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Response to upper-limb robotics and functional neuromuscular stimulation following stroke

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Abstract—Twelve moderately to severely involved chronic stroke survivors (>12 mo) were randomized to one of two treatments: robotics and motor learning (ROB-ML) or functional neuromuscular stimulation and motor learning (FNS-ML). Treatment was 5 h/d, 5 d/wk for 12 wk. ROB-ML group had 1.5 h per session devoted to robotics shoulder and elbow (S/E) training. FNS-ML had 1.5 h per session devoted to functional neuromuscular stimulation (surface electrodes) for wrist and hand (W/H) flexors/extensors. The primary outcome measure was the functional measure Arm Motor Ability Test (AMAT). Secondary measures were AMAT-S/E and AMAT-W/H, Fugl-Meyer (FM) upper-limb coordination, and the motor control measures of target accuracy (TA) and smoothness of movement (SM). ROB-ML produced significant gains in AMAT, AMAT-S/E, FM upper-limb coordination, TA, and SM. FNS-ML produced significant gains in AMAT-W/H and FM upper-limb coordination.

Key words: activities of daily living, coordination, electrical stimulation, functional measure, functional neuromuscular stimulation, motor control, motor learning, rehabilitation, robotics, stroke.

INTRODUCTION

Even after completing conventional rehabilitation, many stroke survivors demonstrate persistent and disabling upper-limb motor deficits. Therefore, it is important to develop more effective methods for restoration of upper-limb motor control following stroke. Two promising methods include robotics and functional neuromuscular stimulation (FNS). According to case series studies, use of upper-limb robotics has produced improvement in shoulder/elbow muscle strength and coordination [1], and in active shoulder/elbow joint movement excursion [2]. In a randomized controlled trial of robotics therapy versus conventional exercise, there was an immediate posttreatment advantage of robotics according to a measure of shoulder/elbow joint movement coordination that persisted at 6-month follow-up testing [3].

Abbreviations: AMAT = Arm Motor Ability Test, AMAT-S/E = AMAT shoulder/elbow, AMAT-W/H = AMAT wrist/hand, FIM = Functional Independence Measure, FM = Fugl-Meyer, FNS = functional neuromuscular stimulation, FNS-ML = FNS and motor learning, ROB-ML = robotics and motor learning, SM = smoothness of movement, TA = target accuracy.

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In contrast to reported improvements in upper-limb impairments, there is a dearth of literature regarding the capability of robotics to produce functional gains in the paretic limb [1]. In a randomized controlled trial, no robotics advantage was shown immediately after treatment as measured by the Functional Independence Measure (FIM), but a robotics advantage was shown at the 6-month follow-up [4]. These results are difficult to interpret because the FIM has shortcomings that include the ordinal nature of the measure, no specific test of the involved limb, and lack of discriminatory capability for whether motor performance gains occurred or independence improved simply because the patient learned to better compensate for the disability.

The available studies of FNS intervention showed results similar to that of robotics, in that impairment gains were demonstrated but functional gains were not demonstrated according to measures of real-world functional tasks for severely involved stroke survivors. FNS produced improvement in the impairment measures of upper-limb muscle tone [5–6], strength, and coordination [7–8]. Encouraging results were obtained for mildly to moderately involved subjects according to tests of simulated functional task movements of grasp and release of cylinders and short translational movements of the arm in the horizontal plane (Box and Blocks, Jebsen Light Cylinder, and Jebsen Heavy Cylinder subscales) [6,9–10]. For subjects in the acute phase (within 3 months of stroke), two randomized controlled studies were performed [9–10]. Subjects had at least partial active wrist and finger movement before treatment (100% of the subjects [9] or 50% of the subjects [10]). Significantly greater improvement was found in the FNS group versus control group in measures of percent change in Box and Blocks and both Jebsen subscales [10]. In the second study of acute-phase subjects, a significantly greater posttreatment gain was found for the FNS group versus control group, according to the number of repetitions that could be performed for functional tasks, such as combing hair or using a fork [9]. For mildly to moderately involved subjects in the chronic phase, a case series study (n = 77) of FNS intervention showed a significant improvement in a subscale of the Jebsen-Taylor Test, Box and Blocks, and Nine-Hole Peg Test [6]). However, for severely to moderately involved chronic stroke survivors, no gains were reported in randomized controlled trials according to measures of actual functional tasks in response to upper-limb FNS treatment [7,11].

One reason for lack of demonstrated robust functional response to robotics or FNS intervention for more severely involved subjects could be the absence of critical characteristics necessary for successful skill acquisition. In motor skill acquisition after stroke, critical practice characteristics are necessary for motor relearning. These include intense practice (repetition of desired motor pattern [12–16]), execution of a motor behavior that closely approximates the desired or normal movement [17–18], attention to the motor behavior [19–20], and variability in practice [21]). Robotics and FNS are technologies that can provide repetition of controlled movements that are close to normal. However, neither robotics nor FNS alone provides practice of movement components within the framework of functional tasks. Conversely, repetition of poorly performed functional movements can be nonproductive. The combination of functional task practice and technology-assisted motor training has the potential to provide more critical practice characteristics during motor learning (ML). Although evidence has shown that ML can improve function for mildly involved stroke survivors [22–24], little evidence has shown that ML can improve function in more severely involved stroke survivors. This study tested response of severely and moderately impaired chronic stroke survivors to daily ML treatment composed of task component and whole task practice in conjunction with shoulder/elbow robotics or wrist and finger FNS.

METHODS

Subjects

We enrolled 12 subjects who were >12 months poststroke. Subjects were required to demonstrate at least a trace (Grade 1) muscle contraction in the wrist extensors and a score of >10 in the Fugl-Meyer (FM) upper-limb coordination measure. Subjects were stratified according to the FM upper-limb coordination score before randomization to one of the two following treatment groups: robotics and motor learning (ROB-ML) or FNS and motor learning (FNS-ML). FM upper-limb coordination is a 66-point scale categorizing severity as 10 to 29 = severe, 30 to 49 = moderate, and ≥50 = mild (≥50, not accepted). The FM measured movement either within or independent of synergistic patterns. The FM measure is recommended for identifying severity levels after stroke [25–29].

We enrolled 24 subjects (>12 months poststroke) in a convenience sample to test the validity of two of the study measures. Additionally, 10 of these subjects were randomly selected to participate in testing the intrarater and interrater reliability of the same two study measures.

The subjects in this convenience sample were required to demonstrate at least a trace (Grade 1) muscle contraction in the wrist extensors and a score of >10 in the FM upper-limb coordination measure.

We recruited subjects using advertisements in a newspaper serving an urban and outlying region. Subject characteristics recorded were stroke type, stroke location, years since stroke, and age. Subjects provided informed consent in accordance with the Declaration of Helsinki, and the institutional review board of the Louis Stokes Cleveland Department of Veterans Affairs Medical Center approved the study.

Technology

Functional Neuromuscular Stimulation

FNS was provided with the commercially available EMS+2™ and surface electrodes (Staodyn, Inc, Longmont, Colorado). The EMS+2™ is a two-channel portable stimulator operated with a 9 V alkaline battery that delivers a biphasic, symmetric, rectangular output for each of the two channels. The flexible PALS® surface electrodes (Axelgaard Manufacturing Company, Ltd, Falbrook, California) are constructed of electrolytic gel and a self-adhering surface with the following dimensions: rectangular, 1.3 × 2.1 in. (for wrist and finger muscles), or circular, 1.25 in. diameter (for thumb muscles).

Robot

The InMotion^2 Shoulder-Elbow Robot (Interactive Motion Technologies, Inc, Cambridge, Massachusetts) provided shoulder/elbow training in the horizontal plane with a supported forearm. The robot utilized the QNX® realtime operating system (QNX Software Systems, Ltd, Ottowa, Canada) that allowed for high-performance control and integrated graphics. The robotics technology allowed for resisted, active, or assisted movement. The robot was a back-drivable impedance-controlled system that allowed for smooth, almost "frictionless," motion. This 2 degrees-of-freedom system functioned in the horizontal plane. The robot was capable of sensing and recording the position and velocity in the horizontal plane. The direct-drive 5-bar linkage system was driven by two brushless motors rated to 7.86 N•m of continuous stall torque with 16 b resolvers for position and velocity measurements. The position data were measured by built-in precision potentiometers (0.9 kΩ/rad). The velocity data were measured by direct current tachometers rated with a sensitivity of 1.75 V/rad/s [30–32].

Interventions

Robotics and Motor Learning

Both groups received treatment 5 hours a day, 5 days a week for 12 weeks. For ROB-ML, during 1.5 h of the daily treatment session, subjects used the robot and practiced shoulder/elbow movements with the forearm and hand supported in a cradle and the wrist and hand in fixed positions (wrist, 20° of extension, fingers resting around a cone) (**Figure 1**). Subjects practiced shoulder/elbow movement accuracy, trajectory maintenance, and movement smoothness. The practice movements were between a center target and targets located on the periphery of a circle 14 cm in diameter (**Figure 2**). The visual display provided online visual feedback of accuracy and coordination success.

The remainder of each session (3.5 h) included practice of functional task components and whole task practice without technology assistance. This portion of the treatment protocol was identical for both groups. We used an array of everyday functional tasks that required shoulder, elbow, forearm, wrist, and hand movements. For each task and task component, we progressed a given subject through joint movements and combinations of joint movements of progressively greater difficulty. Tasks were selected first according to the task's applicability in addressing the coordination deficit of a given subject and then according to the subject's interests and functional goals.

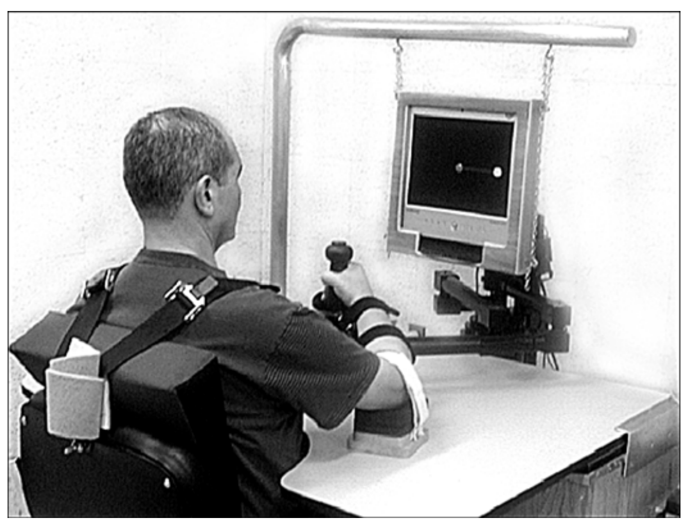

Figure 1.
Subject using robot for shoulder/elbow training. Subject is using robotics to practice shoulder/elbow movements required to move between a target in center of workspace and target in northeast direction.

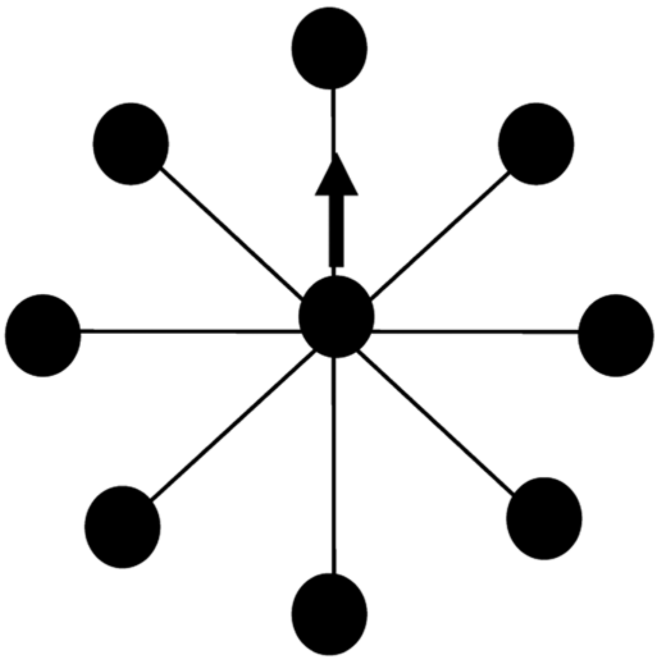

Figure 2.
Visually guided practice targets used by robotics motor learning group. Practice movement pathways afforded by shoulder/elbow robot and viewed by subject on computer monitor. Subject's own hand position in workspace was indicated by a cursor, similar to a computer "mouse" (shown by arrow).

Functional Neuromuscular Stimulation and Motor Learning

For FNS-ML, during 1.5 h of the daily treatment session, subjects used FNS for wrist and finger muscle activation. They practiced single and multiple joint movements using FNS. FNS-assisted coordination training included practice of movements that included wrist flexion/extension, finger and thumb flexion/extension, and simultaneous wrist extension and finger flexion. FNS was used along with task component movements. For example, subjects used FNS wrist and finger extension to assist during preparation before grasping an object. The stimulus parameters were 300 ms phase duration, 30 Hz, amplitude ranging from 1 mA to the highest comfortably produced stimulus, and 10 s on and 10 s off duty cycle. A typical stimulation pattern was 1 s ramp-up, 10 s on, 1 s ramp-down, and 10 s off. The remainder of each session (3.5 h) was task components practice and whole task practice without technology assistance, identical to that described in the previous section for the ROB-ML group.

Measures

The primary outcome measure was the Arm Motor Ability Test (AMAT), a measure of functional capability [33]. Because each of our treatment groups targeted either shoulder/elbow or wrist/hand movements respectively, we used AMAT subscales in secondary analyses. Secondary measures included AMAT-shoulder/elbow (AMAT-S/E) movements, AMAT-wrist/hand (AMAT-W/H) movements, FM upper-limb coordination, and the motor control measures of target accuracy (TA) and smoothness of movement (SM). A blinded examiner scored the AMAT, the AMAT-S/E, and the AMAT-W/H measures from a videotape. Independent staff obtained the remaining secondary outcomes, but since they worked in an adjacent clinical area, group allocation may have been unmasked. Data were collected before and after treatment and at a follow-up session 6 months after the end of treatment.

Primary Measure: Function

The AMAT was an array of 13 functional tasks (28 total task components within the 13 tasks [**Appendix 1**, available online only at http://www.rehab.research.va.gov]) that were videotaped. If a subject was unable to perform any movement components of a given task, a default value of either 60 or 120 s was awarded, according to the standardized instructions [33]. The AMAT score was the sum of the time (seconds) required for all 13 tasks. The AMAT tasks included eating a sandwich, using knife and fork to cut meat, using a spoon to scoop beans and bring them to the mouth, using the telephone, and tying shoe laces. The AMAT was reported as sensitive to change specifically for stroke patients. Interrater reliability was 0.95 to 0.99 [34]. Test-retest reliability was 0.93 [33]. Homogeneity of scores on speed of task performance was 0.93 [33].

Secondary Measures: AMAT-S/E and AMAT-W/H

Because each of the two modalities, robotics and FNS, targeted either shoulder/elbow or wrist/hand respectively, we used two AMAT subscales: AMAT-S/E and AMAT-W/H task component movements (**Appendix 2,** available online only at http://www.rehab.research.va.gov). The subscales were composed of the movement components within each of the 13 functional tasks. Two blinded rehabilitation specialists performed a task analysis separately and rated each of the 28 components and assigned them to AMAT-S/E or AMAT-W/H, depending on whether shoulder/elbow movements or wrist/hand movements, respectively, were required (**Appendix 2**, available online only at http://www.rehab.research.va.gov). Validity and reliability testing of AMAT-S/E and AMAT-W/H were performed (**Table 1**) [35].

Table 1.
Validity and reliability of AMAT-S/E and AMAT-W/H measures.

Measure	AMAT-S/E				AMAT-W/H			
	r_s	*p*-Value	ICC	CI	r_s	*p*-Value	ICC	CI
Convergent Validity* with FIM Self-Care	0.60	0.002	—	—	0.69	0.0001	—	—
Convergent Validity* with SIS Hand Scale	0.59	0.002	—	—	0.57	0.003	—	—
Divergent Validity* with FIM Communication	0.09	0.67	—	—	0.10	0.633	—	—
Intrarater Reliability†	—	0.0001	0.94	0.73–0.99	—	0.0001	0.97	0.85–0.99
Interrater Reliability‡	—	0.006	0.82	0.27–0.97	—	0.0001	0.96	0.79–0.99

*Validity testing was performed with convenience sample of 24 stroke survivors, >12 mo poststroke. Spearman (r_s) model for nonparametric measures was used.
†Testing was performed with a single rater and two rating time periods for each of 10 subjects.
‡Testing was performed with 2 raters and 10 subjects.
AMAT-S/E = Arm Motor Abilities Test shoulder/elbow, AMAT-W/H = Arm Motor Ability Test wrist/hand, CI = confidence interval, FIM = Function Independence Measure, ICC = intraclass correlation coefficient, and SIS = Stroke Impact Scale.

Secondary Measure: Coordination of Joint Movement

The FM coordination scale is an ordinal measure that assigns a score for the upper limb according to one's ability to move volitionally either dependent upon or independent of limb flexor or extensor synergistic patterns. The FM was reported as sensitive, reliable, and valid for measuring isolated joint movement coordination [25–29].

Secondary Measures: Target Accuracy and Smoothness of Movement

Additional secondary measures were TA and SM. These measures were calculated from position and velocity data obtained from the sensors in the InMotion[2] Robot described previously in the "Technology" section. The standardized movement task was to perform a straight line movement from a designated starting position in the center of the horizontal workspace to a target 14 cm away in the northeast or northwest direction, depending on whether the right or left limb, respectively, was involved. This movement was selected so that elbow extension could be one of the required joint movements in the test, because this movement is compromised in many stroke survivors.

Target Accuracy. Accuracy of movement is an important aspect of all functional movements. For a movement to be functional or useful, the movement must be accurate in its end point, and it must be performed accurately in a predictable manner. TA was defined as the distance between the desired target end point and the subject's end point (determined according to inability to move closer to the target [**Figure 3**]). Zero (error) was perfect performance, and the larger the distance of the subject's end point from the desired end point, the worse the performance. TA was calculated as

$$\mathrm{TA} = \sqrt{[(x_t - x_s)^2 + (y_t - y_s)^2]} \ ,$$

where x_t is the *x*-coordinate of the final target position, x_s is the *x*-coordinate of the subject's final hand position, y_t is the *y*-coordinate of the final target position, and y_s is the *y*-coordinate of the subject's final hand position [36].

Smoothness of Movement. SM indicates the control of movement speed that is exerted over the limb during movement. Control of movement speed is critical because for a functionally useful movement, a speed must be selected that is appropriate for the distance to be traversed, the limb segment lengths, and the final end position

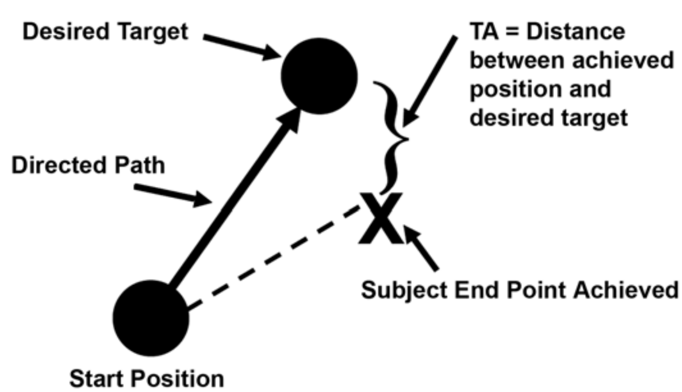

Figure 3.
Target accuracy index. Task was to move from lower to higher circle along large diagonal arrowed pathway. Dashed line is actual pathway taken by subject. "X" is subject's final end point achieved. TA was defined as distance between end point achieved and desired target; perfect performance was defined as TA = 0 (no error).

desired for all segments. Also, for most functional movements, changes in speed must be smoothly executed at critical points in the movement trajectory. In this study, SM was defined as the correlation between an idealized, normal velocity profile versus the subject's actual hand velocity profile during a straight-line movement between the initial and final target (**Figure 4**). A value of 1.0 indicated a perfect correlation between the subject's hand speed profile and the idealized velocity profile for the straight-line movement. The idealized velocity profile is known as the minimum-jerk speed profile. The minimum-jerk speed profile, v_{mj}, for the straight-line motion was calculated after Krebs et al. [37] as

$$v_{mj}(t) = \frac{\Delta}{T}\left(\frac{30t^4}{T^5} - \frac{60t^3}{T^4} + \frac{30t^2}{T^3}\right) ,$$

where t = time, Δ = the distance between targets, and T = the period between the instant that the hand-speed velocity increases above a threshold until it falls below the same threshold (1% of peak speed) for that particular movement (i.e., we were not just correlating each individual curve to a mean minimum-jerk speed profile but to a particular one with the same duration as the individual curve) [37]. The hand speed, $v(t)$, was defined as the change in hand position with respect to time:

$$v(t) = \frac{ds}{dt} ,$$

where s = the hand position as a function of time, v = hand speed, ds = x-y coordinates, dt = change in time. To proceed with the comparison between the minimum jerk profile and the hand speed profile, we translated the minimum jerk profile such that it increased above the threshold at the same instant as the hand speed. The correlation coefficient between two speed profiles, ρ, was defined as

$$\rho = \frac{\Sigma[(V_{norm} - \bar{V}_{norm})(V_{mj} - \bar{V}_{mj})]}{\sqrt{[\Sigma(V_{norm} - \bar{V}_{norm})^2 \Sigma(V_{mj} - \bar{V}_{mj})^2]}} ,$$

where V_{norm} is the normalized hand speed, $\bar{V}_{norm}$ is the mean normalized hand speed, V_{mj} is the normalized minimum jerk profile speed, and $\bar{V}_{mj}$ is the mean minimum jerk profile speed [37].

Data Analysis

Baseline group comparisons were made with the Mann-Whitney U test for the ordinal measures and a one-tailed t-test for the interval-level measures. The variables tested for initial group differences were age, years since stroke, and the outcome measures, which were AMAT, AMAT-S/E, AMAT-W/H, FM upper-limb coordination, TA, and SM. We generated descriptive statistics for individual subject scores as well as treatment group median and interquartile values for ordinal measures or mean and standard deviation for interval-level measures.

We made within-group pre- and posttreatment comparisons for the interval-level measures using t-test and for the ordinal level measures using the Wilcoxon Rank Sum Test. We used the same models to compare posttreatment versus follow-up values.

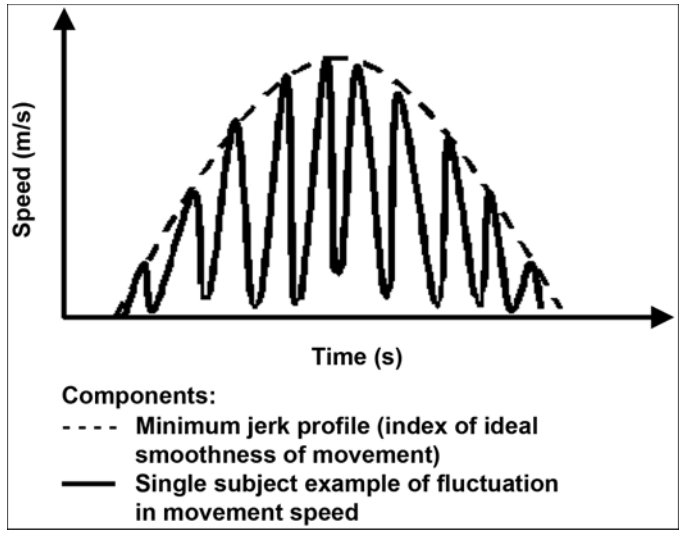

Figure 4.
Components used to calculate smoothness of movement (SM) index. SM index was a correlation between the following 2 curves: ideal speed curve (dashed line) and speed curve generated by subject (solid line).

RESULTS

Subject characteristics are provided in **Table 2**. We recruited and enrolled 13 subjects (attrition: 1 subject). The subject who dropped out of the study was age 32 and living over 2,000 miles from home with a friend in order to participate in the study. She dropped out of the study for personal reasons. No adverse events occurred as a result of the study protocol. Subjects appeared motivated to work on their motor capability and task component practice for the 5-hour daily sessions and throughout the 12-week protocol duration.

Before treatment, no statistically significant differences were found between the two treatment groups according to stroke severity (p = 0.810), years since stroke (p = 0.859), age (p = 0.180), or outcome measures: AMAT (p = 0.127), AMAT-S/E (p = 0.059), AMAT-W/H (p = 0.233), FM upper-limb coordination (p = 0.810), TA (p = 0.877), and SM (p = 0.846). For the AMAT-S/E, comparison of the two groups approached a statistically significant difference at baseline (p = 0.059), with the FNS-ML group having the higher mean (worse initial performance).

After the posttreatment testing session, four subjects were lost to follow-up, three in ROB-ML and two in FNS-ML. We calculated follow-up comparisons using only those subjects who returned for the follow-up testing session 6 months after the end of treatment (n = 3, ROB-ML; n = 5, FNS-ML).

Primary Measure: AMAT Functional Task Measure

A significant gain occurred in AMAT for the ROB-ML group, but not for the FNS-ML group **(Table 3)**. Power analysis of the FNS-ML group data from this study showed that at a power of 0.80 and α = 0.05, a sample size of 36 in the FNS-ML group would have been required for demonstration of a significant gain in AMAT when FNS was limited to the wrist and finger muscles. **Appendix 3** provides information regarding individual subject functional capability before and after treatment and is available online only at http://www.rehab.research.va.gov.

Secondary Measures: Functional Task Components According to AMAT-S/E and AMAT-W/H Measures

For the AMAT-S/E measure, only the ROB-ML group had a significant gain (**Table 3**). Pretreatment scores ranged from 849 to 1,402 s and posttreatment scores ranged from 524 to 1,001 s with a 310 s mean gain in performance. For FNS-ML, pretreatment scores ranged from 713 to 1,076 s and posttreatment scores ranged from 288 to 1,056 s with no significant change.

The contrasting distribution of AMAT-S/E gain scores for FNS-ML and ROB-ML is shown in **Figure 5(a)** and **Figure 5(b)**, respectively. For FNS-ML, individual subject gains ranged from 0 to 425 s and only 50 percent (three of six) of subjects in the group had gains of >200 s (**Figure 5(a)**). Whereas, for ROB-ML, individual subject gains ranged from 225 to 449 s, and 100 percent (all six) of subjects in the group had gains of >200 s (**Figure 5(b)**).

In contrast to the AMAT-S/E measure, the AMAT-W/H showed that only the FNS-ML group had a statistically significant gain in performance (**Table 3**). For FNS-ML, pretreatment scores ranged from 622 to 1,080 s and posttreatment scores ranged from 272 to 1,031 s with a significant gain of 316 s. For ROB-ML, pretreatment scores ranged from 736 to 1,140 s and posttreatment scores ranged from 756 to 1,080 s. Though the ROB-ML group did not have a statistically significant gain in AMAT-W/H, a trend approaching significance was shown.

Table 2.
Subject characteristics (n = 12).

Group	Stroke Type		Years Poststroke		Age Range (yr)		Sex	
	Ischemic	Hemorrhagic	1–3	4	21–49	50–62	Male	Female
ROB-ML	5	1	3	3	3	3	6	0
FNS-ML	6	0	4	2	3	3	3	3

ROB-ML = robotics and motor learning, FNS-ML = functional neuromuscular stimulation and motor learning.

Table 3.
Pre- and posttreatment gains according to primary and secondary Arm Motor Ability Test (AMAT) measures for each of two groups.

Functional Measure	ROB-ML			FNS-ML		
	Pre (Mean ± SD)	Post (Mean ± SD)	Change	Pre (Mean ± SD)	Post (Mean ± SD)	Change
Primary						
AMAT (s)	2123.15 ± 317.54	1648 ± 314.4	–475.15, $p = 0.026^*$	1834.9 ± 292.19	1593 ± 496.7	–241.9, p = 0.329
Secondary						
AMAT-S/E (s)	1098.73 ± 205.89	788.42 ± 195.73	–310.31, $p = 0.023^*$	880.75 ± 157.13	664.1 ± 273.46	–216.65, p = 0.123
AMAT-W/H (s)	1024.42 ± 145.18	864.12 ± 132.04	–160.30, p = 0.073	919.36 ± 161.81	603.19 ± 304.50	–316.17, $p = 0.049^*$

*p-value < 0.05.
ROB-ML = robotics and motor learning, FNS-ML = functional neuromuscular stimulation and motor learning, SD = standard deviation, S/E = shoulder/elbow, W/H = wrist/hand.

The contrasting distribution of AMAT-W/H gain scores for FNS-ML and ROB-ML is shown in **Figure 6(a)** and **Figure 6(b)**, respectively. For FNS-ML, individual subject gains ranged from 49 to 483 s and 83 percent (five of six) of subjects had gains of >200 s (**Figure 6(a)**). For ROB-ML, individual subject changes ranged from a worsening of 44 s to a gain of 384 s. Fifty percent (three of six) of subjects had gains >200 s (**Figure 6(b)**).

Secondary Impairment Measures

Both the ROB-ML and FNS-ML groups had a statistically significant gain in FM upper-limb coordination (**Table 4**). The pre- and posttreatment scores for each subject in each group are provided in **Table 5**. The ROB-ML group had four subjects with gains ranging from 5 to 20 points, and the FNS-ML group had five subjects with gains ranging from 6 to 25 points. The FM upper-limb coordination item scores for cylinder grasp, spherical grasp, and mass finger extension provide information regarding improvement in the moderately to severely involved sample. **Table 6** shows that all subjects in ROB-ML were fully able to perform cylinder grasp at baseline: 50 percent maintained and 50 percent worsened over the course of the study. In contrast, in FNS-ML, 66 percent maintained, 16 percent improved, and 16 percent worsened. **Table 6** shows the pattern of recovery in spherical grasp. In ROB-ML, 83 percent maintained and 16 percent improved, whereas in FNS-ML, 33 percent maintained and 66 percent improved. The level of initial impairment for both groups was greatest for release of grasp or mass finger extension. In both groups, 100 percent of subjects had no discernible finger extension at baseline (**Table 6**). In ROB-ML, 66 percent regained partial extension, and in FNS-ML, 50 percent regained partial extension.

According to the motor control measures of TA and SM, ROB-ML produced a statistically significant gain, whereas FNS-ML did not (**Table 7**). According to the TA measure, the ROB-ML group had pretreatment scores ranging from 1.1 to 19.1 cm and posttreatment scores ranging

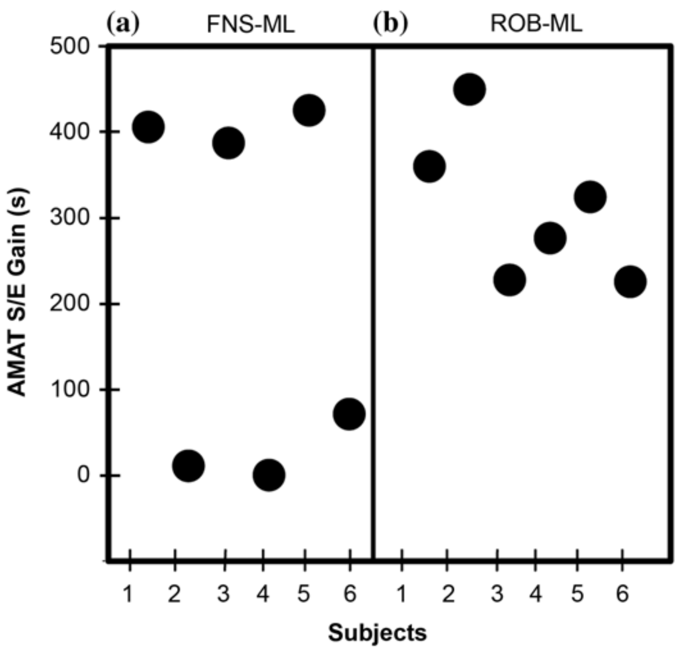

Figure 5.
Gains in Arm Motor Ability Test shoulder/elbow (AMAT-S/E) for each subject. Gains in AMAT-S/E for each subject are shown for **(a)** functional neuromuscular stimulation and motor learning (FNS-ML) group and **(b)** robotics and motor learning (ROB-ML) group. Shoulder/elbow training was targeted in ROB-ML group during 1.5 h session, whereas it was not for FNS-ML group. ROB-ML group had significant gain in AMAT-S/E, whereas FNS-ML group did not. Distribution of individual gain scores illustrates data underlying this result.

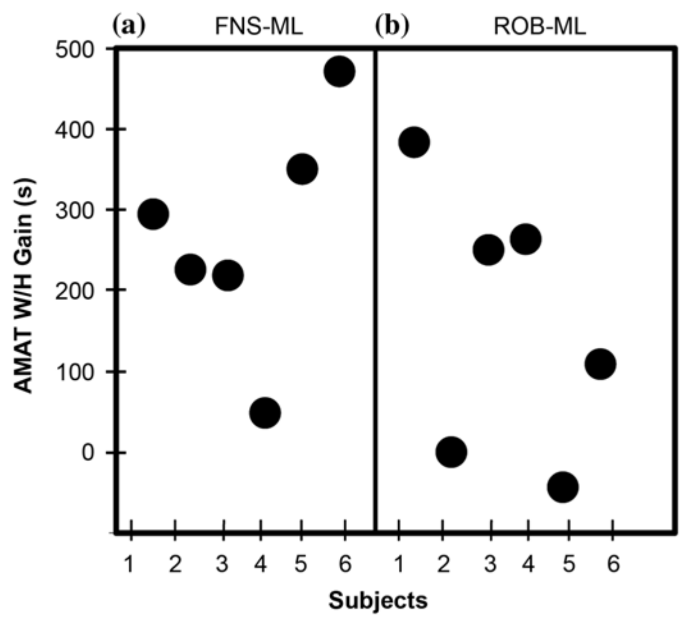

Figure 6.
Gains in Arm Motor Ability Test wrist/hand (AMAT-W/H) for each subject. Gains in AMAT-W/H for each subject are shown for **(a)** functional neuromuscular stimulation and motor learning (FNS-ML) group and **(b)** robotics and motor learning (ROB-ML) group. Wrist/hand training was targeted in FNS-ML group during 1.5 h session, whereas it was not for ROB-ML group. FNS-ML group had a significant gain in AMAT-W/H, whereas ROB-ML group did not. Distribution of individual gain scores illustrates data underlying this result.

Table 4.
Pre- and posttreatment gain according to Fugl-Meyer for each of two groups.

Measure	ROB-ML			FNS-ML		
	Premedian	Postmedian	Pre- and Postchange	Premedian	Postmedian	Pre- and Postchange
Fugl-Meyer (points)	21 (10)*	32 (10)*	$p = 0.026$†	23 (7)*	32.5 (7)*	$p = 0.028$†

*Interquartile range.
†$p < 0.05$.
ROB-ML = robotics and motor learning, FNS-ML = functional neuromuscular stimulation and motor learning.

Table 5.
Pre- and posttreatment Fugl-Meyer scores for subjects in each of two groups.

Subject	ROB-ML			Subject	FNS-ML		
	Pre	Post	Gains		Pre	Post	Gains
1	17	31	14	7	24	35	11
2	18	38	20	8	30	33	3
3	19	25	6	9	17	23	6
4	34	35	1	10	26	32	6
5	28	33	5	11	22	28	6
6	18	21	3	12	19	44	25

ROB-ML = robotics and motor learning, FNS-ML = functional neuromuscular stimulation and motor learning.

Table 6.
Number of subjects who responded to treatment according to three Fugl-Meyer hand performance items in response to robotics motor and learning (ROB-ML) and functional neuromuscular stimulation and motor learning (FNS-ML).

Score Status	Cylindrical Grasp		Spherical Grasp		Mass Finger Extension	
	ROB-ML	FNS-ML	ROB-ML	FNS-ML	ROB-ML	FNS-ML
No. of Subjects with Normal Score at Beginning of Treatment	6	5	1	2	0	0
Improved	0	1*	1	4	4†	3†
Maintained	3	4	5‡	2§	2	3
Worsened	3	1	0	0	0	0

*Subject had a score of 1 at beginning of treatment and achieved a 2 at conclusion (normal).
†Subjects achieved score of 1 (releases active flexion grasp).
‡One subject maintained a normal score of 2 throughout protocol.
§Two subjects maintained a normal score.

Table 7.
Pre- and posttreatment gain according to target accuracy (TA) and smoothness of movement (SM) measures of motor control for each of two groups.

Motor Control Measures	ROB-ML			FNS-ML		
	Pre (Mean ± SD)	Post (Mean ± SD)	Change (*p*-Value)	Pre (Mean ± SD)	Post (Mean ± SD)	Change (*p*-Value)
TA (cm)	8.69 ± 6.68	1.83 ± 2.73	6.86, $p = 0.042$*	7.02 ± 8.89	4.75 ± 8.97	2.27, $p = 0.69$
SM	0.37 ± 0.12	0.67 ± 0.22	0.30, $p = 0.013$*	0.39 ± 0.30	0.60 ± 0.16	0.21, $p = 0.190$

*$p < 0.05$.
ROB-ML = robotics and motor learning, FNS-ML = functional neuromuscular stimulation and motor learning.

from 0.6 to 7.4 cm (lower error score indicated less error). Individual gain scores ranged from 0.3 to 18.0 cm. The FNS-ML group had pretreatment scores ranging from 0.5 to 22 cm and posttreatment scores from 0.6 to 21 cm. Individual gain scores ranged from –0.2 to 7 cm.

The SM measure showed a similar pattern of response. Only the ROB-ML group had a statistically significant gain. The ROB-ML group had pretreatment scores that ranged from 0.26 to 0.55, and posttreatment scores from 0.34 to 0.88. Individual gain scores ranged from 0.08 to 0.56. The FNS-ML group had pretreatment scores ranging from 0.02 to 0.82 and posttreatment scores ranging from 0.45 to 0.84. Individual change scores ranged from –0.36 to 0.57.

Follow-Up Measures

No statistically significant difference was found between posttreatment and follow-up measures for either ROB-ML or FNS-ML for the following measures: AMAT, AMAT-S/E, AMAT-W/H, or FM (**Table 8**).

DISCUSSION

Gains in a Measure of Functional Tasks

The results of the study extend the literature by providing evidence of statistically significant pre- and posttreatment gains in response to ROB-ML, according to the AMAT, a parametric measure, objectively obtained and composed of 13 actual functional tasks. Others showed that robotics could produce impairment gains [1–2] and delayed gains in the FIM [4], a measure of gross function that does not focus on motor ability of the involved upper limb. The current study extends the literature by demonstrating a statistically significant gain for chronic stroke survivors in response to ROB-ML, according to the timed functional tasks of which the AMAT is comprised. The AMAT functional tasks include using the telephone, buttoning a sweater, and eating with utensils. Furthermore, the results support the concept that both robotics and FNS can improve functional task components, according to AMAT-S/E and AMAT-W/H measures, respectively.

Training Specificity

Training specificity is a well-known phenomenon in nondisabled individuals [38–40]. This study extends the literature by providing evidence of training specificity for chronic stroke survivors with persistent upper-limb motor deficits according to functional task components. First, only the ROB-ML group, who received targeted shoulder/elbow robotics training for 1.5 h of each daily session, showed significant gain in AMAT-S/E, whereas the FNS-ML group showed no gain. Second, and conversely, only the FNS-ML group, who received targeted finger/wrist FNS training for 1.5 h of each daily session, showed significant gain in AMAT-W/H, whereas the ROB-ML group showed no statistically significant gain. In both cases, the intensely targeted treatment at specific joints produced the result for the functional task movements exclusively at those joints. Though the ROB-ML group had no statistically significant gain in AMAT-W/H, the trend toward improvement in AMAT-W/H could have been produced by significantly improved shoulder/elbow function for this group which, in turn, produced a more stable proximal arm with which to practice wrist/hand movements during the ML portion of each session or independently.

Both groups had whole task or task component practice for an additional 3.5 h during each daily session. While this aspect of training was a likely contributor to the final result for both groups [41–43], the differential improvement in the targeted joints (shoulder/elbow vs wrist/hand, respectively) of each group suggests that the task practice

Table 8.
Comparison of posttreatment vs follow-up according to Arm Motor Ability Test (AMAT) for each of two groups.

Functional Measure	ROB-ML			FNS-ML		
	Post (Mean ± SD)	Follow-Up (Mean ± SD)	Change	Post (Mean ± SD)	Follow-Up (Mean ± SD)	Change
AMAT-S/E (s)	726.76 ± 215.30	563.63 ± 356.00	–163.13, $p = 0.534$	585.62 ± 217.45	590.17 ± 238.46	4.55, $p = 0.976$
AMAT-W/H (s)	872.33 ± 180.22	624.86 ± 197.88	–247.47, $p = 0.185$	517.57 ± 246.82	507.61 ± 309.57	–9.96, $p = 0.957$

ROB-ML = robotics and motor learning, FNS-ML = functional neuromuscular stimulation and motor learning, SD = standard deviation, shoulder/elbow = S/E, wrist/hand = W/H.

may have been necessary but not sufficient for significant functional gains. That is, the practice characteristics provided by robotics targeted for shoulder/elbow movement retraining were necessary to produce the gains in AMAT-S/E. Similarly, the practice characteristics provided by FNS that targeted wrist/hand movement retraining were necessary to produce the gains in AMAT-W/H.

Training-specific gains could have occurred because of a greater number of repetitions of the targeted movements [12–14] or because performance of the movement was as close to normal as possible [17–18]. Both FNS and robotics provided a method for practicing the desired wrist/hand or shoulder/elbow movements, respectively, in a manner more closely approximating normal than was otherwise possible for our study sample and many stroke survivors [44]. Training specificity can also explain the difference between the two groups for the two measures of shoulder/elbow motor control, TA and SM. According to these two measures, ROB-ML group had a significant gain, whereas FNS-ML did not. The FNS-ML group did not practice shoulder/elbow movement accuracy or movement smoothness for 1.5 h each session using visual feedback. However, the ROB-ML group did practice these aspects of motor control with visual feedback for 1.5 h each session. This practice emphasis on TA and SM only for the ROB-ML group is reflected in the significant gains exclusively for that group. These findings are consistent with that of others in which subjects in the chronic phase after stroke who had >100 robotics practice sessions showed a significant gain in measures of SM [45]. The current randomized controlled study extends the literature by showing that the FNS-ML group who did not receive the robotics training did not show a significant gain in SM.

The current study results support the concept of specificity of training for chronic stroke survivors. Depending upon the manner in which the treatment targeted ML, a differential response occurred in motor control and task component performance. The study results highlight the importance of assigning treatment according to knowledge of both motor control assessment and principles of ML intervention so that the proper technology and exercises are accurately targeted to address motor deficits.

Gains in Severely to Moderately Involved Stroke Survivors

The results of the current study extend the literature by providing evidence that moderately to severely involved stroke survivors in the chronic phase could demonstrate significant gains in functional task components in response to FNS-ML. Others reported gains for more mildly involved chronic stroke survivors. That is, the subjects were required to have initial ability to actively extend and flex fingers and wrist [6,21,46] and to flex shoulder and elbow 60° and 45°, respectively [21]. Others have reported encouraging improvements in response to treatment for these more mildly involved subjects [6,21,46]. In the current study, all the subjects in the sample were severely impaired at baseline with regard to finger extension capability, but over half regained volitional ability to release grasp of an object. Of the subjects in the sample, 75 percent scored zero on the spherical grasp at baseline, but of those, 56 percent regained partial ability to perform this movement. The current study used not only technologies but also provided an intense, supervised treatment schedule of a long duration of 5 hours a day, 5 days a week for 12 weeks. The technologies and this duration and intensity of treatment made possible the finely incrementalized treatment progression that was necessary for individuals who were essentially unable to move at the outset of training.

Gains Obtained with a 1:3 Therapist to Patient Ratio

Our methodology included a single therapist who provided treatment simultaneously for a group of three stroke survivors. The current study extends the literature by providing evidence that a single therapist can provide effective treatment simultaneously for a group of three moderately to severely involved stroke survivors. The current study provides evidence that a ML intervention, combined with robotics or FNS can be successfully and effectively provided using a 1:3 ratio of therapist to subject. This is an important finding because even a very effective, specialized ML intervention will need to be offered in the most efficient, cost-effective manner possible.

Limitations and Difficulties Encountered

The reported results should be interpreted with caution because the sample size was small. For the group receiving ROB-ML, the robot was constrained, in that robotics training was performed exclusively in the horizontal plane for shoulder/elbow movements, with the forearm supported. However, since the beginning of this study, additional robotics options were made available for broader robotics therapeutic application [47]. For the group receiving FNS-ML, the electrical stimulus was applied with surface electrodes that stimulated mass finger flexion and extension. With FNS technology of greater specificity, FNS-induced practice of individuation of fingers would be possible. Subjects in the FNS-ML group tolerated the surface application of the electrical stimulus well, and a good movement response was obtained during stimulation.

CONCLUSIONS

Patients in the chronic phase after stroke (>12 mo), with persistent moderate-to-severe impairments and functional deficits, can improve function in response to treatment using combined ML and technology. ROB-ML and FNS-ML produced differential treatment responses that were consistent with the muscle groups and movements that were targeted by the respective technology as well as the unique characteristics of each of the technologies. Since the shoulder/elbow or wrist/hand responded differentially in this study to specifically targeted treatment, most likely, treatment provided for the four joint systems (shoulder, elbow, wrist, and hand) would produce an incrementally more functional upper limb than would treatment targeted to only two upper-limb joints (shoulder/elbow or wrist/hand). Further study will be needed to determine the answer to that question. Nevertheless, the results indicate that in selecting a treatment technology, it is critical to accurately evaluate the patient's deficits, design the treatment protocol, and select the adjunct technologies that address the specific deficits exhibited by the patient.

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