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Self-directed exergaming for stroke upper-limb impairment increases exercise dose compared to standard care

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Abstract:	Background: One of the strongest modifiable determinants of rehabilitation outcome is exercise dose. Technologies enabling self-directed exercise offer a pragmatic means to increase dose, but the extent to which they achieve this in unselected cohorts, under real-world constraints, is poorly understood. Objective: Here we quantify the exercise dose achieved by inpatient stroke survivors using an adapted upper limb (UL) exercise-gaming (exergaming) device, and compare this with conventional (supervised) therapy. Methods: Patients presenting to a single acute-stroke centre over 4 months with UL impairment were screened. Participants were trained in a single session, and provided with the device for unsupervised use during their inpatient admission. Results: From 75 patients referred for inpatient UL therapy, we recruited 30 (40%), of whom 26 (35%) were able to use the device meaningfully with their affected UL. Self-directed UL exercise duration using the device was 26 minutes per day (median; IQR: 16-31), in addition to 25 minutes daily conventional UL therapy (IQR: 12-34; same cohort plus standard-care audit; joint n=50); thereby doubling total exercise duration (51 minutes; IQR: 32-64) relative to standard-care (Z=4.0, P<.001). The device enabled 104 UL repetitions per day (IQR: 38-393), whereas conventional therapy achieved 15 UL repetitions per day (IQR: 11-23; Z=4.3, P<.001). Conclusion: Summarizing, adapted exergaming enables over a third of stroke survivors with UL impairment to increase exercise duration two-fold, and repetitions eight-fold, compared to standard care, without requiring additional professional supervision.

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Self-directed exergaming for stroke upper-limb impairment increases exercise dose compared to standard care

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Abstract

Background: One of the strongest modifiable determinants of rehabilitation outcome is exercise dose. Technologies enabling self-directed exercise offer a pragmatic means to increase dose, but the extent to which they achieve this in unselected cohorts, under real-world constraints, is poorly understood. **Objective:** Here we quantify the exercise dose achieved by inpatient stroke survivors using an adapted upper limb (UL) exercise-gaming (exergaming) device, and compare this with conventional (supervised) therapy. **Methods:** Patients presenting to a single acute-stroke centre over 4 months with UL impairment were screened. Participants were trained in a single session, and provided with the device for unsupervised use during their inpatient admission. **Results:** From 75 patients referred for inpatient UL therapy, we recruited 30 (40%), of whom 26 (35%) were able to use the device meaningfully with their affected UL. Self-directed UL exercise duration using the device was 26 minutes per day (median; IQR: 16-31), in addition to 25 minutes daily conventional UL therapy (IQR: 12-34; same cohort plus standard-care audit; joint n=50); thereby doubling total exercise duration (51 minutes; IQR: 32-64) relative to standard-care (Z=4.0, *P*<.001). The device enabled 104 UL repetitions per day (IQR: 38-393), whereas conventional therapy achieved 15 UL repetitions per day (IQR: 11-23; Z=4.3, *P*<.001). **Conclusion:** Summarizing, adapted exergaming enables over a third of stroke

survivors with UL impairment to increase exercise duration two-
fold, and repetitions eight-fold, compared to standard care,
without requiring additional professional supervision.

Keywords: Stroke; rehabilitation; physiotherapy; upper limb; exercise gaming; rehabilitation
technology.

Introduction

Upper limb (UL) impairment is the most common physical consequence of stroke [1], with ~60% of stroke survivors experiencing persistent UL functional impairment [2]. Repetitive task-directed exercise accelerates and improves long-term UL recovery [3,4], making occupational therapy (OT) and physiotherapy (PT) as key components of post-stroke management.

Higher exercise doses consistently result in superior UL outcomes in animal stroke models [5,6] and clinical trials [7–11]. However, in practice, the amounts of organized physical therapy provided to patients are relatively low [12]. A UK audit found that OT and PT provision nationally falls below recommended guidelines for post-stroke rehabilitation (45minutes daily over 5 days); with centres delivering on average 40 minutes/day OT across 65% inpatient days, and 35 minutes/day PT over 73% inpatient days (equivalent to 28 and 25 minutes daily respectively) [13]. A review of observational studies of inpatient stroke therapy indicated that the average UL treatment component for OT and PT sessions combined, lasts ~10 minutes; and comprises ~30 repetitions [14]. By comparison, clinically meaningful UL improvements only occur as rehabilitation dose increases from 30 minutes to a minimum of 1-2 hours daily [8,11,15,16] and with daily repetition counts of several hundred [17]. The reasons why practice falls far behind theoretically-optimal

levels of exercise dosage are multifaceted, including barriers such as costs and staffing [18,19] as well as reduced capacity of stroke survivors to initiate and engage in self-directed exercise [20].

In recent years, a growing number of rehabilitation technologies have emerged that boast the potential to provide cost-effective, intensive UL training[21]. However, while such devices provide the *means* to supplement exercise dose, their clinical adoption, thus far, has been underwhelming[22] .Bridging this "translational gap" is a much-needed focus of rehabilitation research; requiring design optimization (cost, complexity, accessibility etc.) [23]; and tests of patient engagement and efficacy [24,25].

One such knowledge gap concerns the extent to which UL rehabilitation technologies can be adopted in real-world, heterogeneous populations, including those with severe weakness, cognitive impairment etc. Studies of rehabilitation technologies to date have typically selected high-functioning cohorts, which limits the applicability of their findings [26]. A related issue is that clinical trials of UL rehabilitation technologies typically control for exercise dosage between treatment groups, in order to test whether interventions are as effective as dose-matched, conventional therapy [27-32]. This entails researchers imposing scheduled therapy sessions, while closely supervising and supporting participants. However, this

confounds one of the main attractions of rehabilitation technologies: i.e. the potential to increase exercise dose without additional cost or manpower. Therefore, to maximise translational potential, trials of rehabilitation technologies should be subject to the constraints of typical healthcare settings, including the need to match professional contact time (rather than exercise dose) between intervention and standard-care cohorts. In such studies, exercise dose achieved becomes an important outcome measure of interest.

The purpose of the current study is to estimate: i) the amount of supplementary exercise that can be achieved using an adapted exergaming system designed for self-directed UL training; and ii) to compare this with exercise dose achieved by conventional, supervised therapy, in a standard hospital setting. The study follows a broad cohort of stroke survivors with UL impairment in the subacute recovery phase, when neurobiological recovery potential is heightened and rehabilitative therapy is typically concentrated. By testing a heterogeneous sample, we also address the question of: iii) how technology-enabled, self-directed exercise supplementation depends upon patient characteristics including physical and cognitive impairment.

A further important divergence from many previous UL rehabilitation technology trials is that our study is

relatively low-resource and "hands-off". In this way we

maximise its applicability to everyday practice, where finding

extra budget and personnel to adopt and implement novel

interventions is a common barrier. Accordingly, the device we

employ is low-cost (~$500), and designed for self-directed

training across a broad range of user abilities[33].

Methods

Ethics

The study was approved by the UK National Research Ethics Service (Ref: 78462). All

participants gave informed written consent prior to recruitment.

Study design

We conducted a prospective feasibility study of a self-directed adapted exercise gaming

device for UL impairment. The device was provided as an adjunct to conventional therapy in

a cohort of subacute stroke in-patients with new UL impairment. Outcome measures were:

feasibility and fidelity of the research protocol; accessibility and acceptability of the device;

supplementary UL exercise dose (duration and repetitions) achieved; and the influence of

participant characteristics on both participation and performance.

UL exercise dose achieved with the device was compared with that recorded during

conventional therapy in the same set of patients and study period. This enabled estimation of

both the supplementary, and total, exercise dose achieved in subjects provided with the

device, who also received standard care. Conventional therapy was not intended to be altered

by, nor incorporate device use. To confirm this, we also conducted a prospective audit of

therapy content and duration in a separate cohort of patients with similar characteristics, receiving standard care only.

Patient population

The study took place at a large London stroke centre (~1200 admissions p.a.) between September - December 2019. All patients presenting with UL impairment suitable for inpatient therapy were screened. In the following two months (January-February 2020), an audit of patient medical records was conducted in a cohort of stroke in-patients with similar characteristics. Inclusion criteria consisted of: i) adults admitted with acute stroke within previous 4 weeks; ii) objective UL weakness due to presenting stroke; iii) capacity to consent. Exclusion criteria consisted of: i) medical instability; ii) UL pain; iii) uncompensated visual impairment; iv) language barrier; v) photosensitive epilepsy; vi) participation in a concurrent research trial.

Intervention

All participants were provided with the adapted exergaming device from enrolment for the remainder of their inpatient admission within the study centre. Patients were taught to use the device by a research therapist in a single ~40minute session. Training employed a standardised script, including: dose-response education; management of compensatory or accessory movements; and safety/adverse events reporting procedures. Participants were encouraged to use the device daily with their affected UL. Relatives or friends were engaged, if available and required, e.g. for device positioning/set up. Personalized recommendations were also issued e.g. use of UL positioning support; and selection of suitable training games. After the first training session, participants (with or without non-professional assistance) were

left to use the device freely without coercion, prompting, or professional supervision. A research team member visited weekly to screen for and resolve any technology support needs.

The adapted gaming device consists of a handheld flexible sensor system that detects both grip force and 6 degrees-of-freedom acceleration, enabling training of precision grip control, finger extension, and wrist movements [33]. The sensor system communicates wirelessly with a tablet on which there are 8 training games providing feedback, that participants select at will (Figure 1). At the start of each session, participants were prompted by the software to exert a maximal force grip. This calibrated the exercise games, enabling engagement across a wide range of motor abilities.

Measures

1. Patient characteristics: The following data were recorded at study entry: age; sex; Edinburgh Handedness Scale (EHS); stroke type (ischemic/haemorrhagic); National Institute of Health Stroke Scale (NIHSS); NIHSS arm-motor subcomponent; Fugl Meyer-Upper Extremity Assessment (FM-UE); Montreal Cognitive Assessment (MoCA); modified Rankin Scale (mRS); Hospital Anxiety and Depression Scale, (HADS); Barthel Index (BI).

2. *Feasibility and fidelity:* We recorded: i) fatigue and pain; ii) adverse events; iii) technical failure and support required; and iv) recruitment and retention rates. At study end point, a feedback survey was administered to evaluate the acceptability of the research protocol, research materials and research process. This incorporated a 5-point Likert scale (dissatisfied, room for improvement, neutral, satisfied, extremely satisfied), and a single binary question: willingness to be randomised to a future trial (yes/no).

3. Accessibility and acceptability: Participants' competence in using the device was rated by the research therapist on a 4-point scale: independent; support for set up only; supervision and support required; or unable to use meaningfully. Competency judgements were made based on the following device functionalities: set up; turning on; accessing the exercise game platform; selecting and executing exercise software; device charging.

Acceptability of the device was evaluated using an 11-item survey based on the Technology Acceptance Model (TAM)[34], that is predictive of novel healthcare technology adoption[35] [36]. Items measured included, perceived usefulness, intentions to use, and perceived ease of use. Participants indicated their level of agreement with each item on a 3-point Likert scale (disagree, neutral, agree). Technology acceptance was indicated by a >75% positive response to affirmative survey items. Participants' comments or supporting statements in the context of their feedback were also recorded.

4. Supplementary dose of UL exercise: Conventional UL therapy doses were extracted from: i) patient electronic clinical records that describe detailed content of each therapy session; and ii) the UK Sentinel Stroke National Audit Programme (SSNAP) database, which itemizes therapy duration and frequency for individual patients. We also recorded whether, as part of conventional therapy, participants had an UL goal documented; whether they were provided with an UL self-exercise training programme (Graded Repetitive Arm Supplementary Programme (GRASP))[37]; and surveyed patients (from the audited group not receiving the device) as to the frequency with which GRASP was used, and the conditions in which it was used (i.e. self-directed or supervised).

Daily durations of exergaming device use were logged both by patients/carers (i.e. start - end times of session), and by the device (i.e. cumulative time on exercise trials). These two logs were strongly correlated (Spearman r = 0.91; *P*<.001) indicating reliability of both measures. However, overall session times included preparatory steps (e.g. device positioning; set up; game selection etc.) and rests, that were not recorded by the device (which only logged active game play); and so the former were 14.5% greater (median; IQR: -0.06 – 20.9%). Since preparatory and rest periods were included within conventional therapy session times, which correspond to "time scheduled for therapy", as conventionally reported in rehabilitation studies [8], we use session times for direct comparison between the two therapy types

In a subgroup of 11 participants we measured repetition counts during both conventional therapy and self-directed exergaming sessions. The age, NIHSS, FM-UE scores and enrolment duration were not significantly different in this subsample to the remainder of the group. During conventional therapy sessions, UL exercise repetition numbers were documented by therapists in clinical records. In order to assess their accuracy, a researcher directly observed conventional UL therapy sessions and counted UL repetitions in audited standard-care patients (n=15), and compared this to counts itemized in clinical records. Since this showed that actual repetition counts were 15% greater than those documented, we corrected the latter accordingly. Repetition numbers per session of continuous exercise; and per day; and exergame type, were electronically recorded by the device during self-directed UL exercise sessions.

Statistical analysis

We report medians, interquartile ranges (IQR); and non-parametric statistical analyses, conducted in Matlab v.2019b. Since enrolment times differed between patients, we calculated

exercise durations both in terms of per patient (per day), and also per day (regardless of

patient, i.e. concatenating all study enrolment days into a single list).

Data availability

Datasets of the current study are available from the corresponding author upon reasonable

request.

Results

Recruitment

140 patients with UL impairment were screened, of whom 65 were unsuitable for research or

therapy (Figure 2). Of the remaining 75, we recruited 30 participants (i.e. 40%), the main

reasons for exclusion being cognitive impairment severe enough to prevent either active

therapy or informed consent. Subjects were enrolled for a median of 8 days (IQR: 5-14). The

total number of enrolment days across all subjects was 381.

Participant characteristics

Participant characteristics of those recruited for intervention, and those audited for standard

care, are detailed in Table 1. There were no significant differences in any measures between

the two groups.

Feasibility and fidelity

There were no reported adverse events, including no increase in pain/fatigue from baseline to

end point. Three episodes of device failure occurred requiring (remote) technical support.

There were 20 reported episodes of minor technical errors, primarily relating to Bluetooth

connectivity between device and tablet, which led to periods of disuse. These were resolved by the research therapist.

All participants rated the research protocol, information provided, consenting process, assessments completed, and researcher visits as "Satisfactory" or "Extremely Satisfactory". 18% rated the intervention training protocol as leaving "Room for Improvement". 82% of participants cited willingness to be randomised in a future trial.

Accessibility and acceptability

4 participants (14%) were unable to use the device with their affected UL due to dense weakness (Medical Research Council Muscle Power Scale 0/5), that persisted throughout enrolment (verified by weekly review or consultation with the treating clinical team). Device user competence varied as follows: 7 (24%) participants were fully independent; 7 (24%) required assistance with set up only; 11 (38%) required supervision from a non-professional (e.g. friend or relative) due to physical /cognitive difficulties.

Across all participants (including those unable to use the device) the technology acceptance rating was 78%, with 73% reporting that they would have liked to continue using the device (intent to use). 56% found the device easy to use and understand (perceived ease of use). 64% felt that the device promoted UL recovery (perceived usefulness). Participants who replied negatively to these items were within the lowest percentile of FM-UE scores and demonstrated the lowest adherence to use.

Supplementary exercise

Conventional therapy duration, for UL and other rehabilitation domains, across all 627 admitted stroke patients during the

trial and audit period (September 2019-February 2020) was 36.6

minutes (IQR: 23.0-61.7) for OT and 37.2 minutes daily

(median; IQR: 25.6-65.7) for PT. This indicates that standard

care dose in our population complied with national therapy

guidelines and exceeded the national average[13]. The self-exercise

programme, GRASP, was provided by therapists to 31/50 (62%) UL-impaired patients

(pooling recruited and audited samples). A survey of 14 participants from the audited group

indicated that GRASP was used exclusively in supervised therapy sessions in 79%; and 1-

2x/week independently in 21%.

Focusing on UL rehabilitation (combining OT and PT), there was

no difference in daily conventional (i.e. supervised) therapy

time between participants receiving the exergaming device

(median: 31.2 minutes, IQR: 0-37.3) versus those in the

standard care audit (median: 23.3 minutes, IQR: 15.0-30.0)

(Z=0.46, *P*>.1). Pooling device and standard care groups, the

median daily conventional UL therapy duration was 25.0 minutes

(IQR: 11.9-34.2) per participant; or 15.0 minutes (IQR: 0-

37.3) per day (Figure 3A). The additional median daily UL

exercise duration achieved by participants using the

exergaming device (including those unable to use the device)

was 26.3 minutes per patient (IQR: 16.0-31.0) (Figure 3B); or

24.5 minutes (IQR: 7.0-37.0) per day. The total daily exercise

duration (i.e. supervised + self-directed) for participants

included in the study was 51.0 minutes (IQR: 31.0-62.5), or

45.0 minutes per day (IQR: 19.3-69.7), both of which were

significantly greater than standard care (Z>3.8, P<.001)

(Figure 3C).

There was no difference in exercise repetition count during

conventional therapy comparing participants provided with the

device versus those in the standard-care audit: 40 (IQR: 33-

52) vs. 36 (IQR: 27-54) per session; or 15 (IQR: 12-23) vs. 15

(IQR: 8-23) per day (Z<0.4, P>.1). Participants using the

device achieved ~60% more repetitions during self-directed

(exergaming) training sessions (median: 67; IQR: 40-90; n=11)

than during conventional therapy sessions (Z=2.0, *P*<.05; n=31)

(Figure 4). Measured as repetition counts per day, the

difference in repetitions counts between participants using

the device, during device sessions, versus all participants

during conventional therapy sessions, was ~7x greater (median:

104; IQR: 38-393 versus 15; IQR: 11-23; comparison: Z=4.3;

P<.001). The median number of exercise types selected by

participants using the device was 3 (IQR: 2-6).

Dependency on baseline characteristics

There was a non-significant trend between UL impairment

severity and exercise gaming duration (UE-FM: Spearman r=0.32,

p = 0.082). Participants in the lowest tertile of UL ability

(UE-FM score 0-25) used the device daily for 14.3 minutes

(IQR: 0-30), compared to participants in mid and upper

tertiles (27.5 minutes; IQR: 22.3-31.5; comparison Z=1.9,

p=0.064). Correlations of device use daily duration with

cognitive score (MoCA), global neurological disability

(NIHSS), age, days from stroke onset, and enrolment duration

were not significant (P>.1).

Discussion

This study demonstrates that inpatient stroke survivors can

achieve significant increases in exercise dose when provided

with an adapted exergaming device, without requiring

additional professional supervision. Participants – who

accounted for 40% of stroke in-patients with UL impairment

undergoing therapy – increased daily UL exercise duration two-

fold (on average), and repetition counts eight-fold, compared

to conventional doses of supervised therapy. The study also

demonstrated that adapted exergames for self-directed UL

rehabilitation were feasible, acceptable and safe; while

compliance with a self-exercise guidebook (GRASP) outside of

supervised sessions was poor[38]. The relevance of these

findings to everyday practice follows from the facts that we

recruited a broad cohort of patients (including those with

severe UL weakness and cognitive impairment); and the

intervention was low cost (device plus a once-off training

session). Thus, a significant proportion of stroke survivors

may potentially benefit from adapted exergaming; while its

adoption could occur with relatively low demands on infrastructure and resources.

The greatest reason for participant exclusion was lack of capacity to provide informed research consent (a requirement of the ethics board). Yet, some training software involved simple grip-release feedback tasks that many individuals with heightened cognitive support needs may still be able to engage in. Indeed, half of our participants had cognitive scores within the impaired range (MoCA 22/30; normal range $\geq$26), and there was no evidence for less device use with reduced cognitive ability. A related consideration is that 62% of participants required some level of assistance in using the device; which may partly account for more severely disabled participants showing a trend to less exergaming engagement (since they depended upon availability of relatives or incidental staff). Levels of self-directed exergaming could potentially be improved by organizational modifications such as making healthcare assistants / volunteers more available or permitting longer visitor hours.

While this study did not test for efficacy outcomes, strong associations exist between exercise dose and UL outcomes [8], across a large range of training methods [10,39,40], suggesting that these results could translate into UL improvements, if the level of exercise supplementation achieved in this study continued over a longer period. A meta-analysis of UL

randomized-controlled therapy trials [8] found that increasing

exercise dose by an average of 33 hours resulted in

clinically-meaningful improvements in functional UL outcomes.

Since we found that adapted exergaming increased UL exercise

duration by 26 minutes per day, we project similar

improvements in UL function could be achieved if continued

daily for 76 days. Although the median length of participation

in this trial was only 8 days by comparison, it is notable

that there was no trend for exergame use waning over time;

with only 1 of 9 patients enrolled for at least 21 days

showing a temporal drop-off.

It remains unclear whether UL exercises carried out with the

exergaming device we used would achieve meaningful

rehabilitation outcomes. The device offers training of a

relatively limited number of distal UL movements - that is a

trade-off for its simplicity, accessibility and low cost.

However, training of functional hand movements can 'carry

over' improvements to more proximal UL components, and may be

more instrumental than proximal / reach to grasp training [41,42].

Extending device functionality, e.g. reaching practice, could

be achieved with further device development (e.g. adding a

wearable armband motion sensor).

A large number of UL training technologies for stroke have

been trialled over the last ten years, and so we highlight the

key differences of the adapted exergaming device tested here.

Robotic and virtual-reality UL training technologies have been
shown in trials to be as good as, or superior to, conventional
supervised therapy, when used typically at least several times
a week, over 2 – 4 months, in sessions of 30-60 minutes,
achieving 300-600 repetitions per session [43-51].However, in
these trials, intervention sessions are generally supervised
by therapists, to encourage high-intensity training, and
support complex equipment set up etc.. These aspects can be
problematic when translating technologies to practice, because
higher doses of training entails higher staffing requirements,
offsetting their cost-effectiveness[52].

To increase the likelihood for adoption, simple, portable UL
training technologies have emerged, that encourage self-
directed exercise. Self-directed therapies can be defined as
when $\geq$50% of intervention occurs outside of direct
professional supervision [53]. However, this still leaves a
burden on formal support structures. When comparing these
techniques it is important to consider participant
characteristics, particularly age, physical and cognitive
ability, which strongly influence the level of exercise self-
engagement [54]. Most studies trialling self-directed UL
exergaming technologies have been highly selective, recruiting
subjects typically younger, less severely affected, and less
cognitively impaired than the average stroke survivor, which
limits their generalizability [55-59]. For example, two studies

achieving higher daily self-administered UL training doses

than in our study (of 31 and 74 mins, respectively; [57,60])

recruited participants ~15 years younger than our cohort; had

milder UL impairment; and either needed to agree to wear a

restraint mitt on their unaffected UL for the majority of the

day throughout the intervention period [60]; or attend an

outpatients clinic weekly [57], implying participants were highly

motivated, with a relatively low global disability status.

Many such research studies also fail to report the nature and

overall number of the screening population, making it

difficult to infer the impact of their findings on unselected

stroke populations. By contrast since our study screened

subacute stroke inpatients, we were able to quantify

participant selection carefully; and recruited a significantly

large proportion of all UL-impaired stroke survivors,

including many with severe weakness and/or cognitive

impairment.

In summary, this is the first trial of self-directed UL

exercise technology in an unselected inpatient stroke

population, showing that exercise dose is significantly

increased by provision of a simple, portable exergaming

device, relative to standard care. The resource implications

of the adapted exergaming system are low, requiring one

training session and a device that if loaned to multiple

patients over its lifetime (for several months at a time)

would cost <$100. These findings make the case for a

randomised controlled trial of adapted UL exergames over the

first 3 months of stroke recovery, spanning hospital and home.

Declaration of Conflicting Interests: PB and EB are cofounders

of Gripable Ltd., an Imperial College London spin-out company.

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Abbreviations:

- BI- Barthel Index

- EHS- Edinburgh Handedness Scale

- FM-UE- Fugl Meyer-Upper Extremity Assessment

- GRASP- Graded Repetitive Arm Supplementary Program

- HADS- Hospital Anxiety and Depression Scale

- IQR- Interquartile rage

- MoCA- Montreal Cognitive Assessment

- mRS- modified Rankin Score

- NIHSS- National Institute for Health Stroke Score

- OT- Occupational Therapy

- PT- Physiotherapy

- SSNAP- Sentinel Stroke National Audit Programme

- TAM- Technology Acceptance Model

- UL- Upper Limb

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Table 1. Participant characteristics

	Device (+Standard Care)		Standard Care (audit)		Group Comparison
	Median or n	IQR	Median or n	IQR	
N	30		20		
Age/years	72.5	61-79	63	54-76	n.s
Sex (female)/n	14 (47%)		14 (70%)		n.s
Hemorrhagic stroke	5 (17%)		6 (30%)		n.s
Premorbid functional dependency (mRS)/0-6	1	0-2	1	1-3	n.s
Delay between stroke onset and enrolment* / days	8.5	5-14	8	2-10	n.s.
Duration of enrolment / days	8	5-14	12	7.5-17	n.s.
Total admission duration/days	18.5	14-38	26	13-37.5	n.s.
Global neurological disability (NIHSS)/0-42	6	2-10	7	4-14	n.s.
Arm weakness (R or L) (NIHSS subcomponent)/0-4	2	1-3	1.5	1-2.5	n.s.
Arm function (Fugl-Meyer Score)/0-66	40	30-45	36.5	18-54	n.s.
Cognitive score (MoCA)/0-30	22	18-24	23	11-29	n.s.
Rehabilitation goal set addressing arm recovery	11 (37%)		12 (60%)		n.s
Provided with GRASP self-exercise program	17 (57%)		14 (70%)		n.s
Discharge functional dependency (mRS)/0-6	3	3-4	4	3-4	n.s

Abbreviations: mRS: modified Rankin Score; NIHSS: National Institute for Health Stroke Score; MoCA: Montreal Cognitive Assessment; GRASP: Graded Repetitive Arm Supplementary Program; n.s.: not significant. Units or score range given. NIHSS and mRS scores are higher for worse disability. Fugl-Meyer and MoCA scores are lower for worse disability. * data collection for

audit was started at delays from onset matching those of patients in device trial whose inpatient therapy duration was most closely matching.

Legends:

Figure 1. Examples of stroke inpatients using the adapted exergaming system. Exergames trained i) finger flexion and release (e.g. here shown controlling the height of a balloon, so as to steer the bird on the beam into the path of the stars) and ii) wrist (here, showing pronation – supination). Full consent was sought from participants for use of these images for publication and research dissemination purposes.

Figure 2. Flow-charts showing numbers of patients screened versus recruited into intervention trial (A), and audited as part of standard care (B).
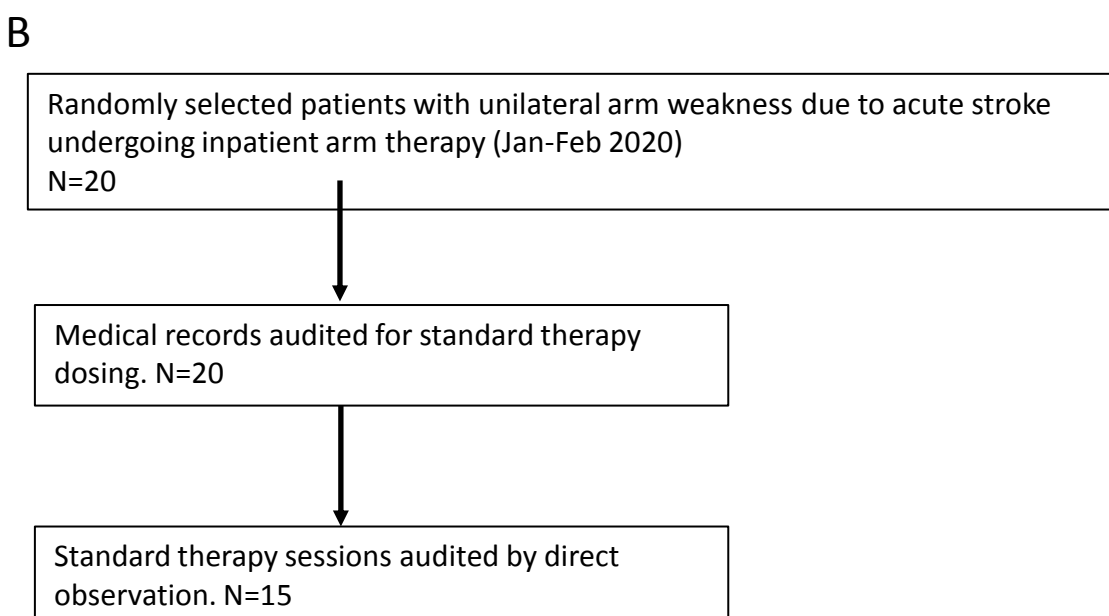
Figure 3: Heatmaps of daily arm exercise duration, with color intensity indicating time (colorbar), broken down by: exercise supervised by therapist (A); self-directed exercise using gaming device (B); and total time (C: i.e. =A+B). Patients are grouped, with the first 30 being those who received self-directed gaming device (i.e. intervention), and the second 20 being a standard care sample. Within these groups, patients are ranked by the number of inpatient days they received supervised therapy. Final column of each heatmap indicates subjects' median daily exercise time.

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Figure 4: Arm exercise repetition counts comparing conventional therapy with device-assisted self-exercise: A: Median repetitions per session; B: Median repetitions per day per patient across all days measured within active therapy period (i.e. net daily = total repetitions / days). Blue circles refer to standard-care (audited) patients; red circles refer to patients provided with device who underwent both conventional therapy and device-assisted self-directed exercise. Conventional counts are corrected for under-reporting. * P<.05; **P<.001

Figure 1

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Please note: Full consent was sought from participants for use of these images for publication and research dissemination purposes.

Figure 2

A

All acute stroke admissions (Sep-Dec 2019)
N=463

Upper limb weakness on admission
N=289

Deficit resolved; transferred to another centre; discharged; medical instability; deterioration; moribund; death. N=149

Screened by research team
N=140

Research ineligible

Participating in conflicting research study. N=19

Transferred or discharged. N=17

Resolved or no objective impairment. N=16

Diagnostic revision. N=2

Therapy ineligible

Severe arm pain. N=7

Clinical deterioration. N=4

Eligible for local inpatient arm therapy and research
N=75

A priori exclusion criteria

Severe cognitive impairment preventing active therapy. N=26

Cognitive impairment precluding consent. N=10

Language / Visual barrier. N=5

Patient declined. N=4

Recruited
N=30

B

Randomly selected patients with unilateral arm weakness due to acute stroke undergoing inpatient arm therapy (Jan-Feb 2020)
N=20

Medical records audited for standard therapy dosing. N=20

Standard therapy sessions audited by direct observation. N=15

Figure 3

A. **Duration of supervised arm exercises / mins**

B. **Duration of self-directed arm exercises / mins**
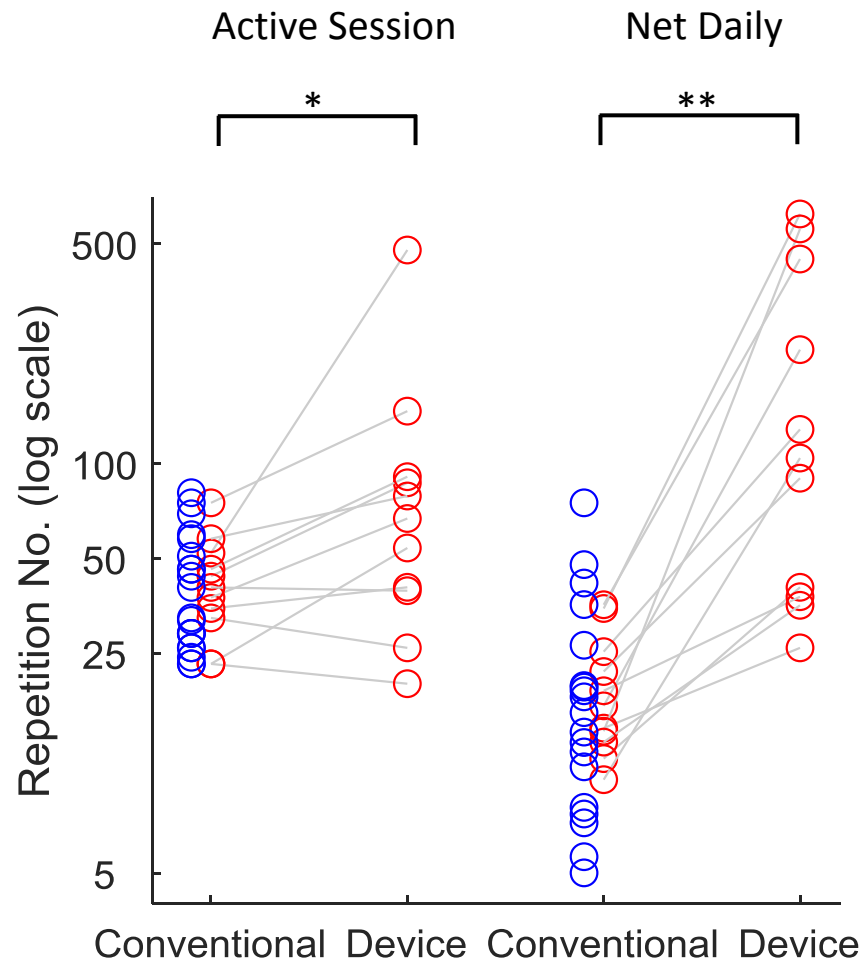
C. **Duration of all arm exercises / mins**

Figure 4

Table 1. Participant characteristics

	Device (+Standard Care)		Standard Care (audit)		Group Comparison
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Cognitive score (MoCA)/0-30	22	18-24	23	11-29	n.s.
Rehabilitation goal set addressing arm recovery	11 (37%)		12 (60%)		n.s
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Discharge functional dependency (mRS)/0-6	3	3-4	4	3-4	n.s

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*Abbreviations: mRS: modified Rankin Score; NIHSS: National Institute for Health Stroke Score; MoCA: Montreal Cognitive Assessment; GRASP: Graded Repetitive Arm Supplementary Program; n.s.: not significant. Units or score range given. NIHSS and mRS scores are higher for worse disability. Fugl-Meyer and MoCA scores are lower for worse disability. * data collection for audit was started at delays from onset matching those of patients in device trial whose inpatient therapy duration was most closely matching.*