Feasibility of a Second Iteration Wrist and Hand Supported Training System for Self-administered Training at Home in Chronic Stroke

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Abstract—**Telerehabilitation allows continued rehabilitation at home after discharge. The use of rehabilitation technology supporting wrist and hand movements within a motivational gaming environment could enable patients to train independently and ultimately serve as a way to increase the dosage of practice. This has been previously examined in the European Supervised Care & Rehabilitation Involving Personal Telerobotics (SCRIPT) project using a first prototype, showing potential feasibility, although several usability issues needed further attention. The current study examined feasibility and clinical changes of a second iteration training system, involving an updated wrist and hand supporting orthosis and larger variety of games with respect to the first iteration. The paper is relevant for the conference, reporting a new telemedicine service, combining physical orthotic support with remote offline supervision, for telerehabilitation at home after stroke. Nine chronic stroke patients with impaired arm and hand function were recruited to use the training system at home for six weeks. Evaluation of feasibility and arm and hand function were assessed before and after training. Median weekly training duration was 113 minutes. Participants accepted the six weeks of training (median Intrinsic Motivation Inventory = 4.4 points and median System Usability Scale = 73%). After training, significant improvements were found for the Fugl-Meyer assessment, Action Research Arm Test and self-perceived amount of arm and hand use in daily life. These findings indicate that technology-supported arm and hand training can be a promising tool for self-administered practice at home after stroke.**

Keywords-stroke; upper extremity; telerehabilitation; dynamic orthotic device; rehabilitation games; home training.

I. INTRODUCTION

Stroke is one of the most common causes of adult disability. Even in the chronic phase, motor problems still persist in the majority of stroke patients [1], leading to difficulties in performing activities of daily living independently. Motor problems that persist in the chronic phase may be partly due to learned nonuse of the affected upper limb [2]. Stimulating the use of the affected upper extremity has shown to overcome the learned nonuse [3].

Technology has the potential to support rehabilitation since it can provide high-intensive, repetitive, task-specific, interactive treatment of the impaired upper extremity. Besides, it has the potential to accurately quantify therapy and monitor patients' progress, while also providing immediate feedback to patients, as well as therapists. Rehabilitation robotics has been shown to be as effective as conventional rehabilitation for the hemiparetic arm [4]-[7]. Most research so far has shown significant improvements in upper limb motor function, although evidence of the transfer of robotic training effects to activities in daily life remains limited, as is observed for most interventions in stroke rehabilitation, including conventional therapy [8]. To maximize independent use of the upper extremity in daily life, it is important to include functional movements of both the proximal and distal arm and hand into post-stroke training, since a generalization effect to improvements on the entire upper extremity was found [9][10].

Most robotic devices are mainly suitable for the clinical setting with direct supervision of a therapist [5]. A next step would be to provide such systems at home, to enable self-administered practice of the arm and hand after stroke [11]. This is especially interesting since an increasing number of stroke survivors is expected, which will result in increased demands on healthcare systems [12]. New ways of providing healthcare services, such as teleconsultation and remote monitoring and treatment in the patient's home are therefore needed.

Telemedicine systems for upper extremity exercise showed promising results in improving health of stroke patients [13]. In addition, healthcare professionals and participants reported good levels of satisfaction and acceptance of telerehabilitation interventions [13][14]. This is in line with the precursor of the current study, using a passive device with three motivational rehabilitation games for arm and hand training at home [15][16], showing that the

training was motivational which was underlined by an average weekly training duration of 105 ± 66 minutes. Usability showed potential, although several usability issues needed further attention. Clinical evaluations showed modest changes in arm and hand function [15].

In the current study, we expanded this research by using a next iteration of the developed training system. Lessons learned regarding usability findings, therapeutic benefit and practical issues which were obtained in the first iteration of patient measurements with the SCRIPT system [15][16] have been taken into account for the design of the second prototype. An updated passive wrist and hand orthosis with improved user interface including nine exercise games was provided. The new games further focused on functional exercises incorporating versatile grasping gestures. The second prototype was evaluated with a new group of chronic stroke patients. The objective of the current study was to examine feasibility (user acceptance and adherence) and clinical changes in arm and hand function of a second generation technology-supported arm and hand training system at home in chronic stroke. The paper is structured as follows: the methods of the study are presented in Section 2, the results are shown in Section 3, followed by the discussion in Section 4 and conclusion in Section 5.

II. METHODS

A. Participants

Participants were recruited from the Roessingh Rehabilitation center, Enschede, the Netherlands and IRCCS San Raffaele Pisana, Rome, Italy. Participants were eligible for inclusion if they (1) had a stroke between 6 months and 5 years ago; (2) were between 18 and 80 years of age; (3) had limited arm and hand function because of the stroke, but having at least active control of 15° elbow flexion and having active finger flexion of at least a quarter of the passive range of motion; (4) were living at home and having internet access; (5) were able to understand and follow instructions; (6) had no additional orthopedic, neurological, or rheumatologic disease of the upper extremity; and (7) no severe neglect or uncorrected visual impairments. All participants provided written informed consent before participation. The study protocol was approved by the local medical ethics committees (Medisch Spectrum Twente, Enschede, the Netherlands and the IRCCS San Raffaele Pisana ethics committee, Rome, Italy).

B. Study design

This feasibility study has a longitudinal design. The participants received six weeks of self-administered technology-supported training for the arm and hand at home. Evaluation of arm and hand function was based on a baseline measurement pre-training and an evaluation measurement within one week post-training, performed at the research lab of the rehabilitation center.

C. Training intervention

Participants used a technology-supported training system [16], which consisted of a slightly adapted version of the

SCRIPT dynamic wrist and hand orthosis [17], a mobile arm support (SaeboMAS, Saebo Inc., Charlotte NC, USA) and a computer with webcam and touchscreen displaying exercise games (Figure 1). The mobile arm support was used to support the weight of the proximal arm. The wrist and hand orthosis is a passive exoskeleton worn on the forearm and hand, customized to the hand size of each participant. It provides extension forces to the wrist and fingers via passive leaf springs and elastic tension cords [17]. The orthosis was equipped with sensors to measure joint excursions of the wrist and hand, which allowed control of nine exercise games. A green marker placed on the hand plate of the orthosis was used to track the location of the orthosis by means of a camera placed on top of the screen to incorporate translational movements of the arm.

The exercise games consisted of various difficulty categories, to match the progress of individual participants. The categories were classified in a game difficulty schedule, ranked according to increasing complexity. Complexity was higher when a game required multiple movement planes (from 1D to 3D), involved a higher number of gestures to control the game, movements with progression from proximal to distal movements or gross to fine manipulation. The gestures needed to control the games were hand opening and closing, wrist flexion and extension, forearm pronation and supination, and reaching forwards, backwards and moving left or right. For hand opening and closing we could distinguish a general grasp, cylinder grasp, tripod grasp and lateral grasp, which have been shown to be reliable hand postures which could be recognized during performance of rehabilitation games [18]. Translational movements of the hand were integrated with wrist and hand movements (e.g., moving the hand to a target, grasping, transferring to a different target, releasing) to emphasize functional, task-specific movements.

The training environment was available within a motivational user interface including feedback on performance, which was displayed on the touchscreen. The general recommendation for training was about 30 minutes per day, six days a week. Participants could train at the time
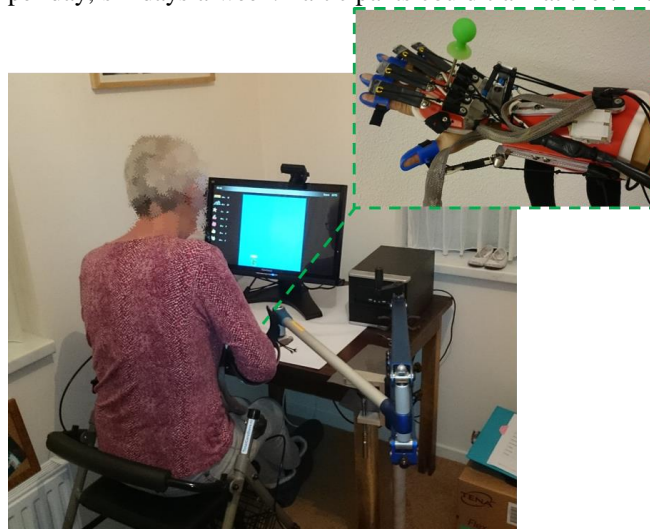

Figure 1. Training system at home.

of the day they preferred and were allowed to practice additionally if they wished to. A trained healthcare professional followed the participants' training progress remotely, offline, via another user interface available on a secured website and provided feedback by means of sending motivational messages when training duration was low. In addition, the healthcare professional visited each participant once per week to ensure competence with the training system, informally monitor progress, and to answer potential questions. Based on performance of the exercise games, in addition to ranking on the game difficulty schedule, the healthcare professional decided if a participant could move up to the next category of games. The professional adjusted the training program for the participants remotely.

D. Evaluation

1) User experience

The frequency and duration of training were automatically stored within the system and displayed in the user interface. The total minutes of training per week were counted to provide the total weekly training duration. These weekly training durations of all six weeks of training were used to calculate the average amount of practice over six weeks.

Motivation during training was measured using the Intrinsic Motivation Inventory (IMI) questionnaire [19]. It provides qualitative information about the content and level of motivation that a participant experienced during the training period (maximum score = 7). A higher score represents higher motivation during training, with a neutral score of four.

The System Usability Scale (SUS) is a 10-item scale providing a global view of subjective usability [20][21]. The questions were scored on a 5-point Likert scale ranging from 'strongly agree' to 'strongly disagree'. Scores are translated to 0–100%, with a higher score representing better usability. Interventions with scores in the 90s are exceptional, scores in the 70s and 80s are promising, and with SUS scores below 50 one can be almost certain that the intervention will have usability difficulties in the field. The SUS and IMI were completed during the post-evaluation measurement only.

2) Arm and hand function tests

Clinical tests were used to quantify general arm function before and after the training. The scales used are valid, standardized assessments, which were performed according to their specific test protocols.

The upper extremity part of the Brunnstrom Fugl-Meyer assessment (FM) evaluates motor status and the degree of synergy-development in the arm (maximum score = 66) [22]. Separate scores were calculated for proximal (maximum = 42) and distal components of the FM (maximum = 24).

The Action Research Arm Test (ARAT) evaluates coordination, dexterity and upper extremity function on the subtests grasp, grip, pinch, and gross arm movement (maximum score = 57) [23].

The Motor Activity Log (MAL) is a semi-structured interview for hemiparetic stroke patients to assess the perceived use of their paretic arm and hand (amount of use

(AOU) and quality of movement (QOM)) during activities of daily living (maximum score = 5 per subsection) [24].

The Stroke Impact Scale (SIS) was used to assess changes in function, activity and participation following stroke. The questionnaire assesses eight domains related to function, activities and participation. Each domain score has a range of zero to hundred percent, with a higher score indicating better quality of life [25].

E. Statistical analyses

Statistical analyses were performed with IBM SPSS Statistics 19 for Windows. Outcomes were non-parametrically tested for statistical significance due to the small sample size. Descriptive statistical methods (median with interquartile range (IQR)) were used to describe the participant characteristics and all outcome measures. Outcomes of each clinical scale were compared between both evaluation measurements using the Wilcoxon signed rank test. The level for significance was set at $\alpha \leq .05$.

III. RESULTS

A. Participants

Nine participants (six in the Netherlands, three in Italy) were included in the study. Two participants were lost to the study. One because of personal problems not related to this study and one having recurrent technical problems with the system. The characteristics of the remaining seven participants are shown in Table 1.

B. User experience

The participants actually used the system, but with a large amount of variation between and within individuals (Figure 2). Median weekly training duration for the group, averaged over six weeks, was 113 (IQR 69 – 158) minutes. One participant (E01) exceeded the advised training duration of 180 minutes per week once, and two other participants (D08 and E03) exceeded the advised duration several times.

The median score on the SUS was 73% (IQR 60% – 83%). On individual level, four participants rated usability over 70% and three participants between 50 and 70%.

Overall, the participants enjoyed the six weeks of training, as reflected in the overall median score on the IMI of 4.4 points (IQR 3.9 – 6.0 points). Table 2 shows individual participant results and group medians on all outcomes.

TABLE I. PARTICIPANT CHARACTERISTICS

	N = 7[a]
Sex	5 male / 2 female
Age	57 (44 – 67) years
Months post stroke	21 (9 – 33)
Type of stroke	5 infarction / 2 hemorrhage
Affected body side	4 left / 3 right
Dominant arm	0 left / 7 right
Fugl-Meyer score (maximal 66 points)	37 (30 – 45)
Action Research Arm Test score (maximal 57 points)	26 (21 – 28)
Stroke severity	6 moderate / 1 severe

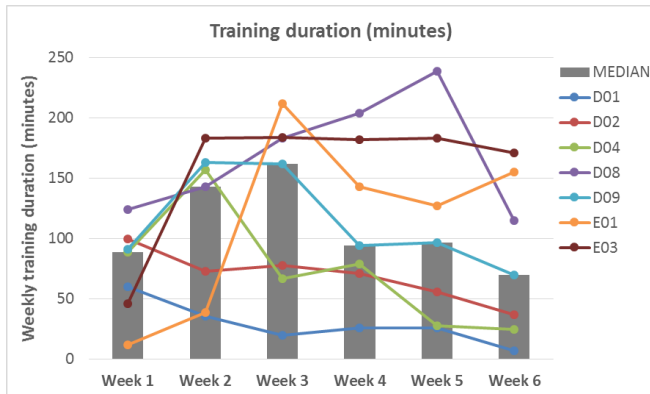a. Results are shown as absolute numbers or median (interquartile range)

Figure 2. Individual (colored lines) and group median (grey bars) weekly training duration.

TABLE III. ARM AND HAND FUNCTION TESTS (MEDIAN (IQR))

Outcome	Pre measurement	Post measurement	*P*-value
FM	37 (30 – 45)	41 (33 – 49)	**0.034**
FM Proximal	21 (21 – 31)	25.0 (23 – 32)	**0.027**
FM Distal	14 (9 – 17)	16 (10 – 18)	0.131
ARAT	26 (21 – 28)	28 (23 – 31)	**0.045**
MAL AOU	0.8 (0.4 – 1.5)	0.9 (0.8 – 1.4)	**0.046**
MAL QOM	0.8 (0.4 – 1.2)	0.8 (0.7 – 1.3)	0.249
SIS	61.4 (50.6 – 68.6)	66.2 (50.8 – 72.1)	0.128

Abbreviations: FM = Fugl-Meyer assessment, ARAT = Action Research Arm Test, MAL AOU = Motor Activity Log Amount of Use, MAL QOM = Motor Activity Log Quality of Movement, SIS = Stroke Impact Scale.

C. Arm and hand function tests

On group level, the Wilcoxon signed rank test showed a significant improvement after training for the FM total, FM proximal part, ARAT, and MAL AOU (Table 3). The FM showed a median improvement of 4.0 points ($P = 0.034$) for the total scale, and median improvement of 3.0 points ($P = 0.027$) for the proximal part only. The ARAT improved with median 2.0 points ($P = 0.045$) over training, and the MAL AOU with median 0.2 points ($P = 0.046$).

Examination of individual scores (Table 2) shows quite substantial improvements for one participant (E01), grossly exceeding the minimal clinically important difference (MID) for FM and ARAT [26], constituting changes greater than 10% of the total score. Participant E03 approaches MCID for FM with six points improvement. In addition, two participants (D09 and E03) exceeded MCID for the MAL QOM, of which E03 also exceeded MCID on MAL AOU [27], and participant E01 approaches MCID for both MAL AOU and QOM.

IV. DISCUSSION

A second generation technology-supported arm and hand training system was evaluated in patients with chronic stroke in their own home. The present findings show that training at home using the training system was feasible, since patients accepted the training well (median SUS = 73%) and were motivated (median IMI = 4.4). This was reflected in a median weekly training duration of 113 minutes (i.e.,

approximately 15 minutes per day). Participants showed improvements in arm and hand function, dexterity and self-perceived amount of arm and hand use in daily life.

The motivation outcomes of the current study indicate that patients perceived the training as motivating, to a similar extent as interventions applying rehabilitation technology in a clinical setting [28][29]. With a median SUS score of 73% the training system was rated as promising. This might be related to a large variation of games available in the current study, which was much appreciated by the participants. Although participants positively valued the training system, several usability issues were identified and should be considered when implementing further design adaptations.

In particular, some games caused errors after leaving the pause screen resulting in incorrect saving of the data, controlling one game was not clear for some participants, and another game had limited fluent game control in poor day light. The game utilized the position of a marker on the orthosis to determine hand position in space, however poor day light impacted on capturing this position accurately. Although these issues were not major, if repeated or cumulative, they are likely to result in frustration and might influence the motivation and attitude towards use of the system, which can negatively affect the adherence to training over time [30].

In the current study, participants were able to make their own decisions about their training schedule, without direct, real-time supervision of a therapist. The rationale for this was to remove the training constraints and increase therapy availability. Compared to previous telerehabilitation studies in which training sessions are often scheduled beforehand and with direct supervision [13][31], the achieved training duration of median 113 minutes per week was substantial,

TABLE II. INDIVIDUAL PARTICIPANT RESULTS AND GROUP MEDIANS ON ALL OUTCOME MEASURES

Participant	Average weekly training duration (minutes)	IMI (1-7)	SUS (%)	FM change (max = 66)	ARAT change (max = 57)	MAL AOU change (0-5)	MAL QOM change (0-5)	SIS change (%)
D01	29	4.0	60	-1	2	-0.04	-0.26	1.8
D02	69	3.4	73	1	-1	0.00	0.00	-0.6
D04	74	3.9	68	3	2	0.28	-0.18	-3.7
D08	168	6.0	83	4	0	0.05	0.05	10.6
D09	113	6.7	95	4	3	0.18	0.67	3.2
E01	115	4.4	58	15	13	0.44	0.44	11.0
E03	158	4.7	73	6	3	0.68	0.56	9.3
Median	**113**	**4.4**	**73**	**4**	**2**	**0.2**	**0.1**	**3.2**
(IQR)	**(69 – 158)**	**(3.9 – 6.0)**	**(60 – 83)**	**(1 – 6)**	**(0 –3)**	**(0.0 – 0.4)**	**(-0.2 – 0.6)**	**(-0.6 – 10.6)**

Abbreviations: IMI = Intrinsic Motivation Inventory, SUS = System Usability Scale, FM = Fugl-Meyer assessment, ARAT = Action Research Arm Test, MAL AOU = Motor Activity Log Amount of Use, MAL QOM = Motor Activity Log Quality of Movement, SIS = Stroke Impact Scale, IQR = Interquartile range.

suggesting that stroke patients do have the incentive to train at home and were able to use the system. This adherence falls within the range reported in other recent studies into technology-supported home-based self-administered upper limb therapy programs after stroke [30][32][33]. On the other hand, most participants did not reach the advised training duration, which is also comparable to these previous home-based studies [15][30][32][33].

One of the major assumptions concerning tele-rehabilitation using technologies is that when patients accept the technology and clinically benefit from it, they will actually use such a system when provided. However in practice, several factors, such as low motivation, fatigue and musculoskeletal issues can result in limited adherence [34], while training dose is an important factor in rehabilitation outcome [35]. When considering individual results, participants who had a rather high amount of training per week (>100 minutes), showed substantial improvements on arm and hand function. This suggests that actual adherence during self-administered practice is a highly relevant outcome. Moreover, stimulation of adherence should receive wide attention when designing and implementing home-based training interventions.

Several strategies can be considered for stimulation of adherence. Research has shown that regular patient-therapist contact during treatment has a motivational effect and can increase therapy adherence [36]. In our study, additional motivational strategies were implemented in a subset of our games [37], to increase participants' independent training time at home. This comprised more direct feedback about training duration, such as showing motivational messages about the duration after completion of each game, or continuously showing a timer during game play. We incorporated approaches from the field of psychology and education theory to further overcome this barrier, such as setting the correct balance between supporting and challenging, to maximize adherence to therapy [37]. However, our adaptive game-difficulty setting was not available in all games. In addition, patients' self-discipline might also play a role in this kind of unsupervised home training. So in future, it is also valuable to look closer at other characteristics such as patients' attitudes, personality traits, coping skills and commitments in daily life [30][32] to enable understanding of the most suitable patients for this kind of self-administered training.

The extent of improvement in motor function of the arm in the present study corresponded with those found in other robot-aided studies in chronic stroke in a clinical setting [4]-[7], and with therapy programs for the upper limb performed at home [13]. Perceived use of the affected arm in daily life as assessed by the MAL did significantly change on group level after six weeks training, which was also reflected in an improved dexterity capacity as measured by ARAT. Three of the games contained functional movements: integration of reaching, grasping and transportation simultaneously, and the inclusion of specific grasps, such as cylinder grasp, lateral grasp and palmar prehension grasp, to represent handling of different objects. This might have played a role in the improvements on activity level in the current study, since task-specificity is an important factor in restoration of arm and hand function after stroke [9][38]. However, these improvements are still modest on group level and not clinically relevant in terms of functional improvements. On the other hand, games with more complex gestures were only made available to patients after some progress was made in simpler games which could impact on the extent of these modest improvements. When these aspects are incorporated more prominently and in more games, exercises become even more functional and task-specific, which is expected to further enhance the clinical impact.

This study was performed with chronic stroke patients, limiting bias from spontaneous recovery and simultaneous other treatments. Home-based training could be considered at an earlier stage, where larger treatment effects would be expected. Further, only data of seven chronic stroke patients with mainly moderate stroke are available. Findings of the present study can only be partly generalized to other stroke survivors because of the small number of participants in this study. Future research should consider implementing a large randomized controlled trial, with sufficient statistical power to compare the effects with a control group.

V. CONCLUSION

The positive results for motivation, usability and actual training duration in this study indicate that home-based technology-supported arm and hand training is a feasible tool to enable self-administered practice at home. The improved arm and hand function and increased performance on activity level (both actual as well as perceived) indicates that self-administered home-based training can have a clinical value. Such an application has the potential to allow a higher dose of treatment than would be possible when depending on therapist availability in a conventional setting, if adherence can be stimulated further. Future research regarding telerehabilitation should therefore pay attention to adherence (stimulation) and the functional nature of exercises. Furthermore, identification of factors associated with better treatment outcomes (e.g., time post stroke, stroke severity and personal characteristics) is needed in order to understand who would benefit most from this technology-supported training at home.

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