

Sensorimotor Training and Neural Reorganization After Stroke: A Case Series

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Background and Purpose: Impaired hand function decreases quality of life after stroke. The purpose of this study was to pilot a novel 2-week upper extremity sensorimotor training program. This case series describes the training program and highlights outcome measures used for documenting behavioral change and neural reorganization.

Case Description: Behavioral/performance changes were identified via sensorimotor evaluation. Activity-induced neural reorganization was examined using sensory functional magnetic resonance imaging, diffusion tensor tractography, and brain volume measurement. Participant 1 was a 75-year-old right-handed man 1 year post-right hemisphere stroke, with severe sensory impairment across domains in his left hand; he reported limited left-hand/arm use. Participant 2 was a 63-year-old right-handed woman who had experienced a left hemisphere stroke 9 months earlier, resulting in mild sensory impairment across domains in her right hand, as well as mild motor deficit.

Intervention: Participants were trained 4 hours per day, 5 days per week for 2 weeks. Training tasks required sensory discrimination of temperature, weights, textures, shapes, and objects in the context of active exploration with the involved hand. Random multimodal feedback was used.

Outcomes: Both participants had improved scores on the Wolf Motor Function Test after training. Participant 1 had no measurable change in sensory function, while participant 2 improved in touch perception, proprioception, and haptic performance. Sensory functional magnetic resonance imaging suggested neural reorganization in both participants; participant 1 had a small increase in brain volume, while superior thalamic radiation white matter connectivity was unchanged in either participant.

Discussion: Participating in sensorimotor training focused on sensory discrimination during manual manipulation was feasible for

both participants. Future research to determine efficacy and identify optimal measures of sensory function and neural reorganization is recommended.

Video Abstract available (see Video, Supplemental Digital Content 1, <http://links.lww.com/JNPT/A38>) for more insights from the authors.

Key words: *diffusion imaging, fMRI, motor function, neural reorganization, sensory discrimination, sensory function, sensorimotor training, stroke*

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INTRODUCTION

Stroke survivors consistently express dissatisfaction with upper extremity recovery. Even when persisting impairments are mild, these impairments negatively influence health-related quality of life.¹ Up to 89% of people with hemiparesis demonstrate upper extremity sensory deficits when tested across domains of touch, temperature, weight, roughness, texture, and/or shape discrimination.² Despite evidence that sensory dysfunction predicts the magnitude of recovery from movement-focused training protocols³ and is unchanged by those protocols,⁴ stroke rehabilitation protocols continue to focus on motor impairment, ignoring the contributions of concomitant sensory deficits.² A 2010 review of poststroke sensory rehabilitation identifies a need for well-designed studies of sensory rehabilitation.⁵ Sensory training paradigms have commonly focused only on sensation, without attention to motor recovery⁶⁻⁸; however, there is intriguing evidence to suggest that training, using tasks that require active hand exploration and sensory discrimination, facilitates both sensory and motor recovery.⁹⁻¹¹

Neural reorganization associated with motor recovery has been well documented. Functional magnetic resonance imaging (fMRI) has been used to study natural recovery from stroke and training-induced changes.¹²⁻¹⁷ Decreases in task-related brain activation in primary and nonprimary motor regions¹⁵ and a reduction in contralesional activity with a concurrent increase in ipsilesional activity are associated with better recovery.¹⁸ More complete motor recovery has also been associated with a more typical ipsilesional activation pattern, involving fewer brain regions than less complete recovery.^{13,14} Interestingly, an increase in activation volume in secondary somatosensory area in the stroke hemisphere correlated with

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better Fugl-Meyer scores at 3 months poststroke,¹⁹ reinforcing the relevance of sensory processing to motor control.

Few studies document neural reorganization associated with recovery of sensory function after stroke. A serial fMRI case study reported a reemergence of activation in the ipsilesional primary and bilateral secondary somatosensory cortices.¹⁸ A study of thalamic stroke identified that recovery of touch perception during bilateral stimulation was associated with increased activation in the primary somatosensory cortex of the ipsilesional hemisphere.²⁰ Proprioceptive training in persons with acute stroke results in ventral premotor and parietal cortex activation changes in the contralesional hemisphere during sensorimotor fMRI; unfortunately, sensory function was not measured.²¹ Limited knowledge of the neural reorganization that accompanies sensory recovery after stroke points to the need for research in this area.

Structural connectivity refers to the physical link between brain regions created by axons, dendrites, and synapses.²² After stroke, a loss of connectivity may occur as a result of direct damage to the axons or through degeneration of axons proximal or distal to the lesion. Diffusion tensor tractography (DTT) is a method of modeling white matter connections in the human brain *in vivo*. Diffusion tensor tractography has been used primarily in cross-sectional studies to explore the relationship between infarct location and sensorimotor pathways²³ and to quantify damage to the corticospinal tract.²⁴ Several studies confirm a strong correlation between structural integrity of the corticospinal tract and poststroke motor function²⁴⁻²⁸; however, there is little direct evidence of white matter remodeling after stroke.²⁹ The sensory component of the superior thalamic radiation (sSTR) includes afferent connections to the somatosensory cortex and thus is the functional analogue of the corticospinal tract.³⁰ Stroke-related structural changes to the sSTR have relevance to sensory function in chronic left hemisphere stroke³¹; however, it is unclear whether DTT measures of the sSTR will be sensitive to reorganization due to training.

The purpose of this study was to pilot a novel 2-week upper extremity sensorimotor training program for individuals with stroke. The training was specifically designed to require high-level sensory processing across multiple sensory domains in tasks that involved manual manipulation of objects. We hypothesized that the training would result in improved upper extremity motor and sensory function that would be accompanied by functional and structural neural reorganization. Two participants are described, who highlight the outcome measures used for documenting behavioral change and neural reorganization.

METHODS

During this study, 6 individuals with chronic stroke completed a 2-week upper extremity sensorimotor training program. Inclusion criteria were (1) one clinical stroke diagnosed earlier than 6 months, (2) age 21 to 85 years, (3) contralesional hand function sufficient to grasp and release a small cylinder (such as a 6-oz frozen juice can) 75 times or more in 1 hour. Exclusion criteria were (1) Mini-Mental State Examination score of 24 or less, (2) other medical condition that would impair sensation in the upper extremity, and (3) significant aphasia or neglect. We used convenience sampling. Our

goal was to enroll participants with poststroke sensory impairment. Given the absence of a brief, valid, screening tool for higher-level sensory impairment and the frequency of poststroke sensory dysfunction, no inclusion criteria for sensory impairment were used. Participants provided written informed consent, approved by The Ohio State University's institutional biomedical review board. A comprehensive sensorimotor evaluation and functional and structural magnetic resonance imaging (MRI) were completed during the week before and after training. The sensorimotor tests and measures are described in Table 1. Behavioral outcomes for each participant are given in Table 2. Measures that most clearly present participant function are discussed in the narrative case descriptions. Sensory fMRI, DTT, and brain volume measurement were examined for evidence of neural reorganization. Two participants whose outcome measures demonstrate the broad range of sensory function and recovery in our sample are described.

IMAGING METHODS

A 3-T magnetic resonance scanner (Philips Achieva; Best, the Netherlands) with volume transmit and 8-channel receiver coil was used to collect structural and functional MRI scans. T1-weighted magnetization-prepared rapid field echo anatomical images of the entire brain were acquired for spatial normalization to a standard atlas. Blood oxygen level-dependent T2*-weighted functional MRIs in the transverse plane (Repetition time/Echo time [TR/TE] = 3000/35 ms, flip angle = 90°, field of view = 23 cm × 23 cm, matrix = 80 × 80 interpolated to 128 × 128) were obtained using gradient echo-echo planar imaging with parallel imaging and a sensitivity encoding (SENSE) reduction factor of 2. Diffusion tensor images were acquired using single-shot echo-planar imaging spin-echo sequence (flip angle = 90°, TR/TE = 9750/92 ms). The acquisition matrix was 128 × 128, with a field of view of 256 mm × 256 mm, which resulted in a 2.0-mm isotropic in-plane resolution. The slice orientation was axial with 2.0-mm thickness without gap. Diffusion-weighting gradient was applied along 32 independent axes with *b*-factor of 1000 s/mm², with a minimally weighted image (*b* factor of 0 s/mm²). SENSE reduction factor of 2.2 was used to reduce geometric distortion caused by Echo planar imaging-based sequence and susceptibility-related artifacts. Total scan time was 6 minutes. Following acquisition, the raw diffusion-weighted images were corrected for potential subject motion and eddy current, using affine transformation of the automated image registration. The elements of the diffusion tensor were calculated voxel-wise across the whole brain. Three eigenvalues and corresponding eigenvectors were calculated. The eigenvector associated with the largest eigenvalue was considered as the principal fiber orientation. Diffusion tensor imaging (DTI) metrics were derived using DTI Studio.⁵⁰ Fractional anisotropy (FA) index, the most commonly used anisotropy measure, is the fraction of the tensor that can be assigned to anisotropic diffusion. Fiber density (FD) is a quantitative description of the white matter fiber integrity expressed as the mean number of "fibers" per voxel in the bundle.⁵¹ Fiber density, like other measures of diffusion data, is based on average water diffusion within a voxel, and a direct relationship to axonal density cannot be assumed.

Table 1. Description of Sensorimotor Tests and Measures

Measurement Tool	Dependent Variable	Description	Directions	Reliability/Validity
Weinstein Enhanced Sensory Test ³²	Touch threshold	Monofilament esthesiometer applied to the tip of index finger. Ladder method used to identify threshold ³²	Indicate when you feel a touch	Interrater reliability for monofilaments (healthy controls) ³³ ICC = 0.965
Wrist Position Sense Test ³⁴	Wrist proprioception	Wrist is flexed/extended passively to a predetermined angle, average error in estimate across 20 trials recorded ³⁴	Align the arrow with your wrist position (protractor visible only to the tester)	Test-retest reliability (persons with stroke) $r = 0.92$ session 1-2, $r = 0.88$ session 2-3, Valid poststroke ³⁴
Hand Active Sensation Test ³⁵ (see video abstract in Supplemental Digital Content)	Weight and texture discrimination	18-item match-to-sample forced choice task without visual assistance	Which of the three is an exact match to the test object?	Test-retest reliability ICC = 0.77. Valid poststroke ³⁵
Haptic Object Recognition Test ^{36,37}	Haptic performance	17 novel objects constructed from Lego™ are matched to 1 of 5 sample objects using manual exploration	With your hand in the bag, select 1 test object, find its match from the 5 displayed. No visual verification was permitted	SEM = 1.3-1.8 (errors), sensitive to training effect in healthy older adults ³⁶ (n = 22)
Nine Hole Peg Test ³⁸	Fine motor performance	Square board has 9 holes evenly spaced and 0.64 cm × 3.2 cm pegs. The average time to place a peg was calculated	Use one hand to place all the pegs in the hole and remove them one at a time as quickly as possible	Test-retest reliability (persons with stroke) ³⁹ $r = 0.83-0.99$
Box and Blocks Test ⁴⁰	Upper extremity functional performance	A timed test of grasp and release of 2.54-cm square blocks over a 14.3-cm barricade. Blocks/60 s was recorded ⁴¹	Move as many blocks as possible to the other side one at a time	Test-retest reliability ⁴² ICC = 0.89-0.97
Wolf Motor Function Test	Upper extremity motor function	15 timed and 2 strength items. A maximum of 120 seconds is allotted per task	Specific instructions of each task are read twice, no practice is allowed. First attempt is timed	Interrater reliability = 0.97-0.99. ⁴³ Test-retest reliability for performance time (chronic stroke) ⁴⁴ $r = 0.90$
Motor Activity Log	Subjective report of upper extremity function	28 activities of daily living scored on a 0-5 scale for AOU and QOM	Use the rating scale to describe how much (or how well) you use your weaker arm while you are doing the specific activities.	Test-retest reliability (subacute stroke) ⁴⁵ QOM:ICC = 0.82, AOU:ICC = 0.79

Abbreviations: AOU, amount of use; ICC, intraclass correlation coefficient; QOM, quality of movement.

^aSubjects were measured at baseline and after completion of training, and intertesting interval was 3 weeks.

Table 2. Behavioral Outcomes^a

Measure	Normal/Impaired Criteria	Participant 1		Participant 2	
		Pretest	Posttest	Pretest	Posttest
WEST, index, in g	Normal threshold for the index and pinky fingers for men/women older than 55 is 0.385/0.15 g ⁴⁶	220 (0.07)	220 (0.07)	0.2 (0.07)	0.07 (0.07)
WPST, °	Criterion of impairment, $\geq 11^\circ$ average error	140.6	17.9	13.5	9
HASTe, matches/18	Criterion of impairment, ³⁵ $< 13/18$	8 (7)	7 (9)	14 (15)	13 (16)
HORT, errors/17	Mean errors for healthy older adults, ³⁶ 2.71 ± 1.45	13	13	7	1
MAL, how much, 0-5 scale	Proposed MCID ⁴⁷ is 10%	1.2	1.6	3.6	4.7
MAL, how well, 0-5 scale		1.2	1.8	3.4	4.7
WMFT, mean in s	MCID (for acute stroke) – 19 s (or – 1.3-s change in mean) ⁴⁸	7.88	5.93	3.57	2.11
NHP, s/peg	Normal range for men/women (60-75 + y) is 2.25–2.9/2.04–2.73 s/peg. MCID for the more/less affected hand is 32.8/6.2 s overall ⁴⁹	43	24	3.1	2.2
BBT, blocks/min	Normal for older adults is 67 blocks. ⁴⁰ MCID for the more/less affected hand is 5.5/7.8 blocks per minute. ⁴⁹	26 (54)	28 (55)	52 (NT)	51 (57)

Abbreviations: BBT, Box and Blocks Test; HASTe, Hand Active Sensation Test; HORT, Haptic Object Recognition Test; MAL, Motor Activity Log; MCID, minimal clinically important difference; NHP, Nine-Hole Peg; WEST, Weinstein Enhanced Sensory Test; WMFT, Wolf Motor Function Test; WPST, Wrist Position Sense Test.

^aScores for uninvolved upper extremity, where available, are given in parentheses.

Lesion Analysis

Stroke lesion location and volume were determined from T2 fluid-attenuated inversion recovery images. Lesion volume was calculated after manually outlining signal abnormality slice by slice in the axial plane.⁵² The location of lesions was determined by visualization of anatomical structures in the T2 image and comparison with a brain atlas.⁵³

fMRI Paradigm

Block-design fMRI with 21-second stimulation epochs alternating with the rest was obtained for a brush discrimination task on the paretic hand. Tactile stimulation of the index finger was generated by manual brushing applied to the distal phalanx at the rate of 1 Hz, timed with an auditory metronome heard only by the examiner. Brushing has previously been used for analysis of sensory perception with fMRI.²⁰

fMRI Data Analysis

Functional magnetic resonance imaging of the brain software library tools were used.⁵⁴ Standard prestatistic processing was applied to individual participant data: motion correction,⁵⁵ non-brain removal,⁵⁶ spatial smoothing = 5 mm, and mean-based intensity normalization of all volumes by the same factor. High-pass temporal filtering and time-series statistical analysis were carried out using a linear model with local autocorrelation correction.⁵⁷ Functional images from each participant were coregistered with their high-resolution image and standard (Montreal Neurological Institute [MNI] 152, 2 mm) images, using linear image registration,⁵⁸ and then optimized using nonlinear registration.⁵⁹ First-level analysis of functional scans, relative to rest, was carried out with $z > 3.0$ and a cluster significance threshold of $P = 0.01$. Anatomical areas were defined on the basis of the Harvard Oxford Structural Atlas (implemented in FSLView version 3.1.2).⁶⁰ The reliability of between-session fMRI in persons poststroke has been tested, using a complex visual-motor hand task; good reliability (intraclass correlation coefficient [ICC] = 0.58, voxel count method) was found, giving confidence to fMRI test/retest designs poststroke.⁶¹ A longitudinal study of texture discrimination fMRI in healthy adults found a consistent location of activation over time, suggesting changes in location of activation can be monitored confidently.⁶²

Diffusion Tractography Reconstruction

Tractography was based on the fiber assignment continuous tracking algorithm.⁶³ The sSTR was isolated using a multi-region of interest (ROI) approach in DTI Studio.⁶⁴ The ROIs were located on the FA color map, according to the brain anatomy of each participant. The first ROI included the entire posterior limb of the internal capsule at the axial level in which the fornix can be identified as a single intense structure. From the reconstruction result of this ROI, the bundle that reaches the postcentral gyrus was isolated at the level of cleavage of the central sulcus. In this method, only the “fibers” between both ROIs are selected, using the “cut” and “cut +” functions in DTI Studio. Tracking was started and stopped in voxels with an FA of 0.2 and a tract turning angle of 40° or more.⁶⁴

Brain Volume

Percentage brain volume change between 2 time points was estimated with SIENA (FMRIB, Oxford, UK),⁶⁵ using MPRAGE (FMRIB, Oxford, UK) images. This method has an error rate of 0.2%.⁶⁶

CASE DESCRIPTION

Participant 1 was a 75-year-old right-handed man 1 year after stroke in the right internal capsule, the lesion extended into the lenticular nucleus, thalamus, and insular cortex. Lesion volume, measured by signal abnormality in a T2 fluid-attenuated inversion recovery, was 14.3 cm³ (Figure 1A). *Sensorimotor Summary:* Participant 1 had hemiparesis and

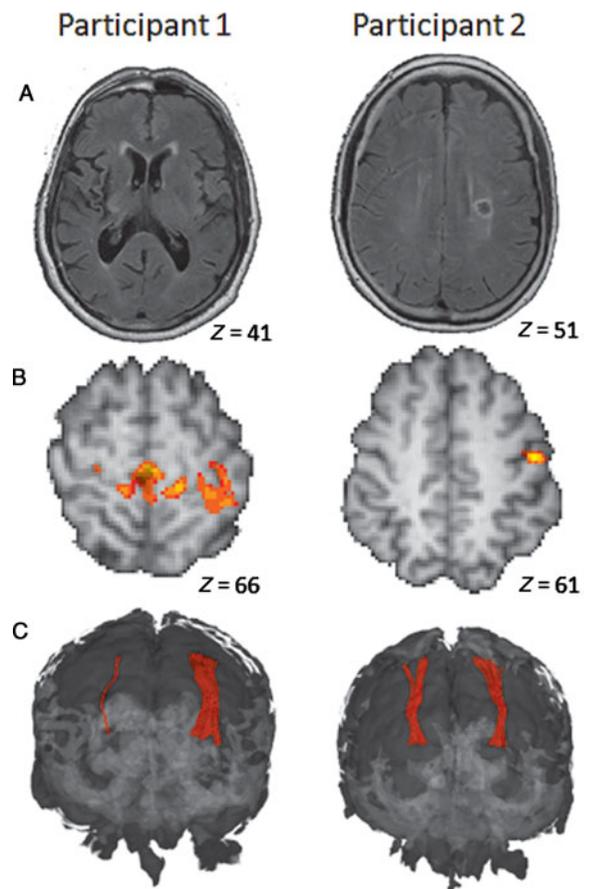


Figure 1. (A) T2 fluid-attenuated inversion recovery image of axial slice in which stroke lesion volume is largest. (B) Statistical parametric map of post-pre contrast of impaired index finger brush discrimination was thresholded at $z = 3.0$, $P = 0.05$, and overlaid on individual high-resolution images. Participant 1 had statistically greater activation in bilateral (although $L > R$) sensorimotor cortical areas after training (shown). Participant 2 had significantly greater activation in the left postcentral gyrus (shown) and in the right inferior frontal gyrus and left supplementary motor area. (C) Coronal view of bilateral sSTR model shown in the 3D brain. Quantification is found in Table 4. Images are in radiological convention in which the right brain is shown on the left side of the image. MNI coordinates of axial slices are indicated.

sensory loss in the contralesional, nondominant, left hand, including absent hot/cold discrimination (identified during training) and impaired touch perception and discrimination and haptic performance. Motor function measured by the Wolf Motor Function Test (WMFT) and performance measured by the Box and Blocks Test and Nine-Hole Peg Test were also impaired on objective measures, and he reported limited arm/hand use on the Motor Activity Log (MAL amount of use = 1.2/5.0). In his ipsilesional, right hand, touch perception was normal and hot/cold discrimination was functional; however, he had impairments of proprioception and discrimination (see Table 2).

Participant 2 was a 63-year-old right-handed woman 9 months after a stroke localized to the left internal capsule and corona radiata. Lesion volume was 2.1 cm³ (Figure 1A). *Sensorimotor Summary:* Participant 2 had functional bilateral hot/cold discrimination; touch perception was impaired. Haptic performance and proprioception were impaired in the right hand; weight and texture discrimination was normal bilaterally. Motor testing identified a mild deficit on both objective and self-reported right-hand use (3.6/5.0 on the MAL amount of use; see Table 2).

INTERVENTION

The participants trained 5 days per week for 2 weeks. Daily sessions lasted 4 hours, and breaks were provided upon request. Both participants completed all 10 days of training. Trainers recorded time on task for each participant on every task. For participants 1 and 2, mean time on task per day was 203 minutes and 215 minutes, mean number of tasks per day was 9.1 and 7.6, while the mean time per task was 22 minutes and 28 minutes, respectively.

The intervention was based on the following principles. Treatment intensity was adapted from constraint-induced movement therapy.⁶⁷ Tasks were primarily unimanual, based on the concept of forced use,⁶⁸ but occasionally bimanual (<10%), dependent on participant ability and task structure. To force a sensory demand, most tasks were performed with vision of task objects obscured by a curtain hung between the participant and the activity.⁶⁹ If obscuring vision resulted in a task being too difficult or vision had no relevance to the task (ie, hot/cold discrimination), the trainer would remove the curtain. A variety of tasks were used (listed in Table 3). They were developed in our laboratory with the goal of requiring sensory discrimination of temperature, weights, textures, shapes, and objects in the context of active exploration with the involved hand⁹⁻¹¹ (see Video Abstract in Supplemental Digital Content for an example of task description). Task variety has been associated with maintaining motivation⁷⁰ and attention.^{71,72} Moreover, across domains, higher-level sensory processing shares a parietal-prefrontal-premotor network as suggested by evidence from neuroimaging studies.^{31,73-75} Tasks were progressed in difficulty, on the basis of performance and participant-specific impairments. Tasks were modified, and/or participants were assisted by the trainer when necessary to accommodate for motor impairment. Random verbal feedback was provided by the trainers; participants also used the nonparetic hand and/or vision for feedback. Student physical therapists trained to

administer this protocol provided one-on-one or one-on-two guidance to the participants.

OUTCOMES

Sensory and motor outcomes for both participants are provided in Table 2.

Participant 1 had no increase in sensory scores in either hand after training. His WMFT scores met the criteria for minimal clinically important difference (MCID); importantly, the MCID was established in a study of acute stroke.⁴⁸ His change in the MAL score was not clinically meaningful.⁴⁷ *Imaging Outcomes:* Participant 1 had low cortical activation overall, during contralesional, left index brush discrimination at pretest and posttest imaging time points. In a post-minus-pretest contrast of impaired hand brush discrimination statistic parametric maps, participant 1 had a statistically significant increase in activation that peaked in the contralesional precentral and postcentral gyri after training; this resulted from less deactivation in these areas at posttest compared with pretest (see Figure 1B). The diffusion tractography models of the right and left sSTRs for participant 1 are asymmetrical, consistent with attenuation of the right sSTR due to right hemisphere internal capsule stroke. The posttest sSTR models are depicted in Figure 1C; as no significant difference was observed between pretest and posttest, only the posttest sSTR models are shown for both participants. For participant 1, FA and FD values for the left (contralesional) sSTR were stable across imaging time points; whereas at posttest in the right sSTR, FA appears to have increased while FD appears to have decreased (see Table 4). It should be noted that this variability is likely due to the relatively small number of voxels in the right sSTR model. Reliability of DTT has not been established for small white matter projections such as this.⁶⁴ Brain volume change was +0.4%, which is slightly above the published error rate of this method of 0.2%.⁶⁶

Participant 2 had a positive change in sensory scores for touch perception, proprioception, and haptic performance, while weight and texture discrimination was in the range of normal at pretest and posttest. Right index finger touch perception improved from a threshold of 0.2 g at pretest to within the range of normal (0.07 g) at posttest.⁷⁶ Mean normal error for the Wrist Position Sense Test is 11°, while standard error of measurement is 2.8°; 8.4° is considered “genuine change.”³⁴ Participant 2 had a 4.5° decrease in error in the Wrist Position Sense Test after training, which represents a 33% decrease in error and a shift from above normal to below normal error. For healthy older adults, the average number of errors on the Haptic Object Recognition Test is 4.7 ± 2.5.³⁶ Participant 2 decreased from 7 errors at pretest to 1 error at posttest. Following training, the MAL scores for participant 2 approached prestroke levels of use at 4.7/5, change in the MAL scores exceeded the arbitrarily established MCID of 10%.⁴⁷ WMFT scores also exceeded the MCID.⁴⁸ Participant 2 had a 29% decrease in time per peg on the Nine-Hole Peg Test and was within the range of normal (18-20 seconds)³⁸ at posttest. Her Box and Blocks Test score was 76% of normal at both time points. *Imaging Outcomes:* Analysis of post-minus-pretest contrast of brush discrimination for participant 2 indicated a statistically significant increase in activation in clusters, peaking in the

Table 3. Sensorimotor Training Tasks

Task	Description
Weighted eggs	Sort plastic eggs filled with 1-, 2-, or 3-oz weights and place into egg carton
Weighted balloons	Sort balloons filled with flour by either grasping whole balloon with gross grasp or with pincer grasp on knot of balloon. 1- or 2-oz difference in weight can be used.
Plastic ice cubes	Frozen and room temperature plastic ice cubes are sorted by temperature with vision occluded. Cubes are removed individually from one container and placed in separate containers.
Immersion bath	Fill 2 tubs with water of equal amounts, 1 warm, 1 cold. Discriminate temperature by submerging arm, hand, or finger. Confirm temperature with other hand.
Hot pack/cold pack	Select pack of certain temperature from within a bag with multiple packs of varying temperature (warm, room, cold). Remove pack and place on table.
Fabric texture discrimination	Match to sample with wooden 3 in × 3 in × 1/2 in tiles covered with textured fabrics (20 total, with 2 of each fabric). Matching can be to visual presentation with the match objects behind a curtain or by comparison of match objects between the paretic and nonparetic hands, vision occluded. Can vary the number of choice tiles per trial
Texture dowels	Wooden dowels with center openings are created with different thickness and/or different textures. Create a target object with 3 dowels on a rod. After manual exploration, participant is asked to recreate the same pattern on another rod. Dowel widths and textures can be varied.
Textured pegboard	Create pegboard with large pegs (3 in × 1 1/2 in). Cover bottom of peg holes and top of pegs with textures. Place pegboard on table and pegs behind curtain. With vision or touch of pegboard, select correct peg from behind curtain through manual manipulation.
Beans and therapeutic putty	Hide beans within a ball of putty. Remove beans and place in container. Vision may be occluded
Clay modeling	Create simple shape out of clay. Participant manually explores object behind curtain and then recreates the shape with his/her clay in front of the curtain.
Lego™ rebuilding	Trainer constructs an object of Lego™ that is manipulated behind a curtain; reconstruction of the object is completed on the visualized side of the curtain. Trainer can alter the number, orientation, and size of blocks used
Silverware sorting	Silverware is laid out behind curtain. Identification is made via manual exploration and then sorted into a silverware holder on the visualized side of the curtain.
Stereognosis	A variety of household objects are placed behind a curtain. Manual exploration is used to identify objects
Dominoes	Place dominoes in a bag. Play a standard game of dominoes. The participant must find the right match by manual exploration of the dots on the dominoes within the bag.
Magnetic letters	Place magnetic letters in a bag, sufficient to spell a word. Letters must be pulled from bag and placed on card with a word written on it. Extra letters can be included to increase difficulty.
Wooden alphabet blocks	Wooden blocks with letters engraved in the sides are placed in a bag. Manual manipulation is used to find a target block. Blocks are stacked as they are removed.
Geometric puzzle	Wooden geometric shapes are placed in a bag. A geometric puzzle diagram is placed on the table. Targeted shapes are manually identified and placed on the puzzle diagram.
Puzzle edges	Puzzle pieces are placed in a bag. Individually, all of the edge pieces are manually removed and placed on the table. They can be connected to shape the border of the puzzle.
Shape sorting	Using a standard infant shape sorter, place shapes in a bag and have a targeted shape manually retrieved from the bag and placed in the sorter.
Byl-Chenai	With vision occluded, a finger is used to feel a small Lucite block fitted with Brad nails that form a pattern. The perceived shape is visually matched to a printed sheet of shape options.
Perfection™	The shapes from the game Perfection™ are verbally identified and then retrieved from a bag and placed onto the game board.
Stone/bean sorting	Different-sized stones/beans are placed in a bag. A given size is designated as the target. All stones/beans of matching size are retrieved from the bag.
Coin sorting	Multiple coins are placed in a bag. A particular coin is designated and removed from the bag and placed in a bank
Bottle caps	Place caps from a variety of plastic bottles of different sizes in a bag. The participant manually explores and identifies the appropriate cap for a designated bottle and then places it on the bottle.
Nuts and bolts	A board, fitted with various-sized bolts and matching nuts is placed behind a curtain. Through manual exploration, each nut is removed and placed in a bowl; nuts are then screwed back onto the bolts behind the curtain.

left postcentral gyrus (Figure 1B), the supplementary motor area, and in the right inferior frontal gyrus after training. The diffusion tractography models of the right and left sSTRs for participant 2 were symmetrical, FA and FD pre- and posttraining values were stable showing typical variability associated with these measures (Table 4).⁶⁴ Percentage of brain volume change was 0.17%.

DISCUSSION

Poststroke tactile sensory dysfunction is common. This article detailed a novel, intensive training program and associated outcome measures, emphasizing sensory discrimination and manual manipulation of objects, which may be a useful

framework from which a clinical trial of sensorimotor training after stroke could be designed. During training, the participants were engaged and able to participate at relatively similar levels, as indicated by time on task, despite differences in hand function. Tasks were easily adapted to meet the functional level of each individual and progressed to challenge emerging skills. Furthermore, this study provides an example of extending measurement to neural reorganization of the sensorimotor system that accompanies functional improvement.

Both participants surpassed the MCID in arm function after training, measured by the WMFT. Their recovery paralleled that achieved from motor-focused training paradigms, such as constraint-induced movement therapy.⁶⁷ It should be

Table 4. Quantification of the Sensory Component of the Superior Thalamic Radiation^a

	Participant 1		Participant 2	
	Pretest	Posttest	Pretest	Posttest
Right bundle				
Volume	46	38	431	371
FA	0.29	0.44	0.48	0.50
FD	2.8	1.0	20.82	16.52
Left bundle				
Volume	720	870	319	351
FA	0.52	0.52	0.49	0.48
FD	23.49	21.64	18.91	17.95

Abbreviations: FA, fractional anisotropy; FD, fiber density.

^aFD is mean fibers per voxel in bundle; volume is the number of voxels in bundle. Lesioned hemisphere is indicated by gray shading.

noted that the MCID on the WMFT of –19 seconds, referred to here, was established in a study of participants with acute stroke.⁴⁸ Therefore, caution should be exercised when interpreting the importance of this change for persons with chronic stroke. Sensory recovery was more variable and difficult to evaluate. Participant 2, with initial mild sensory impairment, demonstrated improvement in touch perception, wrist proprioception, and shape discrimination. Participant 1, with severely impaired sensation at pretest, had not improved in sensory measures by posttest. It is possible that the 2-week intervention was not adequate to show change on the sensory measures when impairment is severe. It is also possible that the more severe motor impairment of participant 1 limited the amount of sensory improvement.

This protocol used a variety of behavioral tests to evaluate function. Review of the results and observation regarding their application yielded several key ideas. The Weinstein Enhanced Sensory Test, although easily completed, did not allow sufficient discrimination of touch perception; thus, the Semmes-Weinstein monofilaments are a preferable measure.⁷⁶ The Haptic Object Recognition Test is very challenging, especially for older adults, because of the cross-modal nature (ie, haptic exploration with visual comparison of unfamiliar objects). It requires visual imagery, perhaps to a greater extent than other shape discrimination measures³⁶; use of another measure of shape discrimination is recommended. The Hand Active Sensation Test discriminates high and low function well but is lengthy to administer; other measures of texture and weight discrimination should be explored. The Wrist Position Sense Test adequately identifies proprioception deficits and was sensitive to change. Finally, our participant with no sensory recovery after training could not discriminate hot and cold. Hot/cold discrimination screening is economical and time-efficient. Future researchers may wish to include temperature discrimination with other measures examined to predict sensory recovery. Motor measures used here were effective in discriminating motor behavior. The largest pre-post test differences were documented using the WMFT and MAL. We included both the Nine-Hole Peg Test and Box and Blocks Test to provide a greater focus on hand and finger function; however, the WMFT seems to differentiate function as effectively as these other measures. In summary, the motor out-

come measures used in this case series are expected to capture change due to training in larger studies, using this protocol. Continued evaluation of sensory measures to identify those that provide the best profile of sensory behavior poststroke is recommended.

Participant 1, with severely impaired left-hand sensation and no measurable recovery of sensory function, had low activation overall during left index brush discrimination, and most notably, the ipsilesional right parietal cortex had no activation that met threshold before or after training. This likely reflects impaired perception of the stimulus at both time points. A post-minus-pretest contrast identified significantly greater activation bilaterally; however, the majority of voxels were in the left sensorimotor cortical areas after training, suggesting predominantly contralesional neural reorganization. In the absence of measurable change in sensory function, we suggest that this functional reorganization may represent the effect of practice imagining sensory stimuli.⁷⁷ However, we cannot rule out the possibility that improved sensory function may have been possible with longer treatment duration or that the posttest activation change might be a precursor for later sensory improvement. Participant 1 had a 0.4% increase in brain volume after training. At just more than the published error rate of 0.2% for the method used, the significance of the increase is difficult to interpret. Overall volume and pattern of activation of participant 2 was within the range of previously published control data at both time points,³¹ evidence that she perceived the stimulus and was performing the task. A contrast of post-minus-pretest right index brush perception identified statistically significantly greater activation in left ipsilesional sensory cortex (Figure 1B), right inferior frontal gyrus, and left supplementary motor area after training. If the statistical difference in fMRI in these 2 participants is taken as evidence of neural reorganization, these findings are in line with others who report better function is associated with a return to contralateral control, as demonstrated by participant 2, while poorer function is more often associated with ipsilateral and diffuse patterns of activation, as demonstrated by participant 1.¹³

Diffusion imaging studies suggest white matter remodeling results from training in healthy children,⁷⁸ adults,⁷⁹ and elders.⁸⁰ Animal studies of training-induced white matter remodeling identify time frames as short as 1,⁸¹ 2,⁸² and 6 weeks.⁸³ At present, there is limited evidence of white matter remodeling after stroke in humans. A recent cross-sectional study of the microstructure of the corticospinal tract after stroke suggests motor skill recovery relates to the remodeling of both ipsilesional and contralesional corticospinal tracts.⁸⁴ Network analysis of poststroke white matter suggests that contralesional regions homologous to the lesion are compromised while other regions exhibit positive adaptive changes.⁸⁵

The participants in this case series have markedly different structural integrity of the sSTR in their lesioned hemisphere. In these 2 participants, ipsilesional sSTR integrity appears to correspond to their level of sensory function. While the sSTRs are nearly symmetrical in participant 2, in participant 1, contralesional sSTR has high FA, FD, and bundle volume values that may reflect contralesional remodeling similar to data from Schaechter et al,⁸⁴ who suggest evidence of contralesional corticospinal tract remodeling. The small

volume of white matter obtained in the right sSTR bundle in participant 1 reflects white matter damage associated with the stroke lesion. Lack of change in sensory function after training in participant 1 points to the possibility that a minimum amount of neural substrate may be necessary for sensory recovery. Given this, it is interesting to consider whether a visuomotor training program with enriched feedback, as described by Quaney et al,⁸⁶ would have yielded better outcomes for this participant. These ideas are important from a prognostic standpoint; however, additional inquiry is needed to identify the minimum functional activation or substrate required to benefit from sensorimotor or visuomotor training.

The tractography method and diffusion parameters used here did not identify a change in sSTR white matter after training in either participant. The 34% increase in FA in participant 1 is likely an artifact of low reliability associated with measurement of small white matter tracts.⁶⁴ Importantly, the tractography method and diffusion parameters used here may not be sensitive to white matter reorganization; alternatively, reorganization may have taken place elsewhere in network. These cases highlight questions for future research on post-stroke white matter reorganization, including (1) what treatment dose is necessary, (2) where microstructural white matter changes might occur, (3) what diffusion parameters are sensitive enough to identify change, and (4) what time-frame is sufficient?

LIMITATIONS

This study lacked a multiple baseline design, and while the participants were in the chronic phase poststroke, natural recovery cannot be ruled out. Study participants did not have aphasia, apraxia, or neglect. We expect these conditions would affect outcomes of future research. We used different sensory discrimination tasks for fMRI and behavioral testing. Because of incompatibility with the MRI, Hand Active Sensation Test scores were not obtained during functional scanning; instead, we used brush texture discrimination, which reliably identifies sensory discrimination dysfunction in stroke survivors.⁸⁷ Prior experience with MRI may impact activation at posttest, consistent with the observation of less variability in experienced than MRI naive participants.⁸⁸ Further research on dose, timing, and duration of training is necessary to generalize this protocol to the greater population of individuals with stroke.

SUMMARY

Sensorimotor training, using a protocol focused on manual manipulation and sensory discrimination, may be an effective method for improving sensory and motor function poststroke and bears further evaluation. Additional research is needed to identify best measures of sensory function that are easily applied and span the breadth of tactile sensory behavior. Conversely, the WMFT and MAL effectively measure change from this and other sensorimotor training paradigms.⁶⁷ Finally, the potential for sensory recovery appears strongly related to the integrity of the sSTR; however, future work must look beyond this large white matter tract for structural change in other components of the sensory discrimination network. It is expected that subsequent evaluation of this protocol, in a

large clinical trial, will elucidate the neural reorganization that supports sensorimotor recovery.

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By Sandra Billinger, Anna Mattlage, Abigail Ashenden, Angela Lentz, Gabe Harter, and Michael Rippee

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