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Short-duration robotic therapy in stroke patients with severe upper-limb motor impairment

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Abstract—Chronic motor deficits in the upper limb (UL) are a major contributor to disability following stroke. This study investigated the effect of short-duration robot-assisted therapy on motor impairment, as measured by clinical scales and robot-derived performance measures in patients with chronic, severe UL impairments after stroke. As part of a larger study, 15 individuals with chronic, severe UL paresis (Fugl-Meyer < 15) after stroke (minimum 6 mo postonset) performed 18 sessions of robot-assisted UL rehabilitation that consisted of goal-directed planar reaching tasks over a period of 3 weeks. Outcome measures included the Fugl-Meyer Assessment, the Motor Power Assessment, the Wolf Motor Function Test, the Stroke Impact Scale, and five robot-derived measures that reflect motor control (aiming error, mean speed, peak speed, mean:peak speed ratio, and movement duration). Robot-assisted training produced statistically significant improvements from baseline to posttreatment in the Fugl-Meyer and Motor Power Assessment scores and the quality of motion (quantified by a reduction in aiming error and movement duration with an increase in mean speed and mean:peak speed ratio). Our findings indicate that robot-assisted UL rehabilitation can reduce UL impairment and improve motor control in patients with severe UL paresis from chronic stroke.

Key words: motor impairment, motor performance measures, neuromotor recovery, neurorehabilitation, rehabilitation robotics, robot-assisted therapy, severe hemiparesis, stroke recovery, upper-limb paresis.

INTRODUCTION

Stroke is the leading cause of severe long-term disability in the United States, with more than 0.75 million strokes occurring every year [1] and over 4.8 million stroke survivors living today [2]. Although improvements in motor function are most likely in the initial 3 months following stroke [3–5], recent research has supported that gains in motor function can occur with intensive motor-learning-based rehabilitation, even many years poststroke [6–11]. Motor learning models that engendered principles of task specificity, repetition, progression, and feedback

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Abbreviations: CIT = constraint-induced therapy, MIT = Massachusetts Institute of Technology, SEM = standard error of the mean, UL = upper limb.

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[12–13] have been incorporated into constraint-induced therapy (CIT) and bilateral arm-training methods [8–9,14–16]. More recently, robot-assisted upper-limb (UL) neurorehabilitation, which also employs motor learning models, has helped reduce motor impairment in persons with UL paresis after stroke [6–7,10–11,17–22].

Robot-assisted rehabilitation provides the elements of repetition and goal-oriented tasks along with quantifiable elements of progress. Robot-enhanced rehabilitation therapy administered to an experimental group within 3 weeks of their first stroke resulted in significant gains in shoulder and elbow motor ability and strength, as compared with changes in a control group who did not receive robotic therapy [17–19,22–23]. Similar improvements have been documented in patients with UL impairments 1 to 5 years poststroke [6–7,11,20–21,24]. The patients in these robotic studies of chronic stroke demonstrated moderate UL impairment at the time of enrollment and participated in an intervention that consisted of passive, active-assistive, and/or resistive robot-assisted therapy [6–7,24]. The mean initial Fugl-Meyer UL Assessment score was 29 (maximum possible score = 66), with increases following the robot-assisted intervention of more than 5 percent on average; i.e., greater than 3.3 point increase in the Fugl-Meyer Assessment [6–7].

In the present study, we extend the investigation of robot-assisted training by employing shorter-duration training, focusing exclusively on patients with severe long-standing UL paresis, and including robot-derived movement quality (motor control) measures. Patients with severe UL impairments are usually prime candidates for compensatory training; they rarely, if ever, use their affected arm in daily tasks. Similar studies of this population are rare because little expectation exists of any measurable functional change since movement of the paretic limb is so limited. Neither CIT, which targets persons with a mild paresis, nor bilateral training, which has been shown to be generally effective in patients with moderate impairments [8], appear to be appropriate for people with very dense hemiplegia. Robot-assisted movement therapy may be the only training protocol at present with the potential to reduce UL impairment in this population. Since gains in motor control and function are likely to be small, we have also focused on detecting gains in underlying motor control through robotic outcome measures. We define improved motor control as the ability of the subject to move the arm in a more accurate and fast (or smooth) fashion. The previous robot-assisted intervention studies of persons with chronic UL paresis employed protocols of 6- to 8-week duration with a frequency of three 1-hour sessions a week [6–7,11,21]. To date, only one other study has used robot-assisted interventions for patients with severe UL motor impairments long after stroke onset [11]. This study investigates the effect of robotic rehabilitation of comparable dosage (18 treatment sessions) and shorter duration (3 weeks) on motor impairment and specifically reports robotic outcome measures in patients with severe long-standing UL impairments after stroke.

METHODS

Participants

In an effort to study individuals with severe UL impairments from stroke, we included individuals with chronic stroke (minimum 6 mo postonset) and a maximum Fugl-Meyer UL assessment score of 15 at baseline. This baseline Fugl-Meyer score represented severe motor impairment in the paretic arm, as demonstrated by limited movement within synergy patterns and no voluntary wrist or hand function. Fifteen participants were enrolled with a mean baseline Fugl-Meyer score of 10.1 ± 0.7 (standard error of the mean [SEM]) (range of 4.0 to 13.7) and a mean Stroke Impact Scale physical domain score of 75.2 ± 4.6 SEM [25–26] (**Table 1**). The Baltimore Department of Veterans Affairs Medical Center Research and Development Committee, via the Institutional Review Board of the University of Maryland School of Medicine, and the Committee on the Use of Human Experimental Subjects of the Massachusetts Institute of Technology (MIT) approved this protocol, and each subject provided informed consent prior to participation.

Baseline Evaluations

To determine the stability of motor performance, we had each patient perform three repeated clinical evaluations (Wolf Motor Function Test [27], Motor Power Assessment [28], and Fugl-Meyer UL Assessment [29]) over a 4-week interval prior to the initiation of training. Robot outcome variables were also measured twice over the same time period prior to training. The mean of these pretraining measures defined the initial baseline score for each outcome variable. Following treatment, participants were administered all clinical and robotic evaluations and their scores defined as the posttreatment score. The posttreatment evaluations occurred within 1 week of the end of the training. The

Table 1.
Subject characteristics ($N = 15$).

Characteristic	Value
Age (yr) (mean ± SEM)	60.9 ± 2.0
Time Since Stroke Onset (mean ± SEM)	5.2 yr ± 5.4 mo
Gender (No.)	Male = 10 Female = 5
Handedness (No.)	Left = 7 Right = 8
Side of Stroke (No.)	Dominant = 8 Nondominant = 7
Multiple Strokes (No.)	Yes = 3 No = 5 Unknown = 7
Stroke Location (No.)	Cortical = 5 Subcortical = 4 Unknown = 6
Baseline Fugl-Meyer (mean ± SEM)	10.1 ± 0.7
Baseline Stroke Impact Scale Physical Domain (mean ± SEM)	75.2 ± 4.6

SEM = standard error of mean.

therapist who performed the clinical assessments was blinded to the robot-assisted training, provided by another therapist. Three months following the end of training, the clinical evaluations were repeated on 13 of 15 participants (two withdrew) to evaluate retention of the training effects. Self-administered Stroke Impact Scale [25] data was collected prior to the initiation of training, following training, and at the 3-month follow-up evaluation session.

Robot-Training Protocol

One week after completion of the baseline evaluation, participants received 18 sessions of therapy delivered over 3 weeks: two 1-hour sessions per day, 3 days a week. This therapy dosage is higher than that delivered in other chronic robot-rehabilitation studies [6–7,11]. Robot therapy was delivered with the use of InMotion2 (Interactive Motion Technologies, Inc., Cambridge, Massachusetts), a commercial version of a robot developed specifically for UL neurorehabilitation at MIT, the MIT-Manus, and described in detail by Krebs et al. [23] and Hogan et al. [30] (**Figure 1**). The training sessions consisted of goal-directed planar reaching tasks that focused on exercising the shoulder and elbow. Eight targets were equally spaced around a center target (14 cm radius center-to-target), and visual feedback regarding target location and robot handle motion was provided on a computer screen. Three "games" were performed during each therapy session that were similar to a previous study [11], with the robot providing (1) no assistance; (2) movement assistance, as determined by an adaptive algorithm based on the individual's performance [31]; and (3) movement assistance at a constant level (e.g., sensorimotor therapy as in prior studies) [6–7]. Subjects moved from the center to peripheral targets and back during each game, in a clockwise direction, and completed 672 goal-oriented reaching movements per training session. The subjects were seated with a trunk strap to limit/prevent forward trunk compensation, with shoulder protraction permitted as necessary during all training and evaluation sessions.

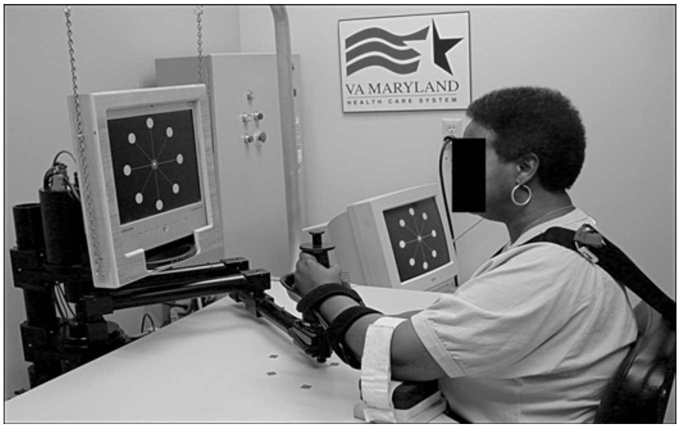

Figure 1.
Stroke patient during robot-assisted therapy.

Robot Outcome Variables

The robot evaluation required that the subject reach for each target around the circle without movement assistance. We defined movement initiation as the moment the subject's speed first became greater than 2 percent of the peak speed and termination as the moment it dropped and remained below the 2 percent threshold. The subject may not have reached the designated target on each attempt, and the variables were calculated based on movement completed. One investigator, who was blinded to the subjects' level of impairment, processed and analyzed the robot-evaluation data. Motor-control variables derived from the robot evaluation data were aiming error (mean absolute angle between actual direction and a straight line between start and target), mean speed (total displacement over total movement duration), peak speed, mean:peak speed ratio (mean speed divided by the peak speed as a metric of movement smoothness [32]), and movement duration.

Data Analysis

We used repeated measures analyses of variance to assess stability $(p \le 0.05)$ in the clinical and robotic variables at baseline. As in other research, parametric and nonparametric analyses were performed and yielded similar results; therefore, only the parametric findings are reported here [7]. Paired student *t*-tests evaluated differences in the clinical evaluation data between baseline, posttreatment, and 3-month follow-up outcomes $(p \le 0.05)$ and compared the robot evaluation data at baseline and posttreatment $(p \le 0.05)$. We calculated Cohen's *d* to determine the effect size of treatment on the clinical and robot-derived measures [33–34]. An effect size of 0.20 was considered small, 0.50 was considered medium, and 0.80 was considered large [33–34].

RESULTS

Although UL impairment scores appeared to have an upward trend across the three baseline clinical tests, no statistical difference was found. In addition, the robotic outcome variables were not significantly different between the two baseline testing sessions (**Table 2**).

Statistically significant improvements in the Fugl-Meyer UL Assessment score ($p = 0.03$) and the Motor Power Assessment ($p = 0.03$) were seen with training (**Table 3**). However, no significant changes were found

Table 2.
Mean baseline evaluation ± standard error of mean ($N = 15$).

Evaluation	Test 1	Test 2	Test 3
Fugl-Meyer Assessment	9.73 ± 0.81	9.93 ± 0.76	10.53 ± 0.80
Motor Power Assessment	30.33 ± 2.85	30.40 ± 3.09	34.87 ± 2.78
Wolf Motor Function Test (mean time [s])	109.75 ± 2.47	109.74 ± 2.36	108.24 ± 2.01
Wolf Motor Function Test Score	1.18 ± 0.04	1.19 ± 0.04	1.21 ± 0.04
Aiming Error (rad)	—	1.162 ± 0.048	1.127 ± 0.037
Mean Speed (m/s)	—	0.038 ± 0.005	0.038 ± 0.004
Peak Speed (m/s)	—	0.137 ± 0.013	0.136 ± 0.012
Mean:Peak Speed Ratio	—	0.276 ± 0.013	0.291 ± 0.014
Movement Duration (s)	—	5.029 ± 0.413	4.671 ± 0.365

Table 3.
Mean ± standard error of mean for motor function scores at baseline, posttreatment ($N = 15$), and 3-month follow-up ($N = 13$).

Motor Function Variable	Fugl-Meyer Assessment	Motor Power Assessment	Wolf Motor Function Test (mean time [s])	Wolf Motor Function Test Score	Stroke Impact Scale Physical Domain
Maximum Score	66	70	120	5	140
Baseline	10.07 ± 0.74	31.87 ± 2.78	109.24 ± 2.21	1.24 ± 0.04	75.20 ± 4.61
Posttreatment	11.27 ± 0.70	36.27 ± 2.02	106.74 ± 1.40	1.24 ± 0.02	74.33 ± 9.53
Change[*]	1.20 ± 0.49	4.40 ± 1.84	–2.50 ± 1.49	0.00 ± 0.03	–0.86 ± 8.83
Effect Size (Cohen's *d*)[†]	0.43	0.47	0.31	0.36	0.01
p-Value Posttreatment to Baseline	0.03[‡]	0.03[‡]	0.11	0.13	0.92
3-Month Follow-Up	10.83 ± 0.70	36.44 ± 2.02	102.94 ± 2.45	1.30 ± 0.04	63.5 ± 9.53
p-Value Follow-Up to Posttreatment	0.38	0.82	0.17	0.18	0.32

[*] Increase in score indicates improvement for all measures except Wolf Motor Function Test (mean time) where decrease in seconds indicates improvement.
[†] Small effect $d = 0.20$, medium = 0.50, large = 0.80.
[‡] Significant change baseline to posttreatment.

on the Wolf Motor Function Test (median time, mean time, or functional ability score), or the physical domain of the Stroke Impact Scale. **Figures 2** and **3** illustrate baseline and posttreatment performance for point-to-point reaching movements during robot evaluations for one representative subject. Robot-assisted therapy resulted in significantly reduced aiming error ($p < 0.01$) and movement duration ($p < 0.01$) as well as increased mean speed ($p < 0.01$) and mean:peak speed ratio ($p < 0.01$) (**Table 4**). At the time of the 3-month follow-up evaluation, UL impairment was not statistically different (reduced) compared with posttreatment levels.

DISCUSSION

These findings provide evidence that persons with severe UL paresis long after stroke onset can demonstrate reduced motor impairment with a brief, intense robot-assisted intervention. Statistically significant gains, with small-to-medium effect sizes (**Table 3**), were found in the Fugl-Meyer and Motor Power Assessment scores, along with improvements in motor control as measured by the following robot-derived measures: aiming error, movement duration, mean speed, and mean:peak speed ratio. Although small, these changes occurred in patients with initial Fugl-Meyer scores < 15, an indication of severe UL paresis, after only 3 weeks of robot-assisted therapy. Thus, this research adds to a growing body of work that massed-practice repetitive-movement interventions can promote changes in motor impairment following a stroke, even with severe UL paresis (Fugl-Meyer < 15).

Several factors may account for the relatively small changes in clinical scores in the present study. Although the number of treatment sessions provided and the type of intervention were comparable with previous research [6–7,10,17–21,24,32,35], the duration of treatment was shorter (3 weeks vs. 6–8 weeks), which possibly limited the magnitude of improvement. In addition, our clinical measures supported that the effects of robotic therapy were primarily limited to the exercised limb segments, namely the shoulder and elbow, as observed in our previous studies [6–7,11]. Therefore, the small, nonsignificant changes on the Wolf Motor Function Test, which evaluates both proximal and distal arm function, were predictable. Although the median score for the Wolf Motor Function Test did not change in these persons with severe impairment, we did see positive trends in the mean movement time and rating scale for functional tasks that involved proximal control, such as reaching from lap to

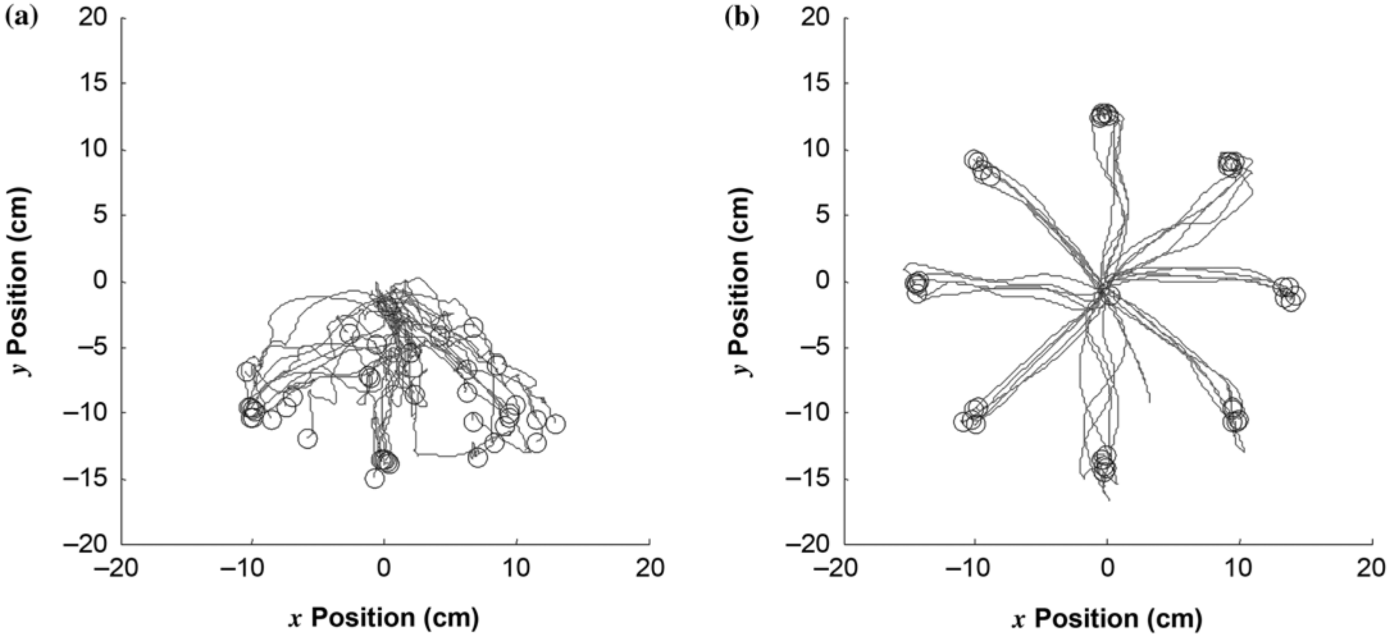

Figure 2.
Movement attempts toward 8 peripheral targets at **(a)** baseline and **(b)** posttreatment. Subject was unable to move arm toward north targets (away from body) at admission but substantially improved over course of therapy.

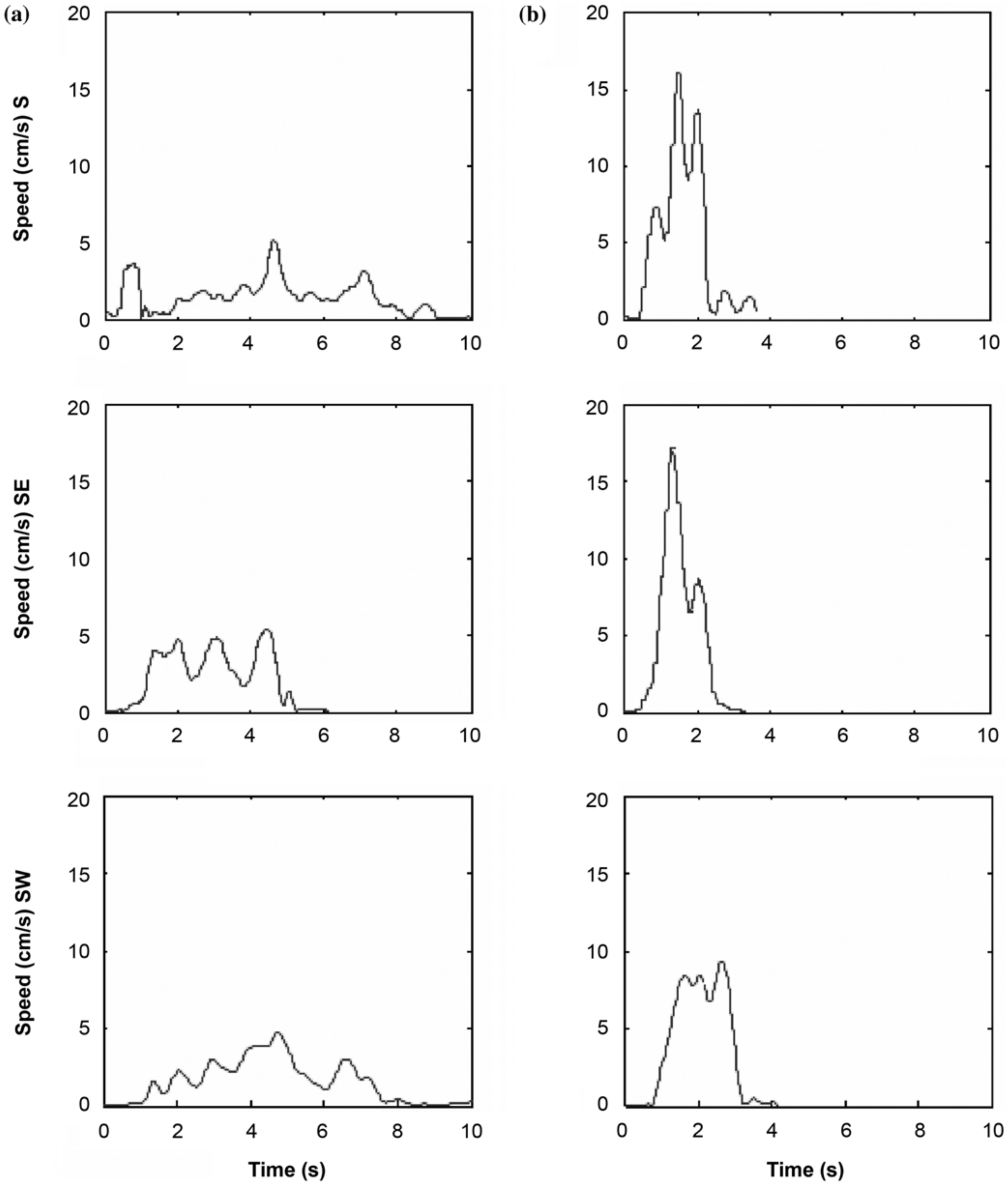

Figure 3.
Speed profiles for third movement attempt toward south (S), southeast (SE), and southwest (SW) targets at **(a)** baseline and **(b)** posttreatment. Note that time duration and peak speed improved greatly at posttreatment.

Table 4.
Mean ± standard error of mean for robotic outcome variable scores at baseline and posttreatment.

Robotic Outcome Variable	Baseline	Posttreatment	Change*	Effect Size (Cohen's *d*)†	*p*-Value
Aiming Error (rad)	1.144 ± 0.040	1.009 ± 0.055	–0.136 ± 0.038	0.73	<0.01‡
Mean Speed (m/s)	0.038 ± 0.004	0.046 ± 0.004	0.007 ± 0.002	0.37	<0.01‡
Peak Speed (m/s)	0.138 ± 0.012	0.132 ± 0.011	–0.006 ± 0.005	0.14	0.27
Mean:Peak Speed Ratio	0.284 ± 0.013	0.360 ± 0.016	0.076 ± 0.012	1.38	<0.01‡
Movement Duration (s)	4.850 ± 0.366	3.357 ± 0.334	–1.492 ± 0.310	1.10	<0.01‡

*Increase in score indicates improvement in mean speed, peak speed, and mean:peak speed ratio; decrease indicates improvement for aiming error and movement duration.
†Small effect *d* = 0.20, medium = 0.50, large = 0.80.
‡Significant change baseline to posttreatment.

table or box (requiring shoulder flexion and abduction) or moving a 1-pound weight along the table surface, following robot-assisted training. The robotic therapy provided to these individuals with severe paresis did not attempt to retrain distal movement. The reduction in impairment remained following a 3-month interval without training, which indicates retention of the small clinical gains. In the absence of a control group, we propose that the combined factors of higher frequency and shorter training duration, task-specific training focused on proximal limb segments, and initial impairment severity [24] all contributed to the small-to-moderate treatment effects indicated by our clinical measures in this small group. Based on our data, which showed modest clinical gains compared with those found in less impaired patients [6–7,21,24], one could argue that robotic therapy for the shoulder and elbow should be used primarily for stroke survivors with Fugl-Meyer scores above 15. However, this interpretation is not supported by another robotic study that enrolled persons with very severe strokes [11]. That study lasted 6 weeks instead of the 3 weeks of the present study, and it excluded persons with multiple strokes, while the present study did not. A larger sample size study is needed to provide the definite answer.

As predicted, we were able to detect changes in the movement quality measures. Similar to previous research [36], these robot-derived motor performance measures were able to detect smaller within-subject changes than did the clinical motor evaluations. Effect sizes for our robot-derived measures were considerably larger than those evidenced by our clinical evaluation scores. Improvements were demonstrated in all robot variables, except peak speed, following the robot-assisted training. Treatment effect size was large for aiming error (*d* = 0.73), mean:peak speed (*d* = 1.4), and movement duration (*d* = 1.1) and small to moderate for mean speed (*d* = 0.37). The lack of change in peak speed is also consistent with previous research [32]. In a related study, Rohrer et al. reported significant improvements in clinical measures (Fugl-Meyer), with increases in mean speed, decreases in movement duration, and improved movement smoothness (as indicated by a higher mean:peak speed ratio) following a robot-assisted therapy program [32]. They showed that early in poststroke recovery, a patient's movements are composed of short, sporadic submovements, with a series of peaks and valleys and a lower mean:peak speed ratio. As subjects improved with training, their reaching movements became smoother with fewer stops and greater mean speed, which suggests improved interjoint coordination because of neural recovery processes. In the present study, large treatment effects for the robot-derived measures indicate that movement accuracy and smoothness did improve with practice in these individuals with severe paresis (**Figures 2–3**). Further studies are needed to evaluate whether these and other robot-derived measures can more reliably detect changes in motor abilities after stroke than conventional clinical evaluations, with potentially limited interrater reliability [37]. This research could also provide valuable information regarding the relationship between neuromotor recovery and clinical measures of performance.

Duncan et al.'s work shows that patients with acute, moderate hemiplegia continue to improve longer than those with mild impairment [4]. Although studies have shown that the greatest gains in motor recovery occur in the first month after stroke [4–5,38], recent studies have demonstrated that gains in UL motor function can occur in persons with impairments from chronic stroke (longer than 6 months) [6–7,10,11]. The subjects in these studies were between 1 and 5 years poststroke, with the mean time being 2 to 2.5 years. The participants in the current study, whose poststroke time averaged 5.2 years ± 5.4 months SEM with a range of 6 months to over 17 years, further demonstrated that reductions in motor impairments can occur poststroke for a much longer time period.

LIMITATIONS

Limitations of the current study include the small sample size and the lack of a randomized control. Additional limitations of the robotic intervention include the use of a single plane of movement without involvement of the hand or wrist and use of a single treatment duration (3 weeks). As the technology advances, future studies on multiplanar repetitive motions of the entire UL, with varied treatment dosing and measures of the durability of the effects, are warranted to provide temporal profiles of motor-control changes across time for persons with chronic, severe UL paresis.

CONCLUSIONS

Clinical implications of the current findings are that individuals with severe UL impairment many years poststroke benefit, to some degree, from robotic rehabilitation. Although the changes in the clinical measures were small to moderate, the very large effect sizes shown in the robot-derived measures indicate the potential for these measures to detect even smaller changes and become useful measures of motor recovery.

Robotic therapy can be highly compliant to the patient's motor actions and, therefore, allows for adaptability of rehabilitation programs even to those with severe motor impairments. Numerous future directions that will employ this technology remain. These include randomized controlled trials that compare outcomes of robotic therapies with other treatment interventions. Investigations of a variety of neurologically mediated UL impairments other than stroke, comparisons of various dosing regiments (frequency and duration) of robotic therapy, and application of robot-assisted therapy to other limb segments and planes of motion are also indicated.

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