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Feasibility Studies of Robot-Assisted Stroke Rehabilitation at Clinic and Home Settings Using RUPERT

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***Abstract*—Task based repetitive therapy has been proposed to help stroke survivors to regain functional control of arm movement. We developed a wearable exoskeleton rehabilitation robot with associated control algorithm and safety protection mechanisms, and a graphic user interface that is easy to use and intuitive to patients and therapists, as the framework for automated and customizable robot-assisted rehabilitation system for clinic and home based therapy.**

The system was tested in two feasibility studies. The first study involved 6 patients to receive therapeutic training during three time weekly clinic visits for 4 weeks. The second study set up the robot-assisted rehabilitation system at patient's house, where the therapeutic training was practiced on a daily base. Two patients were recruited for the home application study.

Patients' performances were assessed using clinical evaluation tools, including Wolf Motor Function Test and Fugl Meyer Assessment (FMA), both before and after the training. The performances of patients during the training weeks were also objectively evaluated by using the robot sensory data.

Keywords—**rehabilitation robot, at-home robot assisted therapy, stroke rehabilitation, video based task training therapy**

I. Introduction

In USA, about 795,000 people experience a stroke each year. Stroke has become a leading cause of serious and long term disabilities[1]. Depending on the severity of the stroke, traditional stroke rehabilitation options include therapist based treatments in a rehabilitation unit in the hospital, in a sub-acute care unit, in a rehabilitation hospital, in home therapy, home with outpatient therapy, or a long term care facility that provides therapy and skilled nursing care.

With advancement in robotics, robot-assisted rehabilitation has provided an alternative to the traditional therapy strategies. Robot-assisted therapy for stroke patients is a highly promising approach and has become a productive research topic ever since the first report by Volpe et al. [2] in 2000. Its advantages include cost reduction by automating the therapy procedure, thus allowing a therapist/physician to work with many patients at the same time, offering the capability of assessing the motion ability improvement quantitatively and objectively, and generating a wide variety of forces and motions for training. The capability of generating a wide variety of motions makes it possible to train patients on tasks simulating activities of daily living (ADL). Many clinical trials have demonstrated that robot-assisted therapy can aid in motor recovery[2-7].

Researchers have identified that training intensity has significantly positive correlation with the efficiency of rehabilitation for stroke patients[10 and 11]. It is also identified that long-term rehabilitation therapy is necessary for generating significant gain in performing ADL[8 and 9]. However, the traditional and most of the existing robot-assisted rehabilitation strategies require either clinic visits for patients, and/or intensive involvement of physical therapists. It makes the intensive training inconvenient or unaffordable for most of the stroke patients. A rehabilitation robot which can be implemented in home setting thus becomes necessary and beneficial for stroke patients.

A wearable robotic exoskeleton system for stroke rehabilitation, Robotic Upper Extremity Repetitive Therapy (RUPERT), was developed by the research group at Arizona State University and was first introduced in 2005[12]. It evolved to the current generation RUPERT IV that has 5 actively assisted degrees of freedom (DOF): shoulder flexion, elbow extension, forearm supination, wrist/hand extension and humeral external rotation, as shown in Fig. 1. For more detail please see our previous publications for the mechanical design of RUPERT, and the structure of its control system[12-14].

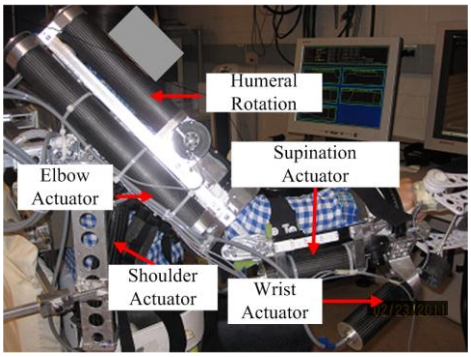

Figure 1. 5-DOFs of RUPERT

RUPERT is designed to be home applicable, which makes intensive long-term therapeutic training convenient and affordable for stroke patients. Design specification includes light-weight, portability, economical, easy and safe to operate. These features are critical for the home application. The caregiver or life partner of a stroke patient can easily learn how to put on or take off RUPERT on the patient and how to operate the graphic-user-interface of the software which implements the training therapy prescribed by the physical therapist. Physical therapists do not have to be present supervising the therapeutic training. They can monitor the progress of training through internet by reading the statistical reports automatically generated by the computer using the sensory data of the robot, and even adjust the therapy parameters remotely based on the progress.

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In this paper, we report preliminary results from two feasibility studies of RUPERT assisted stroke rehabilitation. The purpose of the first study is to test the mechanical structure, the control strategy, the safety, and the feasibility of RUPERT assisted stroke rehabilitation. The second study is to evaluate the feasibility of setting up the RUPERT at patient's house and to be operated for at-home therapy. The patient's life partner or caregiver operated RUPERT to provide therapeutic training on a daily base. The stability of the system operation, the safety of home application, and the feasibility of at-home training are tested.

II. METHODS

Motion Tasks

In both feasibility studies, the motion task that the patients were trained and tested on was a 3-D reaching-out task when RUPERT was worn by patients. The target of each reaching out movement was one of the 8 targets in a 3-D space, as shown in Fig. 2. In each trial, the specific target was presented to the patient in a 3-D virtual reality (VR) displayed on a video screen. Multiple sequential targets were also set up for some patients to simulate some ADLs such as sweeping or grabbing a water bottle to drink, if the performance of reaching all 8 static targets has recovered adequately based on the assessment of therapists. In tasks with multiple sequential targets, the next target was shown on the screen right after the previous one was successfully hit.

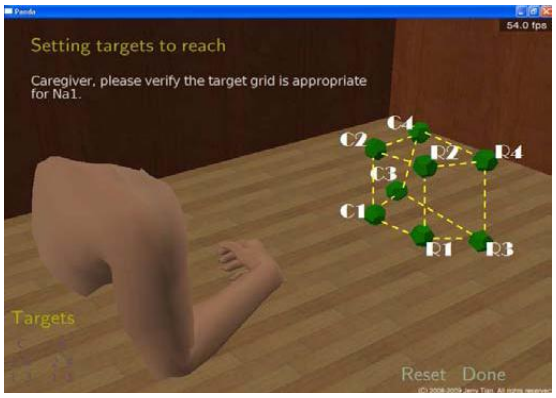


Figure 2. Locations of 8 targets shown in VR

Trunk compensation is a frequent spontaneous strategy adopted by stroke patients to complete many ADLs. However, trunk compensation should be avoided in task oriented rehabilitation training since it attenuates the training effects, and some trunk compensation strategies even bring difficulties to functions under training. For instance, shoulder shrugging or trunk leaning forward was a frequently observed trunk compensation strategy by many patients in our feasibility studies. It made the shoulder flexion (arm up) more difficult though the movement was a critical function in the reaching out task. Since RUPERT does not record the gesture of the body trunk and measures the arm movement from the origin located in the shoulder joint, trunk compensation to facilitate reaching targets in VR was not recognized nor rewarded by the system. In the feasibility studies, patients were encouraged to take self-restraint strategies to avoid or reduce trunk compensation by holding the chair they were sitting on using their unaffected hands. They were also learned quickly that trunk compensation did not improve their performance in the tasks.

Therapeutic Training Modes

Three therapeutic training modes are implemented in the current version of RUPERT: Continuous Passive Motion (*CPM*), *Co-Operative Mode* (COM), and *Testing Mode*.

CPM - In this mode, the subject should be relaxed and the robot does all the work in driving the arm to the target location. A smooth trajectory for each DOF is planned based on the minimal jerk principle from the initial position to the target value. The minimal jerk trajectory is:

$$x(t) = x_i + (x_T - x_i)(10(t/T)^3 - 15(t/T)^4 + 6(t/T)^5)$$

where x_i and x_T are the initial and target values of the DOF, respectively. Parameter T is the planned duration to complete the change of DOF. In RUPERT for the reported study, T was set between 10~20s, which was determined by the therapist based on the functional impairment of the patient. The pneumatic muscle was turned on to drive each DOF to follow the planned trajectory.

Co-operative Mode - This mode requires that the robot and the subject work together to achieve a particular therapy task. Different from *CPM*, in this mode, there is voluntary participation from the subject. The patients were required to maximize their participation in the reaching task. As in *CPM*, a smooth trajectory was also planned for each DOF. If the change of a DOF was faster than the planned trajectory, no assistance from RUPERT was provided. Otherwise, the actuator of that DOF was activated to provide assistance so that the real trajectory of the DOF can follow the planned one.

Testing Mode- In this mode, the patient was required to reach the target all by himself with the RUPERT assistance turned off. This mode is used to evaluate the performance of patient in reaching targets in the beginning of a training session, and after training by *Co-operative Mode* in each training session.

A typical training session started with a *CPM* block and a *Co-operative* block on target R4 (see figure 2). The purpose of *CPM* and *Co-operative* blocks at the beginning of each training session is two folds. First, they warmed up the patients maximally since R4 is the target where all joints extend maximally. Second, they got the patients acquainted with the reaching task, and warmed up the patients' perception on the VR. Then, the patient was tested under *Testing Mode* on all 8 targets, in a random order, twice per target. If any trial was failed, training trials on the failed targets were provided under *Co-operative Mode*, in an ascending order of difficulty to him/her. Each training block consisted of 10 training trials, and two testing trials followed immediately. The training target did not change as long as he/she failed in hitting it in either testing trials. The training session stopped once the

maximum allowed training time was reached, obvious fragility was observed by the caregiver or therapist, or requested by the patient.

Two Feasibility Studies

The first feasibility study was a clinic based therapy. Each patient had the clinic visit 3 times per week, for 4 weeks. During each visit up to 45-minute actual training from RUPERT was provided to the patient. In each session, a physical therapist provided assistance to DON/DOFF RUPERT, launched the computer program and the control system, and monitored the training.

The second feasibility study was at-home therapy after set up RUPERT at patient's house. Each patient was required to use RUPERT for rehabilitation training once per weekday for 4 consecutive weeks. Training in weekends was also allowed upon the patient's willingness. Training twice in a single day was also allowed as long as the fatigue was acceptable to him/her. Each therapy session was around 45 minutes, with actual training for 30 minutes. A physical therapist would visit the patient's house once per week to make sure that the system was working properly and then adjust therapy parameters based on the progress of functional improvement. The therapist may change the set of testing/training targets as in Figure 2, downsize/upsize the target to increase/decrease the task difficulty since small/bigger target size leads to longer/shorter moving distance and accuracy requirement in each trial. The spouse or caregiver of the patient was responsible for DON/DOFF RUPERT, running the computer programs, and launching the control system for each session.

In both studies we evaluated each subject twice, before and after the therapeutic training, on Wolf Motor Function Test (WMFT) and Fugl Meyer Assessment (FMA).

Both evaluations were performed by the same occupational therapist not involved or even aware of the therapy. WMFT consists of 15 motion tests, listed in Table 1. There are two metrics to describe how well a patient completed a task. One is how fast the task was completed. It is in the unit of seconds. If a task was not completed in 120 seconds, it was given up and 120 seconds was recorded. The other metric is the quality of the movement. It was ranked 1~5, where 1 stands for the lowest, and 5 stands for the highest quality.

Table 1. 15 Motion Tasks of WMFT

Tasks	
Forearm to table (side)	Lift Pencil
Forearm to box (side)	Lift Paper clip
Extend elbow (side)	Stack checkers
Extend elbow (side with weight)	Flip cards
Hand to table (front)	Turn key in lock
Hand to box (front)	Fold towel
Reach & Retrieve	Lift basket
Lift can	

Statistical Tests to Evaluate Functional Improvement Using Robot Sensory Data

To evaluate the functional improvement of patients after receiving the therapeutic training objectively, we used the RUPERT sensory data collected during the voluntary movements: the trials under the testing mode. Since on each training day, each target was only tested for a small number of trials to prevent fragile, statistically testing the performance improvement on a daily base will most likely fail to draw conclusion of significance. So, we conducted the statistical tests on a weekly base, i.e., by pooling data in each calendar week together. The significance level of the statistical tests was α=0.05.

We first employed χ^2 tests to investigate the change of the proportion of hitting each target successfully in the first and the last weeks. The χ^2 tests were also conducted to investigate the homogeneity of the proportions in the training weeks.

In addition to the proportion of hitting targets successfully, we are also interested to the quality of voluntary movements. We used smoothness metrics to measure the quality of voluntary movements. Then, we conducted ANOVA on the smoothness metrics to compare whether the means of the smoothness in the first and last weeks changed significantly.

There are multiple metrics to measure the movement smoothness, including jerk metric (JM), speed metric, mean arrest period ratio, peaks metric, and tent metric[15], and the spectral methods[13]. $JM = \int_{t_i}^{t_f} \left\| \mathbf{x}^{(3)}(t) \right\|^2 dt$, where t_i and t_f are the initial and finish time instants of the movement, and $\mathbf{x}(t) = [x_1(t), x_2(t), x_3(t)]^T$ is the location of the end point of the affected upper limb in 3-D space at time t. $\left\| \mathbf{x}^{(n)}(t) \right\|$ is the module of the n^{th} order derivative of $\mathbf{x}(t)$. Higher value of JM stands for smoother movement. We employed all of the above metrics to assess the movement smoothness though we presented only JM as JM is the most popular measurement of movement smoothness[15].

Table 2. Demographic data of patients

Group	ID	Age	Gender	Post-Stroke History (Months)
Clinic-visiting	002	61	F	41
	003	64	M	110
	007	58	M	61
	009	53	F	63
	015	61	M	18
	017	56	M	49
	Mean	59.5	2F/4M	57
Home -App	018	75	M	15
	019	70	F	10

Table 3. WMFT Scores and Seconds of 8 Patients

Group	ID	WMFT(Score)		WMFT(Sec)	
		Pre	Post	Pre	Post
Clinic-visiting	002	40	45	297.21	275.38
	003	50	56	53.37	38.81
	007	39	34	665.16	572.34
	009	35	33	661.61	771.04
	015	24	23	1245.97	1327.98
	017	53	52	98.64	107.69
Home -App	018	48	43	161.75	205.17
	019	47	51	88.76	302.62

III. Results

Recruitment of Patients

Totally 8 chronic stroke patients with at least 6 months post stroke history were recruited for the two feasibility studies. Six of the 8 patients were for clinic-visiting study, and the remaining 2 were for home application study. Table 2 provides the demographic data of the 8 patients.

Results of Clinical Assessment

The summation WMFT of each of the 8 patients was shown in Table 3. Table 4 presented the summation of the FMA setting scores of each patient. In both tables, functional improvement (increase in scores or decrease in seconds) identified by the tests was highlighted by yellow shadows, and functional deterioration (decrease in scores or increase in seconds) was highlighted by shadows with slash lines.

From Table 3, we can see that patients 002 and 003 both showed functional improvement in both WMFT scores and seconds. Patient 007 showed functional deterioration in WMFT score, but improvement in WMFT seconds. Home application patient 019 showed the opposite trend as patient 007. The remaining 4 patients showed deterioration in both WMFT score and seconds. In Talbe 4, patients 002, 009, and 019 showed functional improvement, and the remaining 4 patients showed functional deterioration.

Statistical Tests for Clinic-visiting Feasibility Study

We first conducted χ^2 test to investigate the change of the proportion of hitting the 8 targets between the first and the last training weeks during trials under testing mode. Among the 6 clinic-visiting patients, 3 of them demonstrated significant improvement in the proportion of successfully hitting at least one target. The remaining 3 showed neither significant improvement, nor significant functional deterioration on the hitting rate. Figure 3 demonstrated the proportion of successfully reaching targets where the proportion changed significantly between the first and the last weeks. Targets that were not plotted in Figure 3 were those whose proportion of successful reaching did not change significantly. The three patients demonstrating significant functional improvement were stroke survivors post-stroke at 110 months (patient 003), 49 months (patient

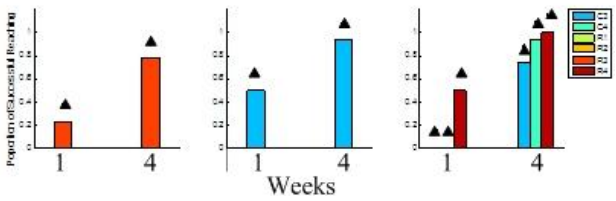


Figure 3. Significantly changed proportions of successful hit during voluntary movements in the first and last weeks for clinic-visiting patients 003, 017, and 002 (left to right).

Table 4. FMA Setting Scores of 8 Patients (Maximum score=66)

Group	ID	FMA Setting	
		Pre	Post
Clinic-visiting	002	42	49
	003	55	51
	007	31	25
	009	36	39
	015	19	18
	017	46	50
Home -App	018	58	56
	019	36	49

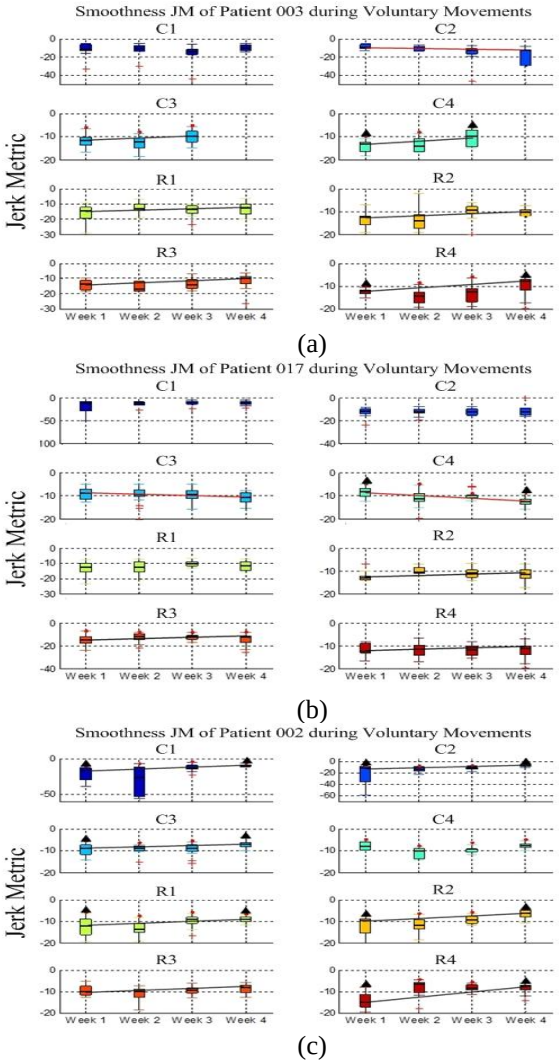
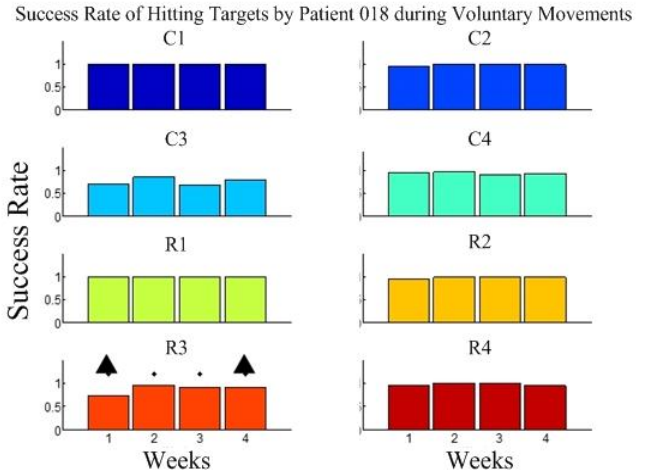


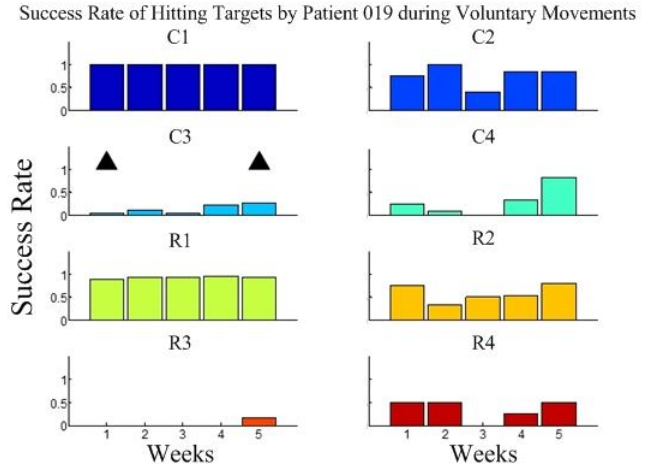
Figure 4. Movement Smoothness JM during voluntary movements for clinic-visiting patients (▲: statistical significance)

017), and 41months (patient 002).

Patients 003 and 002 experienced ascending trend of smoothness JM comparing the first and the last weeks on multiple targets, and no descending trend on any other target (Figure 4 (a) and (c)). Patient 017 experienced ascending trend of JM on 4 targets R2~R4, and descending trend on C3~C4 (Figure 4 (b)).



(a)



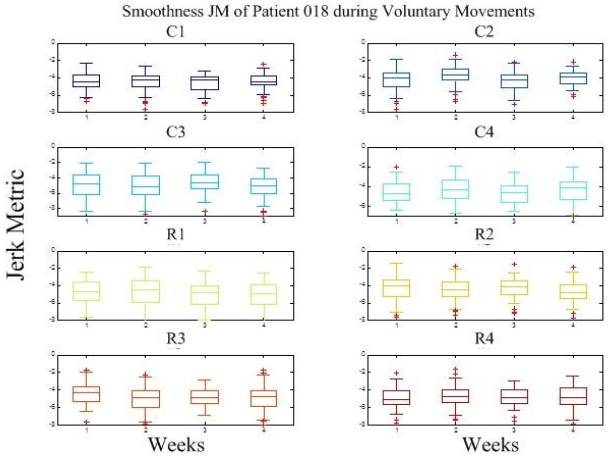
(b)

Figure 5. Proportion of successfully hitting targets of patient 018 (a) and 019 (b). (▲: statistical significance)

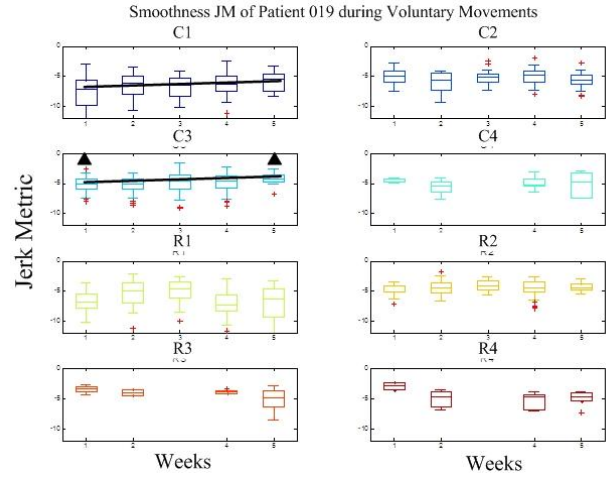
Statistical Tests for Home-application Feasibility Study

We conducted the same performance evaluation as the clinic-visiting patients. Figures 5 and 6 show the change of proportion of hitting targets, and the smoothness JM during successful voluntary trials under testing mode, respectively.

From Figure 5, we can see in the last week patient 018 experienced significant increase in hitting target R3 successfully from the first week (Figure 5(a)). Patient 019 experienced significant increase in hitting target C3 successfully (Figure 5(b)). Patient 019 had very weak performance in the beginning. In order to prevent too early fatigue, her training mostly focused on targets C1~C3 and R1~R2 since the other targets were too difficult to her. We can see that patient 019 experienced a nearly monotone increase in hitting target C3 successfully. The increase is significantly. Although Figure 5(b) shows increase on some other targets,



(a)



(b)

Figure 6. Smoothness JM during successful voluntary movements to targets of patient 018 (a) and 019 (b). (▲: statistical significance)

since the number of trials on those targets was too small, significant conclusion cannot be draw. Patient 018 had strong performance in the beginning on all targets except on target R3. His strong performance on those 7 targets was reserved over the 1 month training.

From Figure 6, we can see that patient 018 did not experience ascending nor descending trend in smoothness JM. Patient 019 experienced increase trend in movement smoothness JM on target C1, and significant increase on C3.

It should be noted that the box plot of different targets and different patients might have different scale on the y axis. Since we are only concerned with the change of smoothness of each patient on each individual target, readers should not be misled by the different scales.

IV. Conclusion & Future Work

In this study, RUPERT was tested in two feasibility studies

to validate the reliability and safety of RUPERT, and its feasibility of home setting application. Six patients received RUPERT-assisted rehabilitation therapy for 4 weeks with 12 one-hour therapy sessions during clinic visits. Two other patients received 4~5 weeks daily therapeutic training in a home-application setting.

Clinical tests were conducted to assess the functions before and after the therapeutic training. Clinical tests showed functional improvement on some patients, but deterioration on some others. There are three possible explanations to it. First, the variance among the involved individuals is too large. The post-stroke history ranges between 10 and 110 months. Second, the training intensity and duration (1 month) might not be enough to generate consistent improvements on all patients. Third, as we observed, the clinical tests were not consistently conducted on all patients.

Statistical tests were conducted to evaluate the performance improvement after the therapeutic training in both feasibility studies using the data collected during voluntary trials where RUPERT was worn. Three out of six clinic-visiting patients demonstrated significant increase in the proportion of successfully reaching one or more of the 8 targets, and no significant function deterioration to other targets. These three clinic-visiting patients also experienced increase in the movement smoothness on reaching multiple targets.

Both two patients in the home-application setting demonstrated functional improvement after the training. They each experienced significant increase in the proportion of successfully hitting one of the 8 targets, and the one on other targets did not change. They also demonstrated significant increase in the movement smoothness on reaching some target.

Both clinical tests and objective statistical tests from robot sensory data agree on the functional improvement of patient 002. They give inconsistent conclusions on other patients.

There are several possible reasons for the inconsistency. First, the number of patients is too small. Because of the small effect size of the clinical studies on stroke rehabilitation, as identified by other researchers[16 and 17], a much bigger sample size is needed before a significant and consistent conclusion can be drawn from the clinical tests. Second, RUPERT IV was at its prototype stage when both feasibility studies were conducted. Safety, operability, and home-setting applicability were the major concerns. The sensory noise was not carefully controlled. Third, we only developed a single RUPERT system. During clinic-visiting study, the mechanical parameters of RUPERT were adjusted back and forth to fit different patients. Each week consisted of training sessions for at least two patients. Although we tried to repeat the mechanical parameters for each patient in different sessions, variance was still introduced due to the adjustment. Finally, variance introduced by fitting might overwhelm the performance improvement. These issues need to be further addressed in our future research.

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