ARTICLES

Combined Functional Task Practice and Dynamic High Intensity Resistance Training Promotes Recovery of Upper-extremity Motor Function in Post-stroke Hemiparesis: A Case Study

Carolynn Patten, PT, PhD;[1,2] *Jody Dozono, MPT;*[1] *Stephen G. Schmidt, PT, OCS*[3]
Mary E. Jue, MSPT;[3] *Peter S. Lum, PhD*[4]

ABSTRACT

Background and Purpose. Weakness is a significant impairment in persons with post-stroke hemiparesis, yet traditional clinical perspectives caution against strengthening in neurological populations. Significant correlations between weakness and functional movement have been demonstrated, however, a clear relationship between increased strength and functional improvement has been elusive. This case study describes a combined program of dynamic, high-intensity resistance training and functional task practice for the upper-extremity in adult hemiparesis. **Case Description.** The patient was a 65-year-old, right hand dominant woman who presented to the Neural Control of Movement Laboratory at the Palo Alto VA Rehabilitation Research and Development Center 16 weeks following clipping of an unruptured aneurysm with consequent dense right hemiparesis. She received 7 weeks of acute rehabilitation according to CARF guidelines (ie, at least 3 hours of two or more disciplines, 6 days per week). Her baseline research evaluation revealed significant upper-extremity deficits at the ICF body structure/function level including: weakness, shoulder pain, mild resistance to passive movement, and need for moderate to maximal assistance in many activities of daily living including bathing and dressing. The Stroke Impact Scale score reporting her perspective indicated she had recovered from her stroke only 50%. The hybrid resistance training-functional task practice intervention, detailed in this report, was delivered 3 times per week for 6 weeks with each session lasting 75:00. **Outcomes.** The subject revealed marked improvements in isometric and dynamic force production in 5 key upper-extremity actions: elbow flexion, elbow extension, shoulder flexion, shoulder abduction, and shoulder external rotation. Strength gains were accompanied by increased EMG activation immediately postintervention and by a combination of increased activation and apparent hypertrophic effects at 6 month follow up. Marked improvements were noted in all clinical and functional measures and in an elbow trajectory-tracking task which served as a surrogate measure of motor control. **Discussion.** Improvements in strength and positive outcome effects at the physiological, clinical, and functional levels were observed in this subject following the experimental hybrid upper-extremity rehabilitation intervention described. Importantly, no deleterious effects were observed including exacerbation of spasticity or musculoskeletal compromise. Observations of improved EMG activation in this case study suggest that improvements in motor activation underlie these strength gains and can likely be attributed to working at a high intensity level.

Key Words: stroke, strength, rehabilitation, biomechanics, motor control, EMG

INTRODUCTION

Stroke is the foremost cause of physical disability in Western Industrialized nations affecting over 750,000 persons in the United States and accounting for over $30 billion (USD) in health care costs annually.[1] Due to marked improvements in acute management, there are now over 4 million living stroke survivors, a third of whom experience significant disability. While the majority of stroke survivors experience some degree of recovery, compromised upper-extremity function remains among the most persistent and significant stroke-related physical disabilities. Despite recognition of the problem, at present there is no clear evidence to motivate effective upper-extremity rehabilitation for persons with post-stroke hemiparesis.[2, 3]

The prominent physical manifestation of stroke is hemiplegia--predominantly unilateral motor dysfunction characterized by a triad of squelae including: weakness,[4] impaired coordination,[5] and spasticity.[6] Traditional views on neurorehabilitation asserted that spasticity was the most severe of this triad and imparted the most significant limitation to recovery of motor function.[7] However, current prevailing thought emphasizes functional and task-specific therapies which focus primarily on activities related to tasks of daily living, and grossly related precursor activities,[8] with practice structured according to principles of motor learning.[9] These elements are thought to drive neural plasticity, which in turn is thought to promote recovery of function at the behavioral level.[10]

Without disregard for these important perspectives, hemiparetic

[1]Rehabilitation Research & Development Center/153, VA Palo Alto Health Care System, Palo Alto, CA (patten@rrd.standford.edu)
[2]Department of Orthopaedic Surgery Stanford University School of Medicine, Stanford, CA
[3]Kaiser Foundation Rehabilitation Center Vallejo, CA
[4]Department of Biomedical Engineering, Catholic University of America, Washington, DC

weakness is poorly understood, especially in the upper-extremity. It has been established that weakness in post-stroke hemiparesis correlates with functional motor performance.[4, 11, 12] Such observations motivate questions regarding the potential to strengthen paretic muscles and, concomitantly, whether improved strength contributes to meaningful improvements in functional use of the limb.

The prevailing biomechanical school of thought regarding muscular strength builds on the phenomenon that muscular force scales as a function of muscle cross-sectional area.[13] However, the capacity to produce muscular force is primarily a neural phenomenon resulting from central nervous system drive and task-specific regulation of neural activity.[14] For persons with neurologic impairments neural aspects of strength and weakness take principal consideration.

Early investigations of resistance training post-stroke targeted the lower extremity of persons in the chronic phase of recovery (see[4] for review). These studies demonstrated fundamental efficacy of resistance training and were suggestive of positive effects on functional movement.[4, 15, 16] There are, however, several important differences between the upper and lower limbs including the specificity and extent of the cortical representation[17] and recognition that spasticity occurs more commonly in the arm. Together these factors influence both the potential efficacy and effectiveness of resistance training for promoting upper-extremity function.

In this paper we describe 2 forms of upper-extremity rehabilitation targeted for persons with post-stroke hemiparesis. The first is comprised entirely of functional task practice and was motivated on the basis of the Motor Re-Learning Approach described by Carr and Shepherd.[18] The second involves a hybrid of functional task practice and dynamic high-intensity resistance training. Both forms of treatment were developed to address 2 primary objectives: first, to provide a structure that could be reproduced across multiple participants and practitioners serving as an active control intervention in a randomized clinical trial and second, to afford the requisite flexibility to accommodate participants of various functional levels while addressing their individual circumstances and rehabilitation goals.

We present a case study describing first evidence that upper-extremity rehabilitation including dynamic high-intensity resistance training produces significant positive motor outcomes and retention of treatment effects without deleterious consequences including exacerbation of spasticity. We anticipate that the combination of resistance training and functional motor relearning would produce significant positive outcomes on anticipated clinical, neuromuscular, and biomechanical indicators of upper-extremity motor function without exacerbation of spasticity.

CASE DESCRIPTION

Examination

History

The patient was a 65-year-old right hand dominant, Iranian-born female who presented to the target research program 16 weeks following left pterional craniotomy and clipping of an unruptured aneurysm with consequent right hemiparesis. Her past medical history was significant for hypertension, hypercholesterolemia, hypothyroidism, depression, and anxiety. Several months prior to surgery, the patient experienced a transient ischemic attack characterized by speech arrest and visual flashing. The diagnostic workup, including MRA and MRI of the head, identified a Nutik-type aneurysm of the left internal carotid artery.[19] An elective aneurysm clipping procedure was subsequently performed. Postoperatively she was slow to arouse and demonstrated a dense right hemiparesis. Follow-up CT and MRI revealed an extensive infarct in the left frontal lobe, temporal lobe, and basal ganglia; hemorrhage in the posterior fossa; and complete occlusion of the left internal carotid artery. Her acute hospitalization, lasting 14 days, was complicated by angina and electrocardiogram changes, however cardiac enzymes, Troponin-I levels, and myocardial perfusion scans were negative. Once medically stable, the patient was transferred to the Kaiser Foundation Rehabilitation Center (KFRC) in Vallejo, California, for rehabilitation.

Tests and measures – admission to acute rehabilitation

The physical examination performed upon admission to acute rehabilitation revealed diplopia, dysphagia, dysarthria, mixed aphasia (alternating between English and Farsi), and moderate to severe right shoulder pain. Medications prescribed during her rehabilitation course are listed in Table 1. She required total assistance for most ADLs (eg, eating, dressing, bathing, toileting, transfers) and all IADLs. Maximum assistance was required for bed mobility and moderate assistance was required to maintain a static sitting posture. Initial attempts at standing required the use of a standing frame. Right upper extremity strength was 1+/5 at the shoulder and 0/5 for the remainder of her upper extremity. Lower extremity strength was 1+/5 to 2-/5 proximally and 0/5 distally. Table 2 details her status at admission to and discharge from acute rehabilitation. Examination for spasticity revealed a Modified Ashworth score of 1 in the right upper extremity in a flexor/pronator pattern. Following assessment, multiple patient-centered functional goals were developed by each therapist, by the interdisciplinary team, and by other disciplines (eg, nursing, recreation therapy, nutrition, social work) in collaboration with the patient and her family.

Course of Acute Rehabilitation

The patient's course of acute inpatient rehabilitation lasted 49 days of which 39 were acute inpatient rehabilitation days and 10 were spent in the KFRC outpatient day rehabilitation program. The comprehensive rehabilitation program included physical therapy, occupational therapy and speech therapy. All disciplines targeted different levels of the *International Classification of Functioning, Disability, and Health* (ICF)[20] including: body structure/function, activity, and participation.

The rehabilitation program for this patient consisted of between 3 and 5 hours per day, 6 days per week of physical, occupational, and speech therapies (see Table 2 for detailed description of therapies) and was augmented with other therapeutic interventions, including rehabilitation nursing and recreation therapy. Challenges encountered during her rehabilitation process included significant

Table 1. Medications and Dosages Used During Acute and Experimental Rehabilitation Periods

Inpatient Rehabilitation	Research Protocol
Lisinopril (Zestril), 5 mg *qd*	Lisinopril, 20 mg, *qd*
Paroxetine Hcl (Paxil), 10 mg, *qd*	Paroxetine Hcl (Paxil), 10 mg, *qd*
Levothyroxine sodium (Levothyroid), 125 mcgs, *qd*	Levothyroxine sodium, 125 mcgs, *qd*
Aspirin, 325 mg, *qd*	Aspirin, 325 mg, *qd*
Docusate sodium (Colace), 100 mg, *bid*	Docusate sodium, 100 mg, *bid*
Lovostatin (Mevacor), 40 mg, *qd*	Lovostatin, 40 mg, *qd*
Trazodone (Desyrel), 50 mg, *qd*	Trazodone, 50 mg, *qd*
Atenolol (Tenormin), 25 mg, *qd*	Atenolol, 25 mg, *bid*
Bisacodyl suppository, *prn*	
Magnesium hydroxide, 2400 mg, *prn qd*	
Clonazepam (Klonopin), 0.25 mg, *bid*	Clonazepam, 0.25 mg, *bid*
Acetaminophen, 650 mg, *prn q 6 hours*	Acetominophen, 325 mg, *qid*

Table 2. Tests and Measures at Admission and Discharge from Acute Rehabilitation

Therapy*	Time (min.)	Individual or Group	General activity description within each therapy
Physical Therapy	30	I	Neuromuscular re-education utilizing PNF and various additional approaches (see text), therapeutic exercise, ROM/joint mobilization, balance, scapular/shoulder taping, resisted task-specific activities including: transfers, bed mobility, gait, ADL's, progression to hands-off functional activities to enhance patient problem-solving and motor learning
PT – Resisted Mat Exercise	30	I	
PT – Gait	30	I	Hands-on resisted gait activities, progressed toward hands-free gait as appropriate, balance training, mobility over a variety of surfaces as appropriate (carpet, hardwood, concrete, stairs, etc.), application of bracing as needed to optimize independence
PT Self Care	30	I	Task-specific activities with the aim of maximizing independence in ADL's, progressed with random and blocked practice in a variety of physical environments
PT Trunk Class	30	G	Addressed specific impairments in a seated position including: strength, static and dynamic balance, coordination, flexibility, endurance. Also addressed functional activities including w/c propulsion & accessory manipulation, scooting, UE reaching tasks, extremity management (e.g. foot on/off footrest, etc)
PT Bulbar	30	I	Addressed dysarthria, dysphagia, breath control, vocal output (volume), head control
Occupational Therapy (OT)	30	I	Task-specific activities for ADL's, IADL's, UE management, UE strengthening, coordination, forced use strategies, use of adaptive equipment
OT dressing	30	I	Dressing training including use of adaptive aids
Speech Therapy (ST)	30	I	Intervention for auditory and written comprehension, verbal expression, attention, cognition and speech clarity.
ST Dysphagia	30	I	Addressing oral-motor control, swallowing proficiency, assessment of readiness for progression from NPO toward a regular diet
Recreation Therapy	30	G, I	Addressing some IADL's, participation in recreational and social therapeutic activities, exploring creative outlets
Total time: Monday-Friday**: time in therapies at** admit**: 3 hrs./day, peak of 5 hrs./day,** discharge**: 4 hrs./day,** Saturday**: 3 hrs./day**			
*Therapies were added according to physical capacity of patient and to increase repetition/intensity of activities as determined by the individual therapist collaborating with the patient			

right shoulder and upper extremity pain, poor endurance, and anxiety, which was expressed by both the patient and her family.

Tests and Measures – Discharge from Acute Rehabilitation

Upon discharge from KFRC the patient demonstrated marked improvement in her functional capacity (see Table 3). Static sitting balance had improved to modified independent, transfers were performed with contact-guard, and the patient was able to ambulate using a wide-based quad cane and an ankle-foot orthosis, 50 feet with supervision, and to continue for a total of 150 feet with contact-guard to occasional minimal assist. Increased assistance over greater gait distances reflected her ongoing problem with fatigue. Although the patient demonstrated improvements in both upper and lower extremity function during her course of rehabilitation, her deficits in upper extremity function were more pronounced. At the time of discharge she demonstrated weak grasp and release with her right hand, but consistently required verbal cues for hand opening in preparation for grasp. Gross manipulation of objects (eg, one inch block) was possible using a tripod or 3-jaw pinch, however, the patient was unable to grasp smaller objects and quickly fatigued. Self-feeding was possible using adapted utensils but she required supervision for set-up and verbal cues. She was able to hold a cup in her right hand to drink with a straw, but required assistance from her left arm to raise the cup to her mouth.

The patient was discharged home with a recommendation to continue physical, occupational and speech therapies on an outpatient basis. Outpatient services were initiated the following day and continued at various sites within the Kaiser-Permanente system at a frequency of approximately one time per week for 13 sessions.

Research Protocol

History and Enrollment

The patient was referred to the Neural Control of Movement Laboratory at the Palo Alto VA Rehabilitation Research and Development Center. After providing signed, informed consent

Table 3. General Description of Each Therapy Offered in Acute Rehabilitation

Measure	Admit KFRC rehab 7/31/03	Discharge KFRC Day-Rx 10/21/03
FIM		
Eating	Total assist	Supervised
Grooming	Max assist	Supervised
Bathing	Total assist	Contact-guard assist
Upper dressing	Total assist	Modified independent
Lower dressing	Total assist	Min (including donning AFO)
Toileting	Total assist	Contact-guard assist
Sphincter control - bladder	Max assist	Minimal assist
Sphincter control - bowel	Max assist	Minimal assist
W/C to bed transfer	Total assist	Contact-guard assist
W/C to toilet transfer	Total assist	Contact-guard assist
W/C to tub bench transfer	Total assist	Contact-guard assist
Locomotion - wheelchair	Total assist	Modified Independent *
Locomotion - walking	Total assist (standing frame)	Minimal assist †
Stairs	N/T – total assist	Contact-guard assist ‡
FIM score total	16	57
Barthel score	0	45
Spasticity	R UE flexor spasticity, clonus: O to 2 beat bilateral ankles	R UE flexor spasticity, R LE hypotonia, clonus: 2 beat L ankle, 10 beat R
Modified Ashworth Scale	1 UE (flexor/pronator)	1 UE (flexor/pronator)
Sensation	Significant R hemisensory loss, light touch & proprioception impaired	R hemisensory loss to light touch, gross proprioception intact
Other:	.5cm+ sublux. R shld, R shoulder pain, diplopia	C/O R UE pain (shld/hand), 1.5cm+ sublux. R shld., R knee pain, diplopia

*Locomotion - wheelchair propulsion modified independent over level surfaces, however score would be 5 on FIM because patient unable to navigate thresholds/ramps

† Locomotion -walking scores incorporated an ankle-foot-orthosis, the patient was at the minimal assist level using the AFO

‡ Stairs - incorporated an ankle-foot-orthosis and rail using step-to gait

and HIPAA authorization she underwent baseline evaluation. She agreed to treatment in a research protocol that was initiated at 16 weeks post-CVA.

Assessment

Clinical and biomechanical assessments were conducted at baseline, immediately following treatment and, to determine whether treatment effects were retained, at 6 months following completion of therapy with no additional intervention.

Clinical Measures. Clinical assessments were performed at all levels of the ICF. Measures observed at the *body structure/function* level included: the upper-extremity Fugl-Meyer Motor Assessment (FMA)[21] and the Ashworth Scale (ASH).[22] The Barthel Index (BARTHEL),[23] the Wolf Motor Function Test (WMFT),[24] and the Functional Independence Measure (FIM)[25] were used to assess *activities* and the Stroke Impact Scale (SIS)[26] was used to assess *participation*.

Strength and Motor Activation. Isometric and dynamic torques were obtained using an isokinetic dynamometer (Biodex System 3.0 Pro, Shirley, NY). Five upper-quarter actions (shoulder flexion, abduction and external rotation, and transverse plane elbow flexion and extension) were tested at 4 criterion speeds (0 (isometric), 30, 75 and 120°/s. Surface electromyography (EMG) was sampled (2 kHz sampling frequency, bandpass filtered between 10 Hz and 500 Hz using a zero-phase second order Butterworth filter (-2dB rolloff)) concurrently with torque from 8 muscles: biceps brachii, triceps brachii, anterior, middle and posterior deltoid, infraspinatus, brachioradialis, and pectoralis major. The area under the torque-velocity curve (AUC) was calculated for each action to assess improvements in static and dynamic force production. The relationship between motor activation and maximal isometric voluntary force production (MVC) was evaluated by plotting the maximal EMG during MVC. The slopes of the EMG-MVC relationships were compared across evaluations to determine whether improved force production was associated with neural (eg, motor activation) or muscular (eg, hypertrophy) adaptations (Figure 1).[14]

Motor Control. A trajectory-tracking task involving coordination of reciprocal elbow flexion and extension was used as a surrogate measure of upper-extremity motor control. The methods and reliability for this paradigm have been elaborated previously.[27] Briefly, custom attachments fabricated to accommodate impaired grasp present in hemiparesis were used to perform the trajectory-tracking task. The dynamometer was operated in isotonic mode with dynamometer settings adjusted (sensitivity = 5, torque = 1 ft-lb) to establish a low-friction condition requiring minimal torque to successfully perform the task. This approach minimized the role of strength in performing a coordinated motor task and thus afforded the opportunity to investigate how improved strength, and motor activation, affect motor coordination. The trajectory-tracking task (Figure 2) involved coordination and timing of 2 cycles of reciprocal elbow flexion and extension through a 70° range of motion and was implemented by orienting the dynamometer in the transverse plane. Criterion trajectories were presented on a computer video monitor at three movement speeds (25°/s, 45°/s and 65°/s). The subject was provided real time kinematic feedback and was instructed to follow the criterion as closely as possible to minimize the difference between the criterion and performed trajectories. Five practice and 5 test trials were performed at each speed. The root-mean-square error (RMSE) was calculated between criterion and performed trajectories and evaluated over the 5 test trials for each criterion speed. The trajectory-tracking task was not practiced as part of the therapeutic intervention.

Tests and Measures – Research Protocol Baseline

Examination. Physical examination upon enrollment to the research protocol revealed mild dysarthria, mild aphasia (ie, naming and repetition), mildly impaired short-term memory, right shoulder pain in the end range of shoulder flexion and abduction, mild sensory loss, and poor endurance. Medications used at this time are listed in Table 1. The subject required moderate to maximal assistance for most ADLs including dressing and bathing, but only minimal assistance for toileting, and maximal to total assistance for most IADLs. Static sitting balance was performed at the modified independent level while dynamic balance (eg, weight shifting, reaching, position adjustments) required contact guard assistance to assure patient safety. Transfers were performed with minimal assistance to contact guard and standing and balancing required only contact guard assistance. The patient was able to ambulate approximately 50 feet with minimal to contact guard assistance, using a wide-based quad cane, her distance being limited by poor endurance. She was able to perform stairs but required both a rail and minimal assistance. Due to limited endurance, her primary mode of locomotion was a wheelchair and due to impaired sitting balance a lap belt was used for safety and to provide stability. The short-term goals expressed by the patient and her family were to increase function of the hemiparetic hand for writing, cooking, and feeding (eg, cutting, utensil use, food transport). Her long-term goal was to return to work as an attorney.

Clinical Assessment. The patient presented with moderate to severe physical and social deficits, which were assessed using standardized clinical tools and are detailed by ICF levels in Table 4. At the ICF *body structure/function* level moderate to severe deficits were revealed as indicated on the upper-extremity portion of the Fugl-Meyer Motor Assessment and slightly increased resistance to passive motion as revealed by the Ashworth Scale. Low performances were revealed at the ICF *activity* level by low, mean scores on the Functional Ability Scale of the Wolf Motor Function Test, markedly elevated median time to perform tasks on the Wolf Motor Function Test, poor self-care and ADL as revealed by the Barthel Index. Functional Independence Measure (FIM) scores revealed that the patient required moderate to minimal assistance on the majority of tasks. She performed poorly at the ICF *participation* level as revealed by very low scores on the social roles/activities and physical domains of the Stroke Impact Scale. From the subject's perspective she was only 50% recovered from her stroke.

Performance-based Assessment. Biomechanical (Tables 5 and 6 and Figure 3) and motor control (Figure 2) assessments revealed significant weakness in all upper-extremity actions when tested isometrically. As illustrated (Figure 3) by both low torques and inability to move at speeds greater than ~40°/s, dynamic torque production was severely impaired in shoulder flexion and

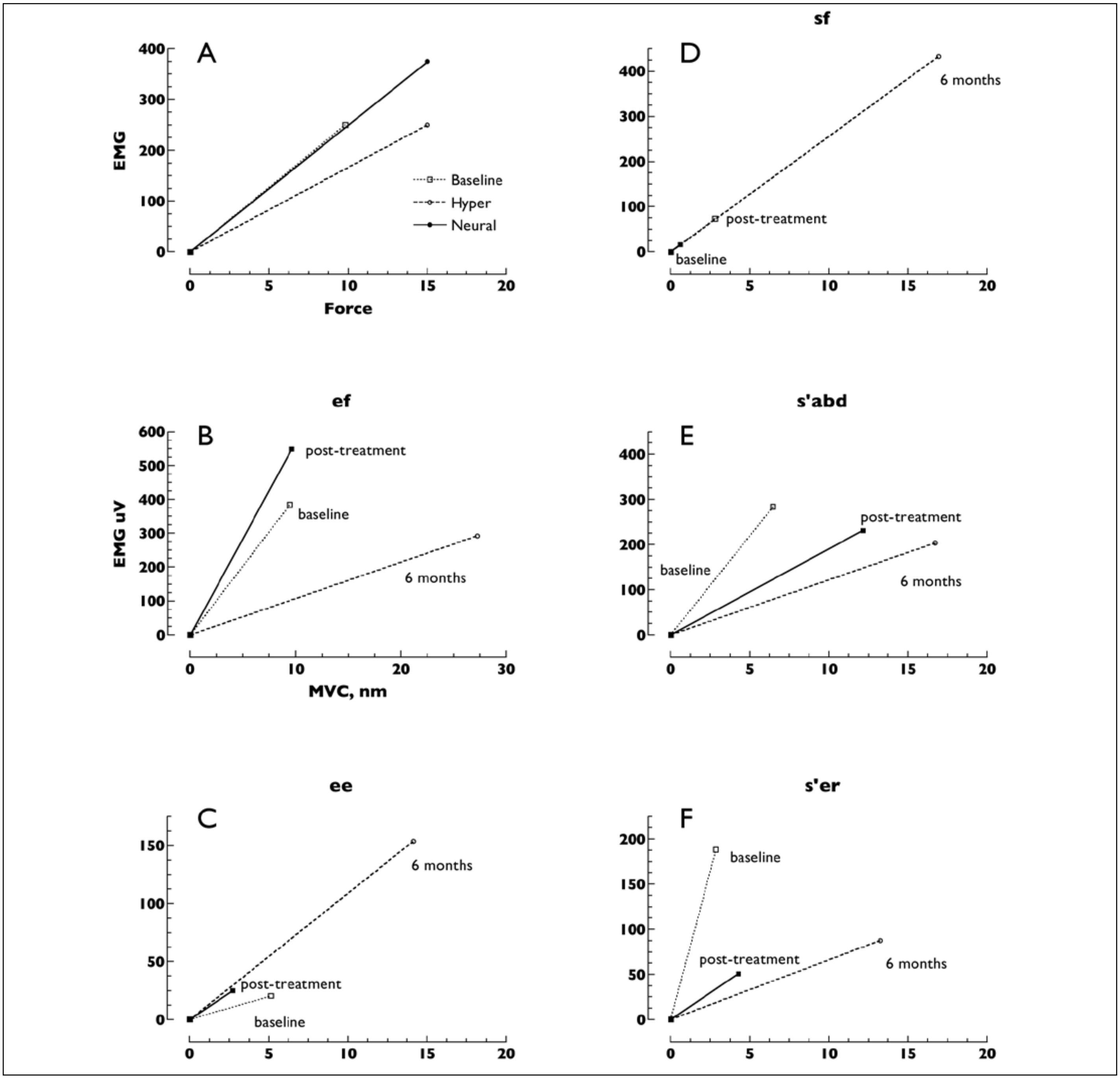

Figure 1. EMG-MVC relationships per joint action across study evaluations.

Panel A – Putative relationships representing neural (solid line) and hypertrophic (dashed line) adaptations to resistance training (after Moritani and DeVries, 1979[14]). Extension of the EMG-MVC relationship from baseline (solid line) corresponds with marked increases in both activation (EMG) and MVC as occur during the neural phase of adaptation. Depressed slope corresponds with increased MVC force but little change in EMG activation as would occur with muscular, or hypertrophic, adaptations mediating strength gains.

Panels B-F – Case study observations for elbow flexion (ef) (B), elbow extension (ee) (C), shoulder flexion (sf) (D), shoulder abduction (s'abd) (E) and shoulder external rotation (s'er) (F). Immediately following the experimental intervention, the slope of the EMG-MVC relationship was markedly increased for elbow flexion, elbow extension and shoulder flexion, indicating gains in EMG activation (i.e., recruitment) per unit MVC force in response to the dynamic high-intensity resistance training. At the six month follow up evaluation, EMG-MVC slopes remained elevated for elbow extension and shoulder flexion indicating that improved strength was mediated predominantly by improved motor activation. For elbow flexion, shoulder abduction and shoulder external rotation, EMG-MVC slopes were depressed at six month follow up suggesting that improved strength involved a significant component of hypertrophy as would be consistent on this extended time frame.

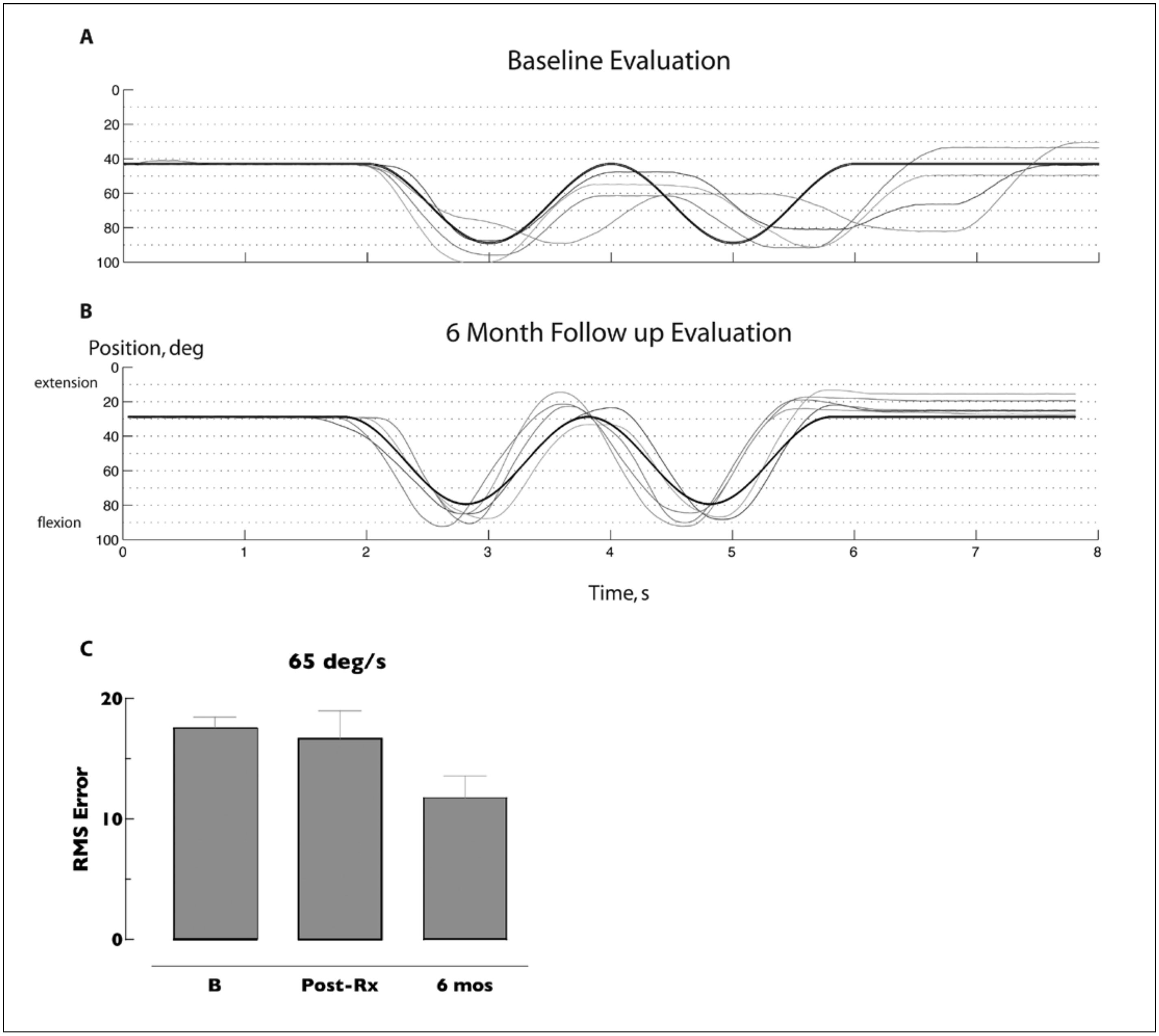

Figure 2. Trajectory-tracking task.

Criterion (heavy black line) and performed (light gray lines) trajectories as presented and recorded on screen for the 65 deg/s condition. The task involved two cycles of reciprocal elbow flexion and extension in the transverse plane starting from flexion. The subject was instructed to match the criterion as closely as possible and real time kinematic feedback was provided to aid performance. To dissociate the strength and dexterity/coordination components of movement, force requirements were minimal (1 ft-lb) and the task was presented at three criterion speeds: 25 deg/s, 45 deg/s and 65 deg/s. Root-mean-square error (RMSE) between criterion and performed trajectories was calculated as an indicator of outcome.

Panel A – At baseline, RMSE was large corresponding to poor temporal patterning with the criterion as can be especially noted in the second movement cycle. Individual trials are presented to enable visualization of similarities in impairment across repeated test trials.

Panel B – Reciprocal motor control is markedly improved at follow up evaluation as can be appreciated by smoothness and continuity of movements and similarity in the patterning of individual trials.

Panel C - RMSE is significantly reduced (35.8%, p = .09) at the six month follow up evaluation. Because the trajectory task was not practiced during intervention, this assessment serves as a surrogate measure of motor control. Each time point reports the mean and standard deviation of five test trials. Significant improvements on the trajectory-tracking task at the fastest test speed suggests: 1) that improved strength does not interfere with reciprocal motor control and 2) neural adaptations to dynamic resistance training may generalize to improved dexterity.

Table 4. Tests and Measures - Research Protocol. Panel A - Clinical Measures. Panel B - Specific Items Contributing to Clinical Change Scores

	Measures	Baseline	Postintervention	6 month follow-up
Body Structure and Function	UE Fugl Meyer (*max points- 66)*	41	53	65
	Ashworth Scale (*range - 0-5)*	2	2	2
	Barthel Index (*max points -100)*	45	60	90
	WMFT – FAS (range – 0-5)	1.87	3.13	4.13
	WMFT Median Time, s	68.75	2.91	2.78
Activities	FIM (*max points-91)*	45	67	85
Participation	**Stroke Impact Scale**			
	Social Role/Activities	8.33	50	75
	Stroke Recovery	50%	70%	80%
	Physical Domain, mn	38.7	41.9	54.8

Table 5. Torque - Velocity Area Under Curve (AUC) Scores by Joint Action

Action	Baseline	Postintervention	6 month follow-up
Elbow Flexion	604	1087	1995
Elbow Extension	417	895	1791
Shoulder Flexion	82	992	1481
Shoulder Abduction	72	515	862
Shoulder External Rotation	**	876	1096

Units are watts and indicate the capacity to produce dynamic torque in a moving joint.
**Subject was unable to produce dynamic torque in external rotation at baseline.

abduction. In shoulder external rotation, the patient was unable to produce dynamic torque. Motor coordination appears only mildly impaired during the first flexion-extension cycle of the trajectory-tracking task, but during the second cycle the subject was unable to match the criterion most likely due to impaired movement speed (Figure 2). The mean RMSE score was 18.31°.

INTERVENTIONS

We have developed 2 experimental protocols for upper-extremity rehabilitation in our laboratory: (1) a functional task practice approach and (2) a hybrid approach that combines functional task practice and dynamic high-intensity resistance training. The hybrid intervention was structured to capture the early, neural phase of strengthening which extends up to 4 - 6 weeks in nondisabled persons.[14] Both the functional and hybrid treatments are delivered 3 times weekly for 6 weeks. All sessions are 75:00 in length.

Functional Task Practice

(Figure 4). First, a progression of 6 therapeutic goals was established. One goal was addressed each week and the intervention progressed to the next weekly goal independent of whether mastery had been achieved on the current weekly goal. Next, 9 activity categories were identified. A variety of specific therapeutic activities were developed for each activity category and the therapeutic activities selected from these categories are practiced within the framework of the weekly therapeutic goal. Specific therapeutic activities are identified on the basis of the individual's level of function, his/her personal goals and needs (Figure 5). Within a session the practice time per activity category is held constant at 10:00 each.

Each session begins with a 10-15:00 period of stretching and passive range of motion delivered by the treating physical therapist. The active portion of each session involves practice of 6 activity categories for 10 minutes each. Each of the 9 activity categories is addressed twice per week and the therapeutic goal is progressed at beginning of each week or after every third session. This approach allows for structure and repeatability of the intervention, while affording freedom for the treating therapist to execute clinical judgment and tailor the therapy to the individual participant's functional level and goals.

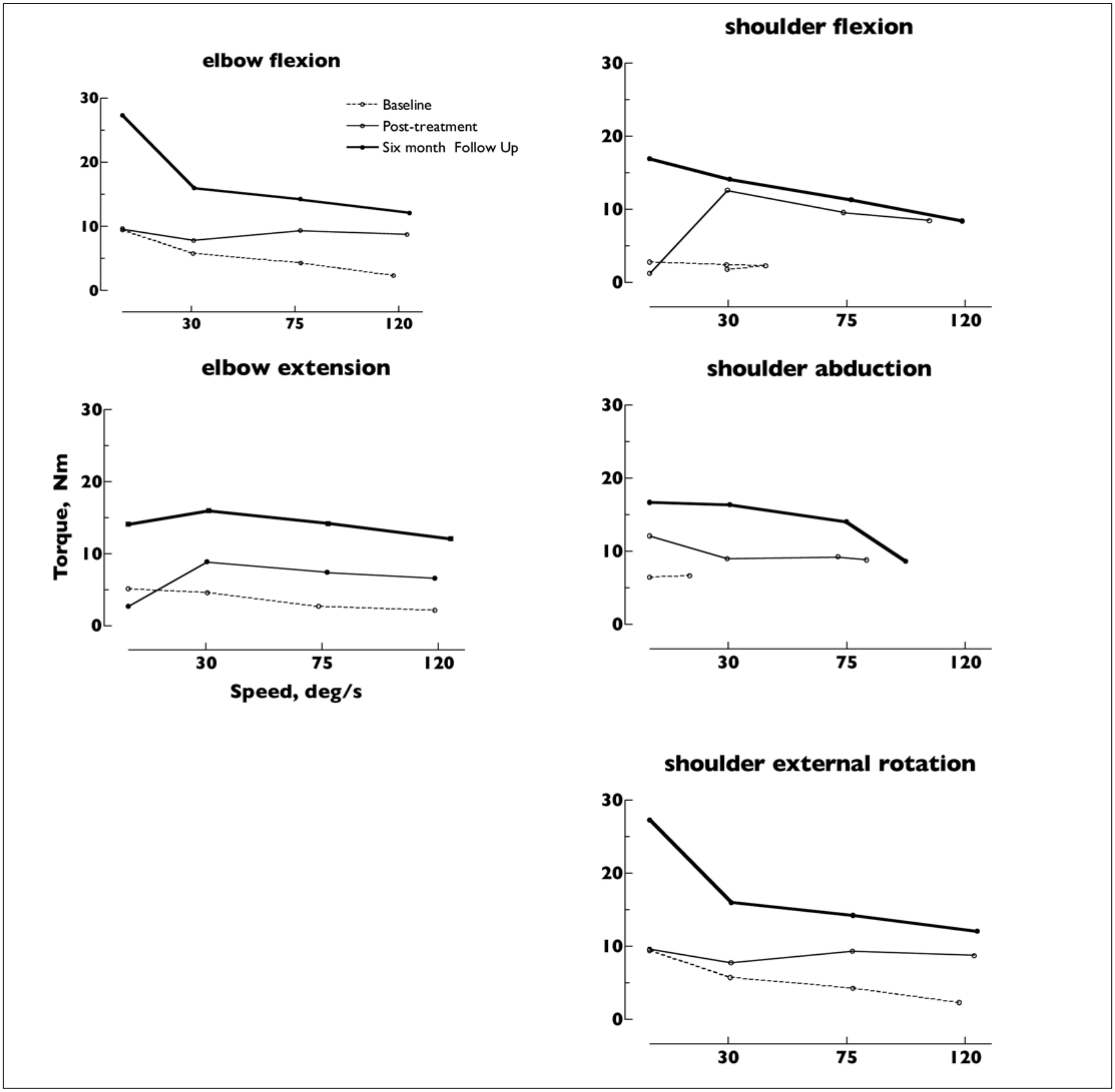

Figure 3. Area under the torque-velocity curve.
Force/torque were obtained at four criterion speeds: isometric, 30 degs/s, 75 deg/s and 120 deg/s. Dashed lines depict performance at baseline, thin solid lines performance post-treatment and heavy solid lines performance at the six month follow up.

The area under the curve (AUC) was calculated by summing the product of the actual torque produced and the mean velocity per interval. The Biodex dynamometer will allow free movement but limits angular velocity to the pre-set criterion. Analog position and torque signals were sampled directly from the dynamometer to determine the torque and actual velocity achieved over a fixed range of motion for each joint action. At baseline the subject was unable to achieve criterion velocity for many of the higher speed conditions; this was especially notable in shoulder flexion and abduction, both of which involve coordinated scapulo-humeral stabilization and movement against gravity. Over the course of the intervention and follow up, both torque and achieved velocity improved, expanding the functional envelope in which the subject can produce force. AUC, analogous to power -- the capacity to produce force during movement- increased remarkably in all five joint actions. These increases stemmed from both increased torque production and the capacity to move at increased speed. Increased power could represent the critical link between increased strength and improved function.

The therapist keeps a written log of the activities and their progression during each therapeutic session. This record facilitates continuity and consistency of therapy and provides clear information to motivate progression of the therapeutic program. For example, activities in the water task category are recorded with the amount of water in the container allowing a record of either the weight (resistance) used in performing the task, or the difficulty of and success at performing the task (ie, number of spills when pouring between narrow mouthed containers). These steps enable an explicit progression in the therapeutic activities and maintenance of a challenging therapeutic environment.

Hybrid Therapy

The hybrid therapy combines the functional task practice, described above, with dynamic high-intensity resistance training. The functional task practice component is structured using the same therapeutic goals described above that are progressed weekly as in the functional task practice approach. Each 75:00 treatment session is divided between functional task practice and dynamic high-intensity resistance training, which is delivered using an isokinetic dynamometer. As in the functional task practice therapy, each session begins with a period of stretching and passive range of motion delivered by the treating physical therapist that is followed by an abbreviated program of the functional task practice protocol. Based on the participant's abilities and goals, 5 of the 9 activity categories discussed above are selected and used in rotation. Within each treatment session, three activities are practiced for 8 minutes each (Figure 4).

The balance of treatment time in the hybrid protocol is spent performing resistance training of 4 reciprocal upper-extremity movements: shoulder ab/adduction, shoulder flexion/extension, shoulder external/internal rotation and transverse plane elbow flexion/extension. Custom attachments, illustrated in Figure 6, have been fabricated and are used to accommodate hemiparetic subjects' impaired grasp enabling them to engage the dynamometer and effectively perform the target upper-extremity actions. Each resistance training session involves three sets of 10 repetitions of each action. The first set is eccentric (ie, controlling an externally

Therapeutic Goals

1. Establish normal scapulo-thoracic/humeral rhythm and stability
2. **Incorporate movement against gravity**
3. Incorporate shoulder ER and stretch to long finger flexors
4. Incorporate bilateral hand movement
5. Weight bearing through UE in shoulder ER, wrist ext, finger ext. Also incorporate reaching and manipulation through hand-directed movements.
6. Incorporate controlled elbow movement

Activity Category	Example Therapeutic Activity: Low Level	Example Therapeutic Activity: High Level
1. Water Task	Sliding hand away from body to reach cup. Lifting empty cup one inch above surface of table, T8 height.	Placing full cups of water on shelf at eye level. Pouring full cups into empty cups at same level.
2. Catch/Release	Lifting ball from surface at T12 height, dropping into bucket at T8 height.	Catching velcro ball on velcro pad within arm's reach, shoulder height. Throw back 10 feet.
3. Drawing/Writing	Using marker to place dots in pre-drawn circles, horizontal surface, T8 height.	Writing block letters on vertical paper surface at eye level.
4. Tool Task	Standing at door and reaching to turn knob to open/close door.	Using screwdriver to place/remove screws at shoulder height.
5. Laundry/Dressing	Smoothing out a wrinkled towel on a horizontal surface at T6 height.	Placing articles of clothing on hangers, hanging them on a bar at eye level.
6. Sport	Tossing/hitting balloon back and forth with therapist.	Playing balloon badminton using racket to hit balloon over net.
7. Feeding	Gripping cup and lifting towards face to attempt to take a sip of water.	Carrying a tray of cups filled 3/4 with water using contralesional arm. Removing cups with opposite hand.
8. Board games/cards	Sliding cards along table at T6 height to place them in appropriate category according to the game rules.	Placing/retrieving Jenga™ pieces to avoid knocking tower of wooden blocks over.
9. Computer task	Playing computer tracking game ("Brickles Plus™") at lowest level of play, using adaptations for poor grip,	Playing computer tracking game ("Brickles Plus™") at a higher level of play, not allowing proximal arm to rest

Figure 4. Outline of the standard functional rehabilitation program. Six therapeutic goals were established patterned after Carr & Shepherd's Motor Re-Learning Approach[18]. Treatment was advanced to the next goal each week. Nine activity categories were identified with a range of specific activities that could be performed in each category depending on the therapeutic objective, the individual's functional level and personal goals. The right hand columns provide examples of specific activities for each category corresponding to a higher and lower functioning individual.

In the functional task practice treatment, all nine categories were used in rotation with six categories practiced for 10:00 each per session. In the experimental, hybrid treatment as delivered in this case study, the subject and therapist chose five activity categories relevant to the patient's goals. Three categories were addressed in each session for 8:00 each and the categories were rotated throughout the sessions.

imposed load) and the second 2 sets are concentric, delivered at different criterion speeds. The dynamometer is operated in isokinetic mode and over the course of treatment speeds are advanced in 30°/s increments over the range of 30-120°/s in concentric mode and in 15°/s increments over the range of 30-75°/s in eccentric mode (Table 7). [Biodex .]

Intervention Dose – Research Protocol

The subject received 18 sessions of the hybrid therapy, described above, thus her treatments consisted of 35 minutes of dynamic resistance training and 40 minutes of functional task practice. The order of therapeutic activities (functional task practice vs. resistance training) alternated each session so as to avoid inducing an order effect. Based on the subject's relatively low functional status and her broad goal of restoring hand function to participate in her role as attorney and homemaker, the following 5 activity categories (Figure 4) were selected and used in rotation: water task, catch/release, drawing/writing, tool task, and laundry/dressing.

Outcomes – Completion of Research Protocol

Following the 6-week hybrid intervention, the subject demonstrated distinct improvements in all measures at the ICF *body structure/function* level. Improvements in the upper-extremity Fugl-Meyer were revealed in the abilities to combine movements in synergy and move independently of synergy as well as to successfully complete motions in the flexor synergy (eg, shoulder abduction, shoulder external rotation, elbow flexion) (Table 8). Scores on the Ashworth scale were unchanged revealing no exacerbation of spasticity. At the ICF *activities* level, performance on the Wolf Motor Function Test revealed dramatic improvements in both the median time to perform upper-extremity tasks (2.91s vs 68.75s at baseline) and the quality of movement as characterized by the Functional Ability Scale (FAS) (3.13/5 vs. 1.87/5 at baseline). At baseline the subject was unable to perform 4 tasks: forearm to box, hand to box, stacking checkers, and turning a key in a lock. Following the hybrid intervention she was able to perform these tasks, although her execution remained slow and labored.[Wolf Motor Function Test .] FIM scores revealed that the subject had improved by at least one functional level in 6 of 7 domains. Importantly, she had achieved independence in 2 critical areas: grooming and toileting. At the *participation* level, dramatic improvements were also noted as the SIS revealed marked improvements in both social role/activities (50 vs. 8.33 at baseline) and stroke recovery (70% vs. 50% at baseline). Despite marked improvements in *body/structure function* noted above, the subject perceived only modest improvement in the SIS physical domain.

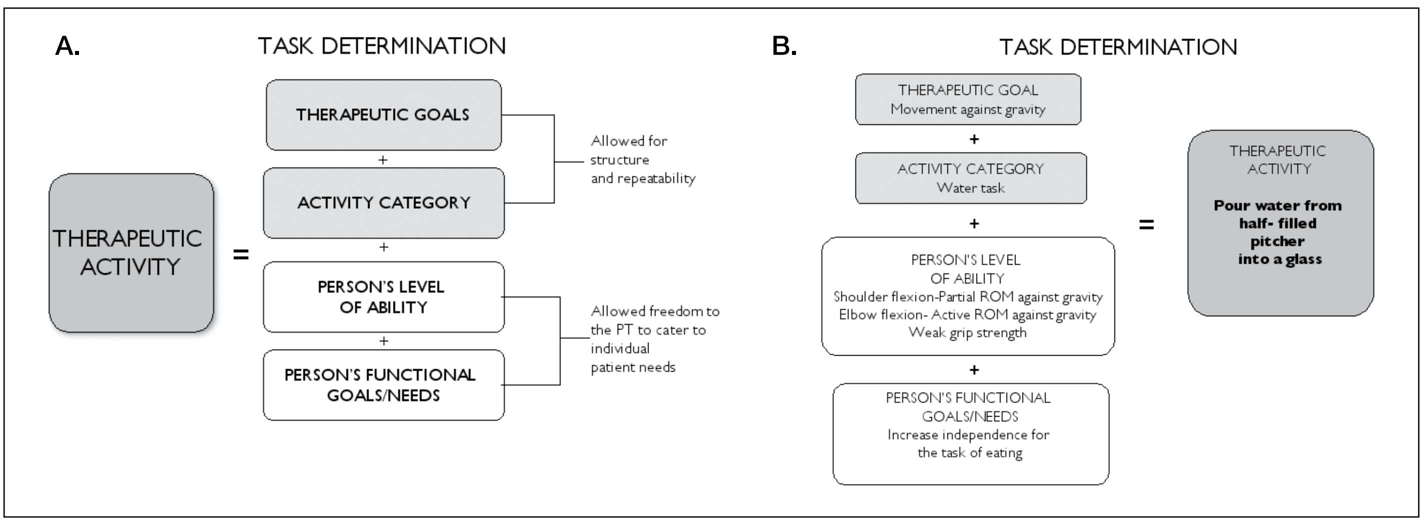

Figure 5. Task determination process
A critical project need was to develop a treatment approach that would allow delivery of a consistent therapeutic program across a three year clinical trial. By nature, treatment activities must allow flexibility to accommodate individual differences and to enable ongoing challenge for the subject. The process of task determination is typically left to the individual practitioner's clinical judgment but obviates consistency and reproducibility of treatment.

Panel A – Within each activity category, specific therapeutic tasks were delivered using the structure presented. Weekly therapeutic goals combined with identified activity categories afforded structure and repeatability of the therapeutic intervention. The individual subject's functional level and goals/needs were incorporated by the therapist to identify the actual activities practiced and the context of task practice.

Panel B – A specific example from the subject presented in this case study. Impairments of full active range of motion at the shoulder and elbow flexion and weak grip strength compromised movement against gravity such as retrieving a pitcher of water and filling a glass. For the Week 2 goal of movement against gravity and the water task activity category, the specific activity was identified to practice pouring water from a half-filled pitcher. The amount of water (resistance), work surface and work height/body position could be controlled and recorded as could key elements of task performance including the number and aperture of the containers being filled, the number of errors (spills), and speed of movement.

Table 6. Isometric Maximal Voluntary Force

Isometric Maximal Voluntary Force			
Action	**Baseline**	**Postintervention**	**6 month follow-up**
Elbow Flexion	9.45	9.67	27.29
Elbow Extension	5.14	5.46	14.13
Shoulder Flexion	2.82	0.64*	16.93
Shoulder Abduction	6.49	12.15	16.72
Shoulder External Rotation	2.87	4.28	13.25
MVC force is in units of newton-meters (Nm) *Subject demonstrated continued difficulty performing shoulder flexion against gravity post-treatment. Data were verified.			

Table 7. Progression of Dynamometer Modes and Speeds Across the Experimental Intervention

Isokinetic Dynamometer Speeds, deg/s			
Week	Set One Eccentric	Set Two Concentric	Set Three Concentric
1	30	30	60
2	30	30	60
3	45	60	90
4	45	60	90
5	60	90	120
6	75	90	120

Performance-based assessments revealed modest improvements in isometric MVC (range: 2.3% - 46.6%), and conspicuous gains in the torque-velocity AUC (range: 44.5% for elbow flexion to >100% for shoulder external rotation) reflecting gains in the capacity for dynamic force production in all upper-quarter actions (Figure 3). As indicated by the slope of the EMG-MVC relationship, these gains in isometric and dynamic strength were accompanied by improved motor activation in elbow flexion, elbow extension, and shoulder flexion (Figure 1).

Outcomes at Six-Month Follow Up

The subject returned for follow up studies following 6 months with no additional intervention. Evaluations at this time revealed both: retention of treatment effects described above, and additional improvements in upper-extremity function across all levels of the ICF. At the *body/structure function* level the upper-extremity Fugl-Meyer scores were advanced by additional improvements in the ability to move independently of and combine synergies. Again, no changes were noted in the Ashworth Score indicating no significant exacerbation of spasticity. At the *activities* level, Wolf Motor Function Test scores revealed improvements in the time to perform all seventeen timed tasks (median time 2.78s vs. 2.91s

Figure 6. Custom fabricated attachments.
Custom-fabricated attachments that interfaced with the Biodex dynamometer were designed to accommodate impaired grasp associated with hemiplegia. These attachments were used for all subjects for both assessment and treatment. Panel A illustrates the configuration for shoulder abduction which included: a trough that supported the upper-extremity in full extension, a spring loaded arm that mechanically adjusted limb length thus accommodating impaired scapulo-humeral rhythm and counterweights to negate the gravitational load. Panel B illustrates the configuration for shoulder flexion which used the same hardware and adjustments as for abduction with the addition of with addition of a wedge spacer that abducted the limb to provide clearance of the instrument against the torso. Panel C illustrates the configuration for elbow flexion/extension. An armrest pad supports the weight of the humerus while a prefabricated splint was used to position the forearm. This configuration allowed isolated flexion and extension in the transverse plane.

Table 8. Relevant items that contributed to change scores.

UE FUGL MEYER

Items *(possible score)*	Baseline	Post intervention	**6 month follow-up**
Flexor synergy (12)	8	12	12
Extensor synergy (6)	6	6	6
Movt. combining synergy (6)	2	5	6
Movt. Out of synergy (6)	0	2	6

FIM

Items (*possible score*)	**Baseline†**	**Post intervention**	**6 month follow-up**
Eating (7)	min A	min A	I
Grooming (7)	mod A	I	I
Bathing (7)	Max A	Mod A	Min A
Dressing upper body (7)	Total A	Mod A	I
Dressing lower body (7)	Max A	Mod A	I
Toileting (7)	Max A	I	I

WOLF MOTOR FUNCTION TEST

Items	**Baseline**		**Post intervention**		**6 month follow-up**	
	Time	**FAS**	**Time**	**FAS**	**Time**	**FAS**
Forearm to table	10.78	3	1.28	4	1.75	4
Forearm to box	NP	1	2.41	3	2.09	4
Extend elbow	6.47	3	1.88	3	2.75	4
Hand to box	NP	1	2.34	3	1.37	4
Lift can	17.04	2	3.69	3	4.63	4
Stack checkers	NP	1	10.57	3	8.22	4
Turn key in lock	NP	1	9.25	3	6.78	4
Fold towel	47.22	2	14.59	3	7.65	5

NP= unable to perform

SIS

Domains (adjusted score)	**Baseline**	**Post intervention**	**6 month follow-up**
Physical Strength	43.75	62.5	68.75
Memory & Thinking	81.25	71.88	100
Mood	75	94.44	69.44
Communication	71.43	92.86	89.29
ADL	47.92	68.75	89.58
Mobility (home/community)	82.5	75	90
Hand Function	40	70	95
Social Role/Activities	8.33	50	75

† Discrepancies were noted between FIM scores at discharge from acute rehabilitation and enrollment in the research protocol such that the subject appeared to have regressed to lower functional levels. She was challenged with anxiety and her family was eager to be supportive but in the process may have tended to over-assist. It is also noteworthy that in the research protocol FIM scores were obtained using a questionnaire form, the FONE FIM[48], rather than a performance based assessment.

post-treatment) and refinements in the execution of movement as indicated by the FAS (mean 4.13 vs. 3.13 post-treatment). [Six Month Follow Up .] On the FIM, the subject demonstrated improvements in 5 of 7 domains and now required assistance for only bathing. SIS scores reflecting *participation* revealed further improvements in the social role/activities domain (75 vs. 50 post-treatment), perception of her overall stroke recovery (80% vs. 70% post-treatment) and physical performance (54.8 vs. 41.9 post-treatment). The subject had returned to work as an attorney, part-time and reported complaints of only mild fatigue (ie, perception of being more tired at the end of a work day) and compromised handwriting. [Free Reaching .]

Performance-based assessments revealed further advancements in physiologic motor recovery as demonstrated by marked improvements in isometric MVC (range 37.4% - >100%) and torque-velocity AUC (range 20.1% - 50.1%). On examination the EMG-MVC relationships revealed a consistent pattern of increased motor activation in elbow extension and shoulder flexion. For elbow flexion, shoulder abduction and shoulder external rotation the EMG-MVC relationships suggest contributions of both neural activation and muscle hypertrophy. A 29.43% decrease in RMSE revealed marked improvement in coordination of elbow trajectory-tracking (Figure 2c).

DISCUSSION

Observations made in this case study confirm our anticipated outcome, that upper-extremity rehabilitation involving dynamic, high-intensity resistance training promoted marked improvements in upper-extremity motor function across all domains of the ICF: body structure/function, activities, and participation without deleterious consequences including joint pain or exacerbation of spasticity. To our knowledge, this is the first report of the outcomes of dynamic isolated upper-extremity joint resistance training for persons with post-stroke hemiparesis. Improvements in strength and function were observed following 6 weeks of intervention in the subacute phase of stroke recovery and, importantly, were not only retained, but advanced following 6 months of no additional intervention. Improvements were noted not only in isometric and dynamic aspects of strength, but in meaningful functional recovery such that the subject regained her premorbid level of participation and resumed her usual social roles. She now experiences only minimal compromise of upper-extremity motor function.

Hemiparetic Weakness and Strengthening in Persons with Post-stroke Hemiparesis

There is growing evidence that weakness is the dominant impairment following stroke[4] and the recent literature has called for more research to better understand hemiparetic weakness and its role in movement dysfunction.[4,29] Traditionally, high exertion activities were considered inappropriate for persons with post-stroke hemiparesis because excessive effort was thought to exacerbate spasticity. This tenet was advanced by Bobath[7] and remains a central theme of the neurodevelopmental treatment approach.[30] However, this percept has been increasingly challenged in the contemporary research literature.[31-33]

Neural vs. Hypertrophic Aspects of Strength. Muscular force is a product of both muscular factors, muscle cross-sectional area and fibre composition, and neural factors, the extent to which muscle is activated by the nervous system.[14] Related to these factors, in nondisabled populations the early, neural, phase of strengthening occurs over the first 4 to 8 weeks and is characterized by: rapid gains in strength; negligible changes in muscle cross sectional area; cross-transfer effects to an untrained homologous limb; and increased agonist muscle activation. These early adaptations can account for strength gains on the order of 30%, or more, if the training load or level of neural drive are of sufficient magnitude.[34] The later, or hypertrophic, phase of strengthening occurs after 4 to 6 weeks[14] and is characterized by increases in muscle cross-sectional area.

Weakness in Neurological Populations. It can be expected that weakness in persons with central nervous system injury results primarily from neural effects. However, until now little research investigated neural and muscular adaptations to strength training in neurologic clinical populations. Weakness following stroke results initially from impairment in neural activation,[35,36] while atrophy—if present—may occur as a secondary effect of chronic inactivity.[37] Accordingly, effective interventions, including resistance training, should be tailored to promote improved motor activation.[36]

This case study is the first to document improved motor activation (EMG) in response to upper-extremity rehabilitation. Longitudinal EMG comparisons can be problematic, especially in subjects demonstrating impaired motor activation. Target EMG during submaximal motor tasks is typically expressed as a ratio of EMG at maximal voluntary force and longitudinal comparisons are made using this normalized EMG ratio. However, when testing for changes in activation, increased EMG at MVC would yield a larger denominator for normalization and produce a lower normalized EMG ratio post-training. To avoid this paradox we evaluated maximal EMG as a function of isometric MVC force. Changes in the slope of the EMG-MVC force relationship over time can then be attributed to neural and muscular contributions to force output following resistance training.[14] The majority of our observed intervention-related effects are consistent with increased motor activation (ie, increased slope or same slope with extension of both EMG and MVC). At the post-treatment evaluation 3 of 5 joint actions demonstrated both an increase in the EMG-MVC force slope and an extension in the EMG magnitude. Indeed, even at the 6-month follow-up study, elbow extension and shoulder flexion demonstrated additional marked increases in EMG activation per unit MVC force. These increases are relevant as elbow extension (triceps) is notoriously weak in hemiparetic persons and shoulder flexion involved the challenge of combined: trunk stabilization, scapular stabilization, and movement against gravity including manipulation of the dynamometer apparatus. Both of these actions were profoundly weak at baseline and remarkable improvements in force production were demonstrated that can be attributed primarily to improved motor activation. Increased EMG amplitude observed in cross-sectional evaluation of isometric MVC in hemiparetic persons was reported in one study and interpreted as an over-reliance on motor unit recruitment.[38] However, we interpret longitudinal increases in EMG as a positive outcome indicating that central motor drive is increased in response to intervention and contributes to increased force production.

That 2 joint actions demonstrated apparent hypertrophic effects over the 6-month follow-up period should not be surprising. Indeed, if the hybrid intervention promoted improved activation of the upper-extremity musculature, the subject would have the capacity for increased limb use over this 6-month time frame and would ostensibly be performing more challenging tasks. Adaptation at the muscle level could then be induced by both repeated use and use at greater loads. Adaptations observed in the EMG-MVC force relationships for elbow flexion, shoulder abduction, and shoulder external rotation between the post-treatment and 6-month follow-up evaluations are consistent with this premise.

Intensity of Neurorehabilitation

Recent investigations argue that increased intensity of neurorehabilitation is associated with improved functional outcome.[3,39] However, the definition of intensity as it relates to rehabilitation continues to be debated. The hybrid intervention delivered in this case study addressed 2 important facets of therapeutic intensity: (1) activities that specifically challenged the subject's functional capacity and (2) increased direct participation in therapeutic activities. The subject had already completed an intense comprehensive rehabilitation admission which included functional and task specific treatment approaches as well as resistance training for stabilization and motion. Indeed, she demonstrated measurable functional recovery during her acute rehabilitation. Our experimental intervention was successful in promoting additional recovery at the behavioral and functional levels, these behavioral improvements were accompanied by increased motor activation and these increases in motor activation generalized to improved control and coordination of movement (ie, trajectory-tracking) not simply force and strength tasks. These positive outcomes of the experimental intervention can most likely be attributed to the therapeutic intensity afforded by the specific activities (ie, resistance training, isolated joint exercises allowing stabilization and focused activation of target muscles, dynamic training challenging the subject's capacity).

Is there a link between strength and function?

While strength is typically assessed clinically using isometric manual muscle tests or hand-held dynamometry,[40] recent investigations conducted in our laboratory have revealed that hemiparetic strength impairment is exaggerated with increasing movement speed.[41,42] This exaggerated dynamic strength impairment is strongly associated with impaired EMG activation rather than co-contraction of antagonist muscles[43] and also suggests that hemiparetic weakness has been underappreciated. Rather than focusing on isometric strength impairments or improvements in a particular joint action or speed, the area under the torque-velocity curve (AUC) characterizes the functional envelope within which the subject can produce useful force and quantifies the capacity to produce torque during movement. As illustrated in Figure 3, increases in the AUC were remarkable for all joint actions and, we believe, represent a key link between improved strength and improved movement function. Despite recognition of the correlation between weakness and impaired movement function,[11] a clear relationship between improved strength and improved movement function has been elusive. Indeed, current sentiments in neurorehabilitation practice favor "strengthening in function" rather than performing systematic resistance training with isolated exercises.[44, 45] Our observations from this single case study indicate that strengthening, both isometrically and dynamically, with the goal of maximizing the capacity for muscle activation is successful in promoting improved upper-extremity function. This result most likely stems from the dynamic nature of the resistance training that challenged the subject both to move at higher speeds and provided repetitive practice at producing greater force and motor activation dynamically.

Is more therapy better?

An additional explanation for the results of this case study might simply be that more therapy promotes greater recovery of function.[46] Among issues currently being investigated in neuro-rehabilitation are not only the dose, but the optimal timing and duration of intervention.[47] Current practice in the United States allocates the majority of rehabilitation resources proximate to the acute event with the rationale that early intervention is most likely to promote recovery of function.[48] The subject discussed in this study presents an interesting case for consideration of this rationale.

By any standards in North America, the subject discussed in this case had already received a generous dose of acute rehabilitation. However, at the baseline evaluation of the research protocol she demonstrated profound weakness and functional compromise. It can be argued that the acute rehabilitation effort may have laid groundwork that prepared her to benefit from the intense experimental intervention. While the trajectory of spontaneous recovery following stroke remains to be fully elucidated, it must be considered her enrollment in the research protocol at 16 weeks post-CVA may have coincided with an optimal region of this trajectory. Without strong evidence to substantiate clinical practice, it is the case that the current constraints of cost containment in medicine foster an attitude that achievement of minimal functional improvement is 'good enough' for discharge. In contrast, the scientific evidence documenting neural plasticity has yet to clarify the full extent of neural and behavioral recovery possible following adult stroke. Traditional models of rehabilitation fail to approach the requisite dose to promote meaningful recovery of motor function. In this regard, 6 additional weeks (27 hours) of highly structured and intense intervention, and the increased spontaneous activity that resulted from this intervention, might represent a critical volume of therapeutic intervention necessary to induce long lasting effects.

Relevance to Current Clinical Practice

Primary findings from this case study are: first, that high-exertion activity did not produce deleterious consequences, either joint injury or exacerbation of spasticity, and second, that inclusion of dynamic high-intensity resistance training promoted meaningful, functional upper-extremity recovery in this subject with adult hemiparesis. Success resulting from the hybrid intervention presented here might be attributed to multiple facets of the resistance training intervention: a substantial increase in therapeutic intensity; isolated joint exercises promoting trunk and synergist stabilization to enable focused activation of target muscles; and dynamic training challenging the subject's capacity. The dynamometer affords control over many of these relevant training parameters and these were used to full advantage in the current study. While isokinetic dynamometers may not be universally available in the neurorehabilitation setting, it is possible to provide challenging resistance training incorporating dynamic contractions, high intensity and functionally relevant movements with tools traditionally available in the clinical setting. Moreover, there are many forms of resistance training: PREs, isotonic, isometric, manual resisted, isokinetic, and each form addresses different neuromechanical aspects of strength. It remains to be determined in future work which neuromechanical aspects of resistance training are most critical.

FUTURE WORK

A great deal of investigation remains to be conducted to fully understand the effects of intensity, duration, timing of neurorehabilitation, and the specific therapeutic activities required to promote optimal recovery of function. Beyond the clinical, behavioral, and strength measures reported here, kinematic analysis of key motor actions will afford greater insight regarding the specific motor control strategies developed over the course of the dynamic high-intensity resistance training intervention. Finally, it is important to acknowledge that the experimental intervention discussed in this case study involved a hybrid of functional task practice and dynamic high intensity resistance training. The outcomes might differ were task practice and resistance training delivered separately and this remains a question for future investigation.

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Erratum

In the Volume 30 Number 2 issue of the *Journal of Neurologic Physical Therapy*, Figures 1, 2, and 3 on pages 70 and 71 were printed without the clarity needed to see the white and/or grey bar graph(s). You may view and download the correct figures from the Neurology Section website at neuropt.org. We apologize for the inconvenience this error may have caused.