in the conventional therapy group) for reasons unrelated to the study. Therefore, data for 19 participants were analysed in the Wii-therapy group and 21 in the conventional-therapy group.

The characteristics of participants with stroke are in Table 1. The groups did not differ in age, sex, time since stroke onset, disability, apraxia, hemispatial neglect, FMA-UE, sensation, spasticity or strength, or any of the outcome measures, except for the MAL quantity score, which was significantly higher in the conventional- than Wii-therapy group.

In the Wii group, 4 participants could not hold the hand-held manipulandum and required a bandage to keep it in place during therapy sessions. Four participants used the other hand to help for more than 50% of sessions. One participant required manual guidance from the physiotherapist for more than 50% of sessions.

Pre- vs post-training kinematics

All participants with stroke successfully completed the task. As shown in Table 1, healthy controls had greater elbow extension and less forward movement of the trunk than those with stroke.

For the primary outcome, we found no significant between-group difference in change in elbow extension (p=0.61, d=0.16); however, elbow extension angle increased pre- to post-intervention in both groups (Table 2 and Fig. 3), with no group*time interaction (p=0.61). We found no significant between-group difference in change in trunk position (p=0.71, d=0.13); however, trunk position was reduced pre- to post-intervention (i.e., was less forward) in both groups (Table 2 and Fig. 3), with no group*time interaction (p=0.71).

We found no significant between-group differences in changes in the other kinematic variables.

Pre- vs post-training clinical outcomes

We found no significant between-group differences in change in FMA (impairment), ARAT, Box and Block Test (function) or MAL scores (upper-limb use), or the SIS (quality of life) (Table 2). However, the conventional-therapy group was significantly more satisfied with the therapy received than the Wii group (median score: 10 [IQR 8.1; 10] and 6.7 [IQR 5.4; 9.2], $p=0.008$, $d=0.77$).

Pain and perceived effort across the conventional-therapy and Wii sessions

We found no significant difference between groups in median change in pain rating (Wii: median 0.0 [IQR -0.2; 0.1], conventional therapy: median 0.0 [IQR -0.1; 0.9], $p=0.78$, $d = -0.002$) or median Borg rating of the perception of effort (Wii: median 3.7 [IQR 3.3; 4.8]; conventional-therapy: median 3.7 [IQR 3.0; 5.0], $p=0.78$, $d = -0.15$).

Movement patterns used during Wii therapy

In the stroke group (Wii-therapy only), arm acceleration changed (increased) from the second to final Wii sessions, and the amount of acceleration differed across games ($F[1,13] = 5.97$, $p < 0.031$; $F[2,12]=20.93$, $p < 0.0005$), with no interaction (Fig. 4). The amount of trunk acceleration did not change across the sessions but differed across games ($F[2,12] = 24.3$, $p < 0.0001$), with a significant session*game interaction ($F[2,12] = 5.93$, $p= 0.02$). For the arm, the mean acceleration was significantly different for the healthy control than stroke group, particularly for boxing (Fig. 4A). We found no significant differences between the healthy control and stroke participants for trunk acceleration (Fig. 4B).

Discussion

This single-blinded, randomised controlled trial of 40 individuals with moderate-mild [26] chronic stroke compared the effects of supervised Wii and conventional upper-limb therapy on reaching kinematics and included comprehensive clinical testing of motor impairment and activity capacity. In contrast to our hypothesis, we found no difference in change in elbow extension or forward trunk motion between groups.

Effect of Wii therapy and conventional therapy on recovery and compensation

Unexpectedly, participants did not develop more compensatory trunk movement after Wii therapy. The physiotherapist reported that, despite her verbal discouragements, the participants in the Wii group used compensatory movements in their attempts to score points, contrary to the conventional-therapy group who performed fewer compensatory movements because the exercises were individually adapted. In the study by Michaelsen et al. [8], participants in both the trunk restraint and control groups (similar to the conventional therapy in the present study) were also instructed not to move the trunk during the exercises; however, in contrast to the present study, elbow extension was reduced and trunk motion increased by the end of training. This worsening of outcomes occurred mainly in the group with lower initial FMA scores (mean [SD] 38 [8.8]); these scores were similar to those in the present study (median initial FMA score 42, CI 24;49.5). An important difference between these studies was that the participants in the Michaelsen et al. study performed a reach-to grasp task, whereas those in the present study performed a pointing task. Therefore, the increase in trunk compensation might have related to difficulty with the grasping component of the task because trunk motion may assist hand orientation [27]. Another methodological difference that may have affected the results is that the participants in the Michaelsen et al. study underwent 15 therapy sessions, and those in the present study underwent 12.

The inertial analysis showed that during Wii sessions, participants with stroke actually produced a similar amount of trunk acceleration as the healthy control group, and furthermore, their arm acceleration increased over the sessions. Along with the result of a study of the effect of CIMT on trunk and upper-limb kinematics [28], these results suggest that individuals with moderate-mild motor impairment do not systematically develop compensatory trunk movement in response to upper-limb training with the trunk free. This finding also demonstrates the importance of analysing movements produced during sessions to gain an understanding of why and how such interventions might improve outcomes [10,29].

Effect of Wii and conventional therapy on impairment, function and trajectory kinematics

We found no difference in the effects of either therapy on any of the outcomes measured, although participants were more satisfied with conventional than Wii therapy.

The minimum detectable change and MCID for upper-limb joint angles has been little studied and is complex, owing to large variations depending on the task assessed [22,30]. However, the mean change in elbow extension (Wii group: 4.5°, 95%CI -0.1; 9.1; conventional-therapy group: 6.4°, 95%CI 0.6; 12.2) was likely below threshold levels [22,30]. Mean changes in the clinical scores for impairment [14] and function [15,16] were also surprisingly small (Table 2). The most likely explanation for this is that the therapy duration was too short to induce substantial change. Although another study of similar duration and design as the present study showed more consequent improvements in clinical outcomes [31], a recent, large trial showed substantial change in motor impairment and activity after 90 hr of upper-limb therapy over 3 weeks [32]. Intensive rehabilitation has also been found to drive recovery via enhanced brain plasticity [33]. We believe that both interventions were sufficiently challenging because the median Borg scores were close to 4 in both groups, which corresponds to "somewhat hard".

Changes in trajectory kinematics were also very small. Results in the literature differ in terms of the effects of therapy on trajectory kinematics [28,34,35], probably because of differences in the tasks and variables analysed. There may be only a short time frame for improvements in motor control to occur [36], although motor control variables can improve in the chronic stage of stroke with very intensive therapy such as CIMT [28,34]: 3 hr per week as in the present study may be insufficient to effect these variables.

Satisfaction

The results of the satisfaction questionnaire suggest that patients with stroke may prefer conventional therapy with a therapist rather than therapist-supervised gaming therapy. Other studies have found higher levels of satisfaction with gaming therapy when used as a self-treatment adjunct to conventional therapy in the hospital or home setting: it may be that although people with stroke find gaming systems motivating [37], they are more satisfied with therapy provided by a therapist, involving richer interaction and enhanced feedback.

Limitations

The first limitation is that the training dosage was low, as discussed above. Second, there was no follow-up assessment to determine long-term effects of interventions. The study also included patients a very long-time post-stroke, which may have contributed to the marginal degree of recovery in both groups. A potential source of bias is that the same therapist carried out both interventions. When the study was designed, it was planned that a pool of therapists would carry out the interventions; however, organisational difficulties prevented this. Feedback regarding compensations was not standardized for each group, which may be a confounding factor. Given the stroke sample studied, the results cannot be generalized to patients with more severe motor impairment. Also, because both types of therapy were supervised by a physiotherapist, the results cannot be applied to patients performing unsupervised Wii therapy. Finally, inter-individual variation in elbow extension improvement was higher than expected, which suggests that the present study may have been underpowered.

This study has several strengths: it was designed to evaluate all the domains described by the International Classification of Functioning, Disability and Health; it included kinematic measures combined with clinical measures in order to elucidate upper limb sensorimotor recovery [10]; and the outcome measures selected are recommended for evaluating motor interventions in chronic stroke [38].

Conclusions

The results of this study showed increased elbow extension and reduced forward trunk motion after both supervised Wii and conventional therapy. However, the low level of improvement across the kinematic and clinical outcomes suggests that the dose of 12 hourly sessions over 4 weeks was insufficient to induce clinically important changes. These results suggest that gaming devices could be useful as a treatment add-on, to provide additional practice time for patients who are followed by a therapist, or for individuals with stroke who no longer have access to rehabilitation, it could be a means to maintain the motor function they have acquired. However, studies should first determine the effect of un-supervised Wii therapy on compensation versus recovery and clinical evaluations of function.

Funding. This study was funded by a PHRIP grant from APHP.

Acknowledgements. We sincerely thank all the individuals with stroke and control participants who participated in this study. We are also very grateful to Dominique Rouat, Elisabeth LeBomin, Erika Imandt, Marie-Anne Le Bris and Magalie Carcaille for their help with patient recruitment and organization, and to Julien Boudarham, Yves-Marie Vasse and all the therapists who participated in the patient evaluations. Many thanks to Gilbert Pradel and Tong Li for supplying the accelerometers and performing the recordings. Thanks to Nabila-Yasmine Domingo for study coordination, Idir Ghout for the statistical analysis and all the clinical research assistants involved.

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Table 1: Participant characteristics and baseline measures

	Total n=40	Wii-therapy n=19	CT n=21	P-value
Age mean (95%CI)	56 (52.1;59.9)	55.8 (49.7;61.9)	56.2 (50.5;61.9)	0.89
Females n (%)	16 (42%)	6 (31%)	10 (47%)	0.43
Right hemisphere stroke n (%)	28 (70%)	13 (68%)	15 (71%)	0.06
Left hemisphere stroke n (%)	13 (30%)	6 (28%)	7 (31%)	
Mean months since stroke onset (95%CI)	66.4 (48.7;84.1)	71.1 (43.5;98.7)	62.2 (37.7;86.7)	0.49
Median Barthel Index (IQR) (0-100)	95 (90; 100)	95 (90;100)	95 (90;100)	1
Median AST Bedside apraxia(IQR) (0-12)	12 (11;12)	12 (11;12)	12 (11;12)	1
Median Bell's neglect score (IQR) (0-35)	34 (33;35)	34 (32;35)	34.5 (33;35)	0.49
Sensation median (IQR) (0-24)*	21.5 (17;24)	21 (17;24)	22 (15.5;24)	1
Spasticity median (IQR) (0-4)*	1.00 (0.58; 1.65)	1.00 (0.67 ;1.33)	0.83 (0.56; 1.89)	0.90
Strength median (IQR) (0-5)*	3.3 (2.8;3.7)	3.5 (2.2;3.6)	3.2 (2.8;3.9)	0.69
Fugl-Meyer score median (IQR) (0-66)	41.5 (25;46.75)	41 (25;46)	42 (24;49.5)	0.75
ARAT median (IQR) (0-57)	19.5 (4.5;37)	18 (6;34)	30 (4;38.5)	0.49
MAL quantity median (IQR) (0-5)	**1.3 (0.6;2.4)**	**0.7 (0.5;1.6)**	**1.7 (1.0;2.8)**	**0.02**
MAL quality median (IQR) (0-5)	1.2 (0.7;2.6)	1.0 (0.5;2.3)	1.5 (0.8;2.8)	0.17
Box and block test mean (95%CI) (0-150)	12.2 (8.2;16.2)	11.6 (5.4;17.8)	12.8 (7.4;18.2)	0.20
SIS mean (95%CI) (0-100)	34.6 (32.5;36.7)	33.9 (31.2;36.6)	35.1 (31.9;38.3)	0.48
Healthy controls				
Elbow extension mean (95%CI) (degrees)	128.9 (121.4;136.4)	-	-	
Forward trunk motion mean (95%CI) (cm)	-38.6 (-41.0;-36.2)	-	-	
Participants with stroke				

Elbow extension mean (95%CI) (degrees)	98.3 (93.4;103.2)	100.5 (94.1;106.9)	96.1 (88.7;103.5)	0.38
Forward trunk motion mean (95%CI) (cm)	-30.7 (-32.9; -28.5)	-29.5 (-33.3; -25.7)	-31.8 (-34.1; -29.5)	0.33
Peak velocity mean (95%CI) (m/s)	0.46 (0.43;0.49)	0.47 (0.43;0.51)	0.44 (0.40;0.48)	0.42
Number of peaks mean (95%CI) (n)	4.0 (3.4;4.6)	4.4 (3.6;5.2)	3.6 (2.7;4.5)	0.21
Curve index mean (95%CI)	1.28 (1.20;1.36)	1.30 (1.17;1.43)	1.26 (1.17;1.35)	0.59
Movement Duration mean (95%CI) (seconds)	43.2 (39.2;47.2)	44.3 (39.4;49.2)	42.0 (35.6;48.4)	0.58

The ranges for each scale (min-max) are provided in brackets in the first column.

*A total score was calculated by averaging the scores for each part of the upper limb or muscle.

** Between Wii and CT groups for MAL Quantity score Mann-Whitney Z = -2.23 ; p = 0.02

n : number, 95%CI: 95% confidence interval range, IQR: interquartile range.

Table 2. Change in primary and secondary outcomes pre to post intervention.

Change pre to post intervention				
	Wii-therapy	Conventional-therapy	P-value	Effect size
Elbow extension mean [95%CI] (degrees)	4.5 [0.1; 9.1]	6.4 [0.6; 12.2]	0.61	0.16
Forward trunk motion mean [95%CI] (cm)	-3.3 [-6.2; -0.4]	-4.1 [-6.6; -1.6]	0.71	0.13
Fugl-Meyer score median [IQR]	0.0 [-1.0; 3.0]	2.0 [-2.0; 7.0]	0.43	0.21
ARAT score median [IQR]	2.0 [-1.0; 6.0]	1.0 [0.0; 5.0]	0.93	-0.22
MAL quantity score median [IQR]	0.1 [-0.1; 0.1]	-0.05 [-0.4; 0.3]	0.83	-0.14
MAL quality score median [IQR]	0.0 [-0.3; 0.2]	0.1 [-0.4; 0.7]	0.51	0.15
Box and block test score mean [95%CI]	0.2 [-1.1; 1.5]	2.0 [0.5; 3.5]	0.08	0.58
SIS score mean [95%CI]	-0.7 [-2.9; 1.5]	1.7 [-0.6; 4.0]	0.16	0.46
Peak velocity (m/s) score mean [95%CI]	0.03 [-0.001; 0.06]	0.004 [-0.03; 0.04]	0.32	-0.32

Number of peaks (n) score mean [95%CI]	-0.3 [-0.9; 0.3]	0.3 [-0.2; 0.8]	0.18	0.48
Curve index score mean [95%CI]	0.04 [-0.05; 0.13]	-0.0 [-0.04; 0.04]	0.46	-0.25
Movement Duration (m/s) score mean [95%CI]	-4.1 [-7.8; -0.4]	-0.3 [-3.7; 3.1]	0.16	0.47

n: number, 95%CI: 95% confidence interval range, IQR: interquartile range, ARAT: action research arm test, MAL: motor activity log, SIS: stroke impact scale, p-value: significance level of t-test and Mann-Whitney test for group comparison

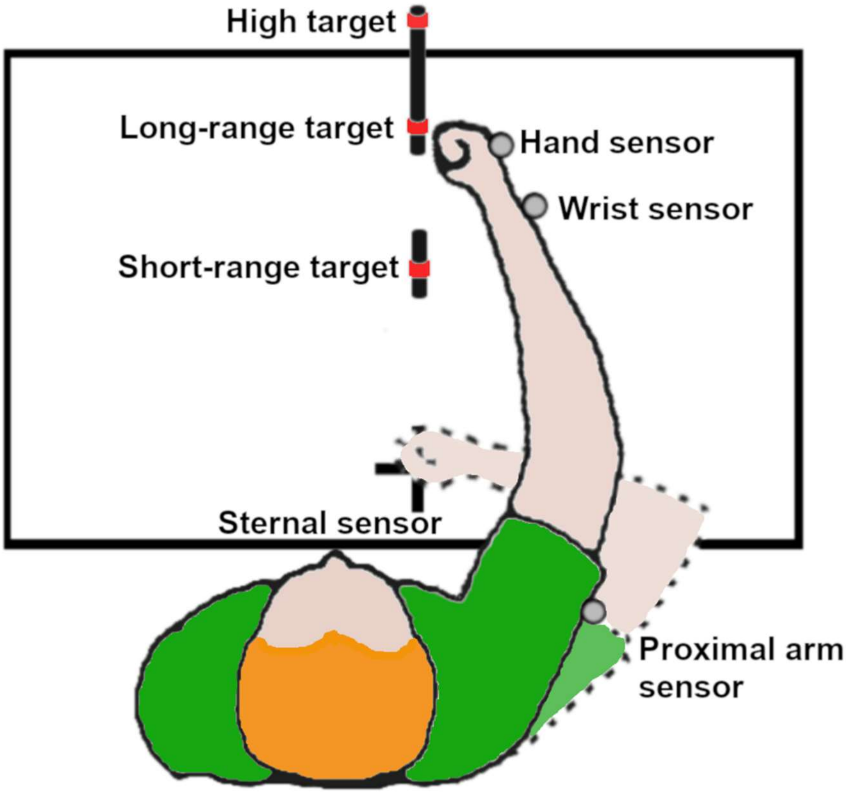

Figure 1. Task set-up for kinematic analysis. The target was a circle of red tape (1-cm diameter) around a thin post that was placed in 3 positions: short-range, long-range and high. The long-range position was set with the patient sitting in position at the table, their back resting against the back rest. Participants were asked to extend their arm fully without protracting the shoulder girdle (the healthy arm could be used: the distance was transposed to the other side) and the target was positioned level with the wrist fold, 10 cm above the table top. The high position was at the same distance, but the target was at the participant's shoulder height. The short-range target was then set at 60% of the distance between the starting position and the long-range target, at a height of 10 cm off the table.

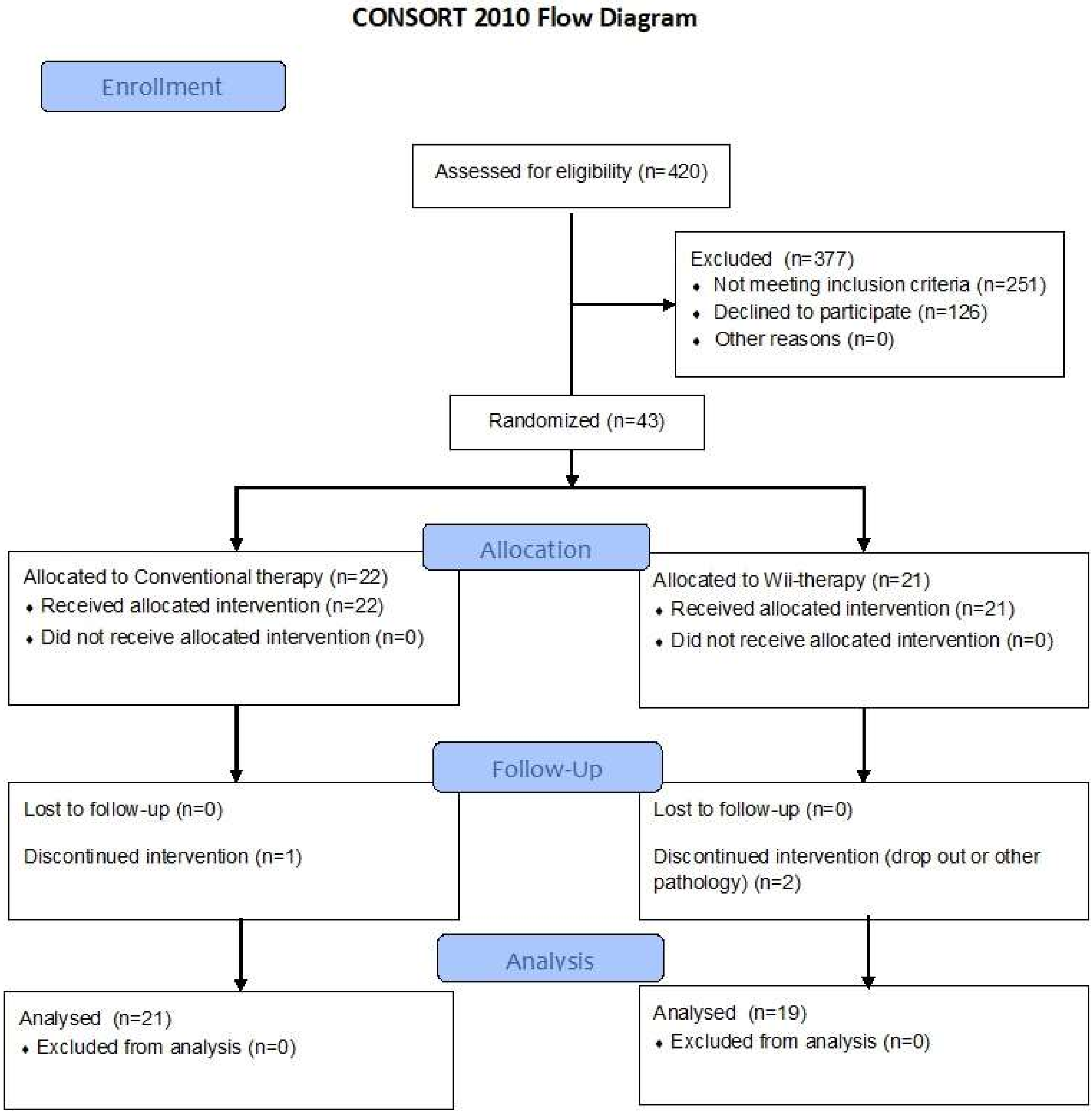

Figure 2. Flow chart of the inclusion of participants with stroke. Fourteen healthy control subjects were also included in the study, so the total number of inclusions was 57.

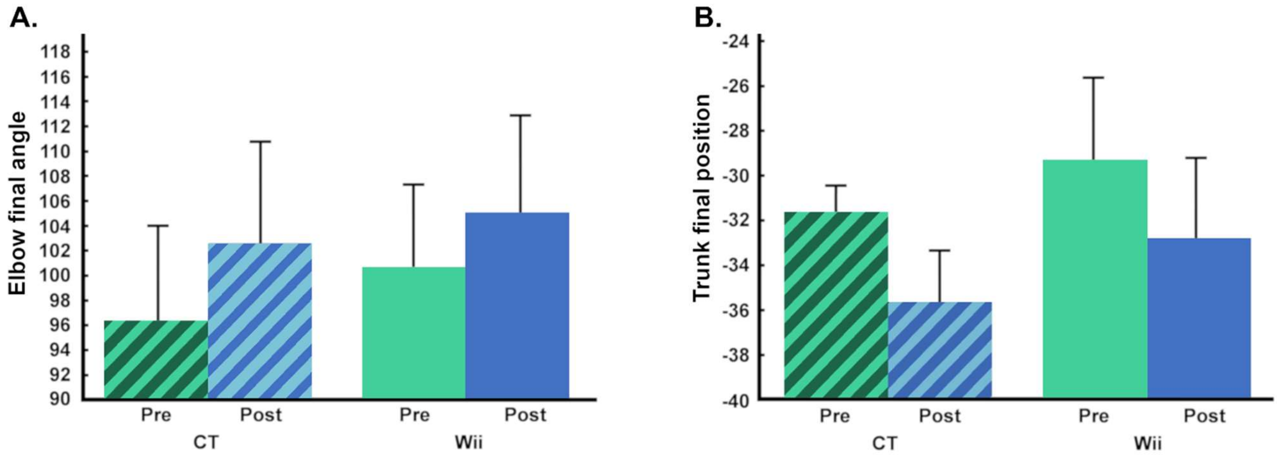

Figure 3. Mean final elbow extension (angle) (A) and mean trunk position (distance) (B) before (green) and after (blue) Wii (solid bars) and conventional therapy (hatched color). For the trunk, values that are more negative indicate less forward motion. Data are mean (95% confidence interval). CT, conventional therapy.

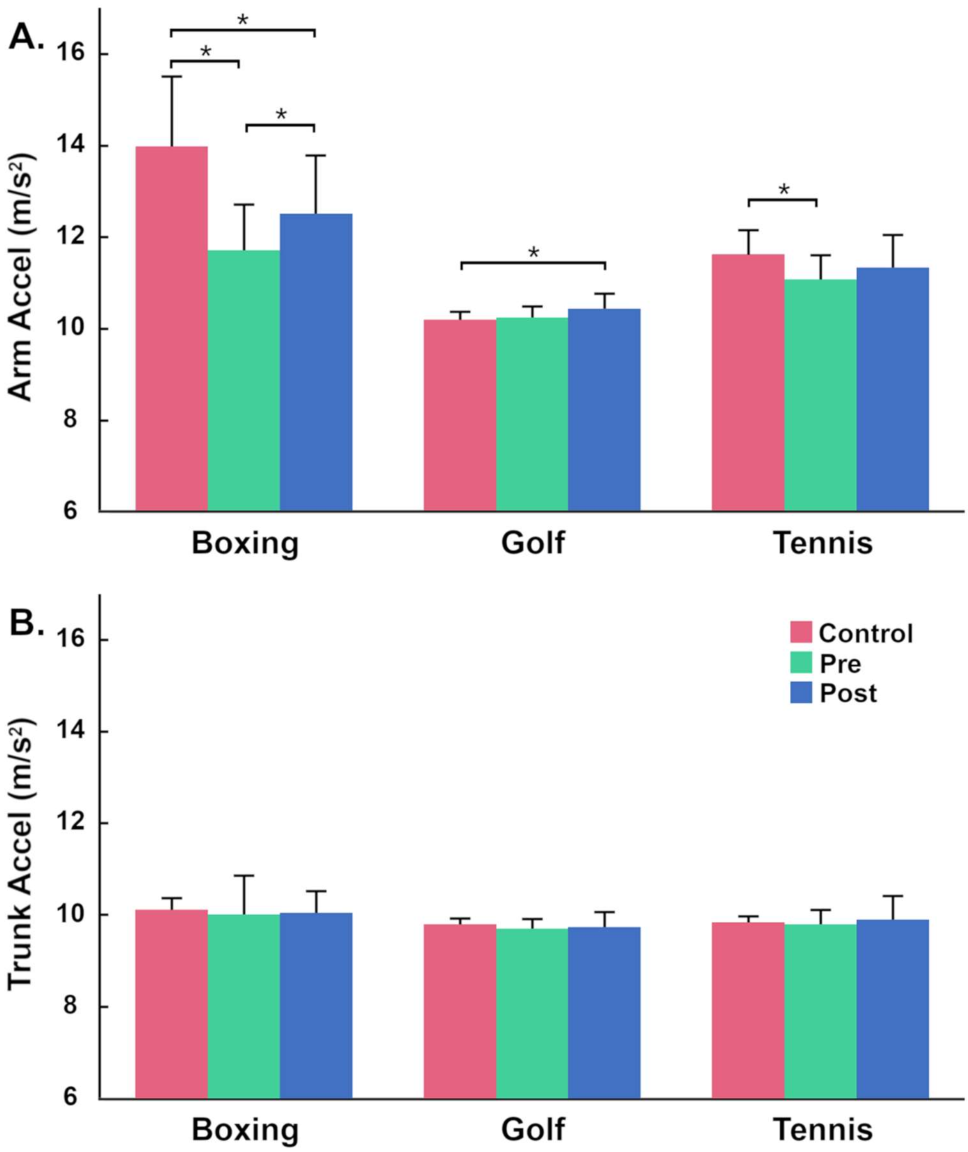

Figure 4. Acceleration values for the arm (A) and trunk (B) inertial measurement unit for different Wii games in the stroke and healthy control groups. Data are mean±SD. * $p<0.05$

Supplemental file

<u>Clinical evaluation</u>

Sensation was evaluated for the shoulder, upper arm, forearm and hand by asking the participant to compare the sensation of stroking with simultaneous stroking by the therapist on both upper limbs. Sensation was graded as normal (3 points), mild reduction (2 points) or major reduction (1 point).

Proprioception was evaluated by the therapist positioning the hemiparetic upper limb in 2 different shoulder, elbow and wrist configurations and asking the participant to copy the position with the other limb (eyes shut). Proprioception was graded as normal (3 points), mild reduction (2 points) or major reduction (1 point).

Spasticity (Modified Ashworth Scale) [1] was graded for the shoulder adductors and internal rotators, elbow flexors, extensors, pronators and supinators, wrist extensors and flexors and finger flexors. The mean score for all muscle groups was calculated.

Strength (Medical Research Council scale) [2] was graded for the shoulder adductors, internal and external rotators, elbow flexors, extensors, pronators and supinators, wrist extensors and flexors and finger flexors and extensors. The mean score for all muscle groups was calculated.

Hemispatial neglect was evaluated with Bell's test [3]. The number of ticked bells was counted. A patient with more than 6 omissions on one side of the page was considered to have hemispatial neglect.

Apraxia was evaluated using the 12 items of the Apraxia Screen of TULIA bedside test, which involves the reproduction of simple, coordinated gestures [4].

The **Barthel Index** was used to describe performance and independence in activities of daily living [5].

Pain was rated at the beginning and end of each session by asking participants to mark their level of pain on a 10-cm line (left, no pain; right, maximal imaginable pain). The location of the pain was also noted.

Perceived effort was rated at the end of each session using the 10-point Borg scale [6]: 0, no effort; 10, very, very difficult.

The upper-extremity Fugl-Meyer Assessment (FMA-UE) [7] was used to evaluate gross upper limb and hand motor impairment. The upper-extremity subsection informs the capacity to carry out shoulder and elbow flexion-extension movements.

Gross manual dexterity was measured by the Box and Block test [8,9]. Performance was quantified by the number of 2-cm x 2 cm wooden cubes displaced from one side to another side of a box in 60 s. The greater the number of cubes, the better the function.

The Action Research Arm Test [9], was used to assess the ability to perform simple and complex grasp movements and global arm movements. This clinical scale tests the capacity to grasp different sizes of objects, pinch grip for several digit combinations, grip and object displacement with precise targets as well as global movements.

The Motor Activity Log (MAL) [10] was used to measure restrictions in participation in activities of daily living (ADL) perceived by the patient. The MAL is a semi-structured interview to evaluate how much and how well the paretic arm contributes to ADL. Participants were asked to rate the quantity and quality of movements made by the paretic arm during 30 different ADL, each rated from 0 to 5.

Quality of life was assessed by a validated French translation of the Stroke Impact Scale (SIS) [11]. The SIS is a self-report questionnaire that evaluates 8 items: hand function, strength, ADL, mobility, communication, emotion, memory and thinking, and social participation. Participants were asked to rate each item from 1 to 5 and rate their perception of their percentage recovery.

Satisfaction was evaluated at the end of the rehabilitation period by asking participants to mark their level of satisfaction with the rehabilitation received on a 10-cm line (left, not at all satisfied; right, totally satisfied).

Kinematic evaluation

Set-up

An electromagnetic, 6 degrees-of-freedom motion tracking device, the Polhemus Fastrak system (SPACE FASTRAK, Colchester, VT, USA) with 4 electromagnetic sensors was used to record kinematic data (sampling rate: 33 Hz). The sensors were fixed to the participant with tape: one on the manubrium of the sternum; one at the insertion of the deltoid (using a Velcro strap wrapped around the participant's arm); one on the dorsum of the forearm, 2 fingers' width proximal to the wrist joint line; and one on the dorsum of the hand, over the middle of the third metacarpal bone. The 3D position of the following bony landmarks was digitized (radial and ulnar styloids, medial and lateral epicondyles) as described [12]. The position of the glenohumeral rotation centre was calibrated from passive circumduction movements of the upper arm [13]. Then the position of those anatomical points was calculated in the local reference frame of the corresponding sensor. The 3D positions of the anatomical points can then be computed during any movement by means of local-to-global transformation using the position and orientation of the corresponding electromagnetic sensor [12]. The Polhemus magnetic source was fixed to the underside of the edge of the table closest to the participant, and the participant sat directly in front of it. Therefore, the sternal sensor was behind the source, which is why values presented for trunk motion are negative.

Inertial evaluation

Data analysis

Data recorded from the inertial units were used to quantify the "amount" of movement made by the participants with stroke and control participants. Because rigorously removing the gravitational component of the acceleration over a long time is difficult (one game lasted on average 7 min), we used the following method. First, the X, Y and Z acceleration data were filtered with a low-pass filter (10 Hz cut-off frequency). Then, we computed the acceleration norm and removed the constant part of this signal to finally obtain its RMS value (Accel). Thus, the amount of acceleration (Accel_arm for the inertial unit on the arm, Accel_trunk for the inertial unit on the trunk) was the first dependent variable.

Content of conventional therapy

	No. participants activity ticked for	%	No. sessions in which activity was carried out	%
Aims:				
1. Postural control	21	100		
2. Musculoskeletal range of motion	21	100		
3. Oedema	21	100		
4. Alignment	21	100		
5. Manipulative ability of the hand	21	100		
6. Sensory ability	21	100		
7. Muscle activity Paretic limb	21	100		
8. Transport ability of the arm	21	100		
9. Prevent/reduce pain	21	100		
10. Muscle activity non-paretic limb	0	0		
11. Incorporate arm into balance and mobility activity	21	100		
12. Awareness of 2° complications	21	100		
Gross position of patient during activities used:				
1. Supine	19	90	172	68
2. Prone	9	43	45	18
3. Side lying on unaffected side	18	86	136	54
4. Side lying on affected side	10	48	26	10
5. 4-point kneeling	5	24	10	4
6. 2-point kneeling	2	10	5	2
7. Unsupported sitting	18	86	86	34
8. Supported sitting	14	67	57	23
9. Asymmetrical sitting	0	0	0	0
10. Perch Sitting	13	62	30	12
11. Standing	20	95	149	59
12. Prone standing	4	19	16	6
Treatment activities				
1. Soft tissue mobilisation				
1.1 Stroking	2	10	5	2
1.2 Effleurage	0	0	0	0
1.3 Lymph drainage techniques	0	0	0	0
1.4 Pettrissage				
1.5 Specific compression (trigger points)	3	14	5	2
1.6 Myofascial release	0	0	0	0
1.7 Frictions	8	38	15	6

2. Joint mobilisation				
2.1 Accessory movements	0	0	0	0
2.2 Passive movements	20	95	171	68
2.3 Active movements	20	95	193	77
3. Facilitation of muscle activity/movement				
3.1 Mental imagery	16	76	54	21
3.2 Patient-generated cueing	7	33	16	6
3.3 Therapist-generated cueing	20	95	107	42
3.4 "Hand on" to induce a desired motor response	19	90	114	45
3.5 Active assisted	20	95	121	48
3.6 Facilitated arm/hand activity from another body part	11	52	18	7
4. Positioning	0	0	0	0
5. Specific sensory input				
5.1 Tactile stimulation	20	95	126	50
5.2 Proprioceptive stimulation	13	62	71	28
5.3 Electrical stimulation	0	0	0	0
6. Splinting techniques	0	0	0	0
7. Exercise to increase strength				
7.1 Resistance from the therapist	21	100	131	52
7.2 Resistance from body weight	21	100	108	43
7.3 Resistance from equipment	21	100	134	53
7.4 Gravity neutral repetitive movement	21	100	134	53
8. Balance and mobility incorporating upper limb activity				
8.1 In, or from, lying	14	67	39	15
8.2 In, or from, kneeling	3	14	5	2
8.3 In, or from, sitting	14	67	39	15
8.4 In, or from, standing	12	57	37	15
8.5 In walking	7	33	17	7
9. Upper-limb functional tasks				
9.1 Bilateral functional activities	20	95	89	35
9.2 Unilateral reaching activities that are object directed	16	76	55	22
9.3 Unilateral reaching activities that are spatially directed	19	90	68	27
9.4 Dexterity exercises	17	81	68	27
10. Education for patient				
10.1 To encourage self-monitoring of upper limb	14	67	48	19
10.2 Transfer training	2	10	4	2
10.3 Limb handling and positioning skills	4	19	19	8
10.4 Integration of upper limb in wheelchair propulsion	2	10	2	1
11. Other interventions/techniques	0	0	0	0

Form from Donaldson et al. [14]
At the end of each conventional therapy session, the therapist completed the form by ticking the aims for the session and the techniques and positions used to provide a record of the content of the sessions.
The total number of possible sessions was 252 (21 participants x 12 sessions); however, 10 sessions were missed, so the total number of sessions was 242.

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