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Patterns of Impairment in Digit Independence After Subcortical Stroke

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Raghavan, Preeti, Electra Petra, John W. Krakauer, and Andrew M. Gordon. Patterns of impairment in digit independence after subcortical stroke. *J Neurophysiol* 95: 369–378, 2006; doi:10.1152/jn.00873.2005. The nature of impairment in hand motor control after stroke and its relationship to hand function are still not well understood. In this study, we investigated digit independence in patients with subcortical stroke ($n = 8$) and moderate hand impairment, defined by wrist and hand Fugl-Meyer scale scores $\leq 25/33$, and age-matched controls ($n = 8$). Subjects made cyclical flexion-extension movements of an instructed digit while keeping the other digits as still as possible. Movements of the metacarpo-phalangeal (MCP) joints of the five digits were measured using an instrumented glove. The ability to move an instructed digit individually (individuation index), and the ability to keep a noninstructed digit as still as possible (stationarity index) were determined for each digit. Contrary to the finding of normal thumb individuation in a recent study of patients with variable hand motor impairment after stroke, we found that independent movement for all digits was significantly impaired, although individuation and stationarity were differentially affected for each digit. All the digits, including the thumb, showed a similar impairment in individuation. In contrast, stationarity was affected in a digit-dependent pattern: the thumb was affected least, and the middle finger was most impaired. Stroke subjects did not extend their digits fully to the baseline position, and the angular displacement at maximum digit extension correlated significantly with digit individuation. Contrary to expectation, digit independence correlated weakly with clinical tests of hand function, which emphasize grasp. This suggests that corticospinal projections might be separated with respect to function rather than finger topography.

INTRODUCTION

Functional tasks such as grasping small objects, playing a musical instrument, using sign language, and typing require one or more digits to move independently of the others. Independent digit movements depend on the integrity of the corticospinal tract. Animal studies show that complete lesions of the corticospinal tract result in a permanent loss of the ability to produce independent digit movements (Lawrence and Kuypers 1968; Passingham et al. 1983). However, only a few studies in humans have attempted to characterize the impairment in digit independence in detail after corticospinal damage and relate it to hand function.

A technique for measuring digit independence, first established in monkeys, examines flexion–extension movements of the digits with a task that requires movement of only one digit at a time (an instructed one) (Schieber 1991). The movement trajectories of the instructed digit in relation to that of each noninstructed digit are used to calculate two indices that

quantify two different aspects of digit independence: 1) the *individuation index* reflects the degree to which a given instructed digit moves individually while the other digits remain still, and 2) the *stationarity index* reflects the degree to which a given digit remains still whenever it is a noninstructed digit. Individuation and stationarity of a given digit need not necessarily covary, because individuation requires alternate activation of digit agonists and antagonists when the digit is instructed, whereas stationarity requires active stabilization of the digit when it is noninstructed (by co-contraction of the digit agonists and antagonists) and/or by passive (biomechanical) stabilization (Schieber 1995). A highly independent digit, however, will have both high individuation and stationarity indices. For example, a perfectly individuated digit and a perfectly stationary digit would have indices of 1. In a study of healthy humans, subjects showed almost perfect individuation and stationarity of the thumb, followed by that of the index finger, then the little finger, and finally the middle and ring fingers (Hager-Ross and Schieber 2000). The average value of the indices lay in a relatively narrow window between 0.8 and 1.0, and the average individuation and stationarity indices across all digits were highly correlated. Furthermore, there were no differences in digit independence between the dominant and nondominant hands (Hager-Ross and Schieber 2000).

There have been few quantitative studies of finger independence in humans after damage to the motor cortex or corticospinal tract. Lang and Schieber (2003) showed that digit independence was impaired in a group of patients with partially subjectively defined mild residual pure motor hemiparesis from ischemic lesions confined to the motor cortex or the corticospinal tract. However, they unexpectedly found that individuation of the thumb was normal, individuation of the index finger was only slightly impaired, whereas individuation of the middle, ring, and little fingers was substantially impaired (Lang and Schieber 2003). A follow-up study showed that impaired individuation is caused by reduced selectivity of finger muscle activation (Lang and Schieber 2004b). Normal individuation of the thumb could result from either true sparing of thumb projections or because surviving projections may be sufficient for independent thumb movements because of the thumb's greater biomechanical independence compared with the other digits (Lang and Schieber 2003). In a study examining multi-digit force production after stroke, forces produced by the index and middle fingers in opposition to the thumb were also less impaired compared with that produced by the other fingers (Li et al. 2003). Taken together, these results imply that the radial digits are relatively spared poststroke, although this may

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not be true for all strokes because there have been reports of predominant involvement of the ulnar digits after small cortical strokes (Kim 2001). However, radial digits may be spared in patients with mild residual motor impairment, although degree of impairment was not clearly defined in the studies mentioned above. Lang and Schieber (2003) reported the extent of motor impairment, measured by the Fugl-Meyer Scale (FMS), in only four of seven subjects examined, and the scores in these subjects varied from mild ($>60/66$) to moderate (30–50/66). It is possible that their finding of spared thumb individuation was driven mostly by the mildly impaired patients. Thus it is not known if the thumb would be similarly spared in a group of patients with uniformly moderate degree of hand motor impairment as defined by the wrist and hand subcomponents of the FMS. In these patients, independence of all the digits, including the thumb and index finger, may be impaired similarly; and consequently, digit independence may affect hand function more adversely.

The purpose of this study was to investigate the extent to which digit independence is affected in patients with moderate hand motor impairment—defined by wrist and hand FMS scores $\leq 25/33$ —from a subcortical stroke and to further delineate the relationship between impairment in digit independence and clinical measures of hand function. We hypothesized that all the digits, including the thumb, would have reduced independence in this group of patients, and that the relationship between impairment in digit independence and hand function would be pronounced.

METHODS

Subjects

Eight right-handed subjects with hemiparesis (5 women and 3 men between the ages of 27 and 79 yr) and an equal number of right-handed age-matched control subjects participated in the study. All subjects had sustained a single hemiparetic stroke at least 3 months previously. Five subjects had right hemiparesis and three had left hemiparesis. Subject characteristics are shown in Table 1. All subjects met the following inclusion criteria: 1) previously right hand dominant; 2) a score of $\leq 25/33$ on the wrist and hand subcomponents of the FMS (Fugl-Meyer et al. 1975), suggesting $\geq 25\%$ motor impairment in the wrist and hand; 3) presentation with either a pure motor or a sensorimotor lacunar syndrome, a score of >24 on the Folstein's Mini Mental Status Examination (Cockrell and Folstein 1988) ruling

out 4) clinically significant cognitive dysfunction and 5) aphasia; 6) ability to bisect a straight line within 5% of the midpoint ruling out clinically significant spatial neglect (Schenkenberg et al. 1980); 7) ability to accurately show use of scissors, suggesting absence of ideomotor apraxia (O'Hare et al. 1999); 8) ability to perceive the direction of passive displacements of the metacarpo-phalangeal (MCP) joints of all five digits with eyes closed, suggesting clinically intact joint position sense; 9) subcortical location of stroke—verified by official radiology report and from viewing of brain MRI, FLAIR sequence, by J.W.K. (patients 3, 4, 7, and 8), from official radiology reports (patients 2 and 5), and from the patient's medical record (patients 1 and 6); and 10) ability to complete the experimental protocol with the involved hand. Patients were excluded if their history suggested 1) coexistent neurological problems such as Parkinson's disease; 2) arthritis, surgery, or other significant injury to the upper extremities; 3) botulinum toxin injections in the upper extremity musculature in the last 3 months; or 4) treatment with intrathecal baclofen. Subjects with stroke were referred by physicians specializing in the treatment of stroke in the New York metropolitan area. Control subjects were recruited by public advertisement. The experiments were conducted at the Hand Motor Control Laboratory at Teachers College, Columbia University. The study protocol was approved by the Teachers College Institutional Review Board, and all subjects provided informed consent in accordance with the declaration of Helsinki. Subjects were reimbursed for travel expenses to and from the laboratory.

Clinical measures

All patients underwent standard neurological and musculoskeletal evaluation including measurement of upper extremity range of motion (Norkin and White 1995) and tone in the affected shoulder, elbow, and wrist joints by the modified Ashworth scale (MAS) (Bohannon and Smith 1987). Upper extremity motor impairment was measured by the upper extremity component of the FMS (Fugl-Meyer et al. 1975). The FMS has shown high reliability (DeWeerd and Harrison 1985; Sanford et al. 1993) and validity (DeWeerd and Harrison 1985; Wood-Dauphinee et al. 1990) for the assessment of motor impairment in hemiparetic stroke patients, and FMS scores have been shown to reflect residual corticospinal function (Hendricks et al. 2003). Upper extremity functional ability was measured by the Wolf motor function test (WMFT) (Wolf et al. 2001), tasks 8 to 13 of which quantified hand function. These tasks consisted of 1) lifting a can with a cylindrical grasp; 2) picking up a pencil using a three-jaw chuck; 3) picking up a paper clip using a pincer grasp; 4) stacking two checkers onto a center checker; 5) flipping cards over using supination at the forearm; and 6) using a key-pinch grip to turn a key fully to the left

TABLE 1. Clinical characteristics of subjects with hemiparesis

Patient	Age, Years	Lesion Location	TSS, mo	MAS*	FMS†	Purdue Pegboard‡	WMFT§, s
1	27	L basal ganglia and IC	36	1,1+,1	24/48	2.4	10.2/6.3
2	34	L putamen-capsular hge	109	0,1+,0	20/56	5.2	10.0/5.8
3	54	L PLIC	3	0,0,1	16/44	4.4	6.5/4.0
4	75	L PLIC & thalamus	69	0,0,1	18/46	7.2	4.8/3.7
5	79	L IC	37	0,1+,0	20/40	1.6	12.5/7.2
6	42	R capsular-basal ganglia hge	68	1,1,1	23/49	6.6	5.0/3.3
7	73	R IC and corona radiata	6	1+,1,0	25/47	7.2	10.7/6.5
8	63	R pons	127	0,1+,1	18/37	1.0	9.8/6.3

*MAS score of muscles across the shoulder, elbow and wrist joints of the affected upper extremity (0, no increase in muscle tone; 1, slight increase in muscle tone manifested by a catch and release or by minimal resistance at the end of the range of motion; 1+, slight increase in muscle tone manifested by a catch, followed by minimal resistance throughout the remainder of the range). †FMS scores of the wrist and hand out of a maximum of 33 over those of the total upper extremity out of a maximum of 66. ‡Purdue pegboard scores represent the average number of pegs inserted in 30 s over five trials. §WMFT scores represent the mean time taken to complete tasks 8–13 involving fine motor skills over the average time taken for all 15 tasks. R, right; L, left; IC, internal capsule; PLIC, posterior limb of the internal capsule; TSS, time since stroke; MAS, modified Ashworth scale; FMS, Fugl-Meyer scale; WMFT, Wolf motor function test; hge, hemorrhage.

and right. Hand function was also assessed by the Purdue pegboard test (Desrosiers et al. 1995; Hurlvitz et al. 2003), which consists of using precision grip to pick up small pegs and place them into holes on the pegboard as fast as possible. We used both the WMFT and the Purdue pegboard test to assess hand function comprehensively. Handedness was confirmed by a laterality quotient of more than +80 on the 10-point Edinburgh Inventory (Oldfield 1971). The clinical characteristics of each patient are shown in Table 1.

Experimental protocol

Subjects wore a right- or left-handed instrumented glove (CyberGlove, Virtual Technologies, Palo Alto, CA) in their affected hand, and the wrist was stabilized in neutral position with a wrist orthosis (Carpal Mate Wrist Support, FLA Orthopedics). They were seated with the elbow flexed at $\sim 90^\circ$, and the forearm and hand resting in mid-prone position on a foam support surface ($8 \times 5 \times 2$) on the table in front of them. The MCP and proximal and distal interphalangeal (PIP and DIP) joints of all five digits were in neutral (0° flexion-extension), and the digits were outstretched beyond the edge of the foam support to enable obstruction-free digit movements; this position was defined as 0° , and the glove was calibrated for each subject relative to this position. Subjects were instructed to perform digit movements at a self-selected pace. Stroke patients performed the task with their affected hand, and age-matched control subjects used the hand that corresponded to the affected hand of stroke patients.

Subjects were asked to make maximal cyclical flexion-extension movements of the instructed digit from the MCP joint while keeping the other (noninstructed) digits as still as possible. The subjects were specifically instructed to flex the digit, mainly at the MCP joint rather than at the PIP joint to control for intersubject differences in the degree to which these joints moved, and extend the digit back to the starting position. However, passive flexion at the PIP joints was noted in the instructed digit (the CyberGlove we used did not record movement at the DIP joints), although the amplitude of the MCP joint movement was the largest. Two sets of 10 cyclical flexion-extension movements per instructed digit were recorded with a rest break between sets. The order of instructed digit movement was counter-balanced across subjects. The wrist splint maintained the wrist in a neutral position during the task, but allowed maximum range of digit MCP joint flexion ($\sim 90^\circ$). The subjects had full view of their hand and digits during the protocol. All subjects practiced the task before the trials were recorded and showed full understanding of the protocol.

Data analysis

CyberGlove data were sampled at 120 Hz. The angular excursions of the MCP and carpometacarpal (CMC) joints of the thumb and the MCP and PIP joints of index, middle, ring, and little fingers were obtained and filtered at 8 Hz to eliminate low-frequency noise caused by tremors. However, because of specific instructions to the subjects to move the digit from the MCP joints, we used only the angular displacements of the MCP joints to determine finger independence. First, we determined the extent of movement of each digit relative to the movement of the instructed digit by calculating the normalized angular displacement of the MCP joint for each digit (Lang and Schieber 2003) over the 10 movement trials as follows

$$\frac{\text{Total angular displacement of that digit over 10 trials}}{\text{Total angular displacement of the instructed digit over 10 trials}}$$

The normalized angular displacement equals 1 when a given digit is the instructed digit and is usually <1 when it is a noninstructed digit. We used these normalized data to calculate the following two indices to quantify two different aspects of digit independence: the

individuation index and the stationarity index (Schieber 1991). The individuation index is a measure of how well a digit is able to move individually (i.e., with minimal movements of the other digits); it was calculated as 1 minus the average normalized angular displacements of the noninstructed digits during instructed movement of a digit as follows

$$\Pi_j = 1 - \left[\left(\sum_{i=1}^n |N_{ij}| \right) - 1 / (n - 1) \right]$$

where Π_j is the individuation index for the instructed j th digit, N_{ij} is the normalized angular displacement of the i th digit during the j th instructed movement, and n is the number of digits ($n = 5$). To remove the normalized angular displacement of the instructed digit plotted against itself, 1 was subtracted from both the numerator and the denominator. The individuation index of a perfectly individuated digit is 1. We used the higher individuation index from the two sets of trials for further analyses and used the corresponding trials in the calculation of the stationarity indices, movement excursions, and movement frequencies as described below.

The stationarity index is a measure of the degree of stillness of a digit when it is noninstructed. It is derived from the normalized angular displacement of a given noninstructed digit as follows

$$SI_i = 1 - \left[\left(\sum_{j=1}^m |N_{ij}| \right) - 1 / (m - 1) \right]$$

where SI_i is the stationarity index for the non-instructed i th digit, N_{ij} is the normalized angular displacement of the i th digit during instructed movements of the j digits and m is the number of instructed digits ($m = 5$). The stationarity index of a digit that remains perfectly still when it is noninstructed is 1.

To examine whether digit independence depends on the range of digit excursion, we measured the absolute angular displacement of the MCP joints of the instructed digits at maximum flexion and extension and computed the range of digit angular excursion as the difference between the displacement at maximum flexion and at maximum extension. The movement frequency was calculated by dividing the number of flexion-extension movements performed by each instructed digit by the time taken to perform them.

Statistical analyses

A 2 (group) \times 5 (digits) ANOVA with repeated measures on the second factor was performed on all measures. Post hoc comparisons were performed with Tukey's honestly significant difference procedure to identify differences in digit means when the main effects and interactions of the ANOVA were statistically significant. Pearson's correlation tests were used to identify relationships between the individuation and stationarity indices and clinical measures. All the statistical tests were performed using SPSS 11.5 (SPSS, Chicago, IL), and significance levels were set at $P < 0.05$.

RESULTS

Figure 1 shows representative traces of the angular excursions of the MCP joints of the thumb, index, middle, ring, and little digits during instructed movements of each of the five digits for a stroke patient and a control subject. Note that the control subject hardly moved the noninstructed digits during instructed movements of a given digit, although the thumb and index fingers, as expected, showed slightly less movement in noninstructed digits than the middle, ring, and little fingers. In

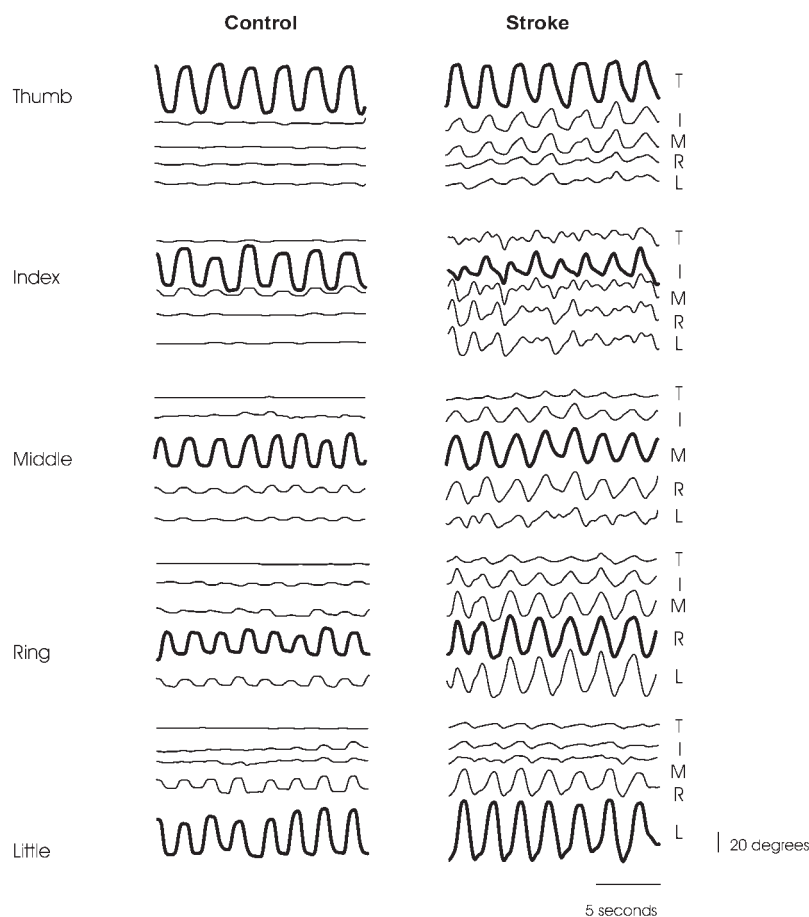


FIG. 1. Representative traces of the angular excursions of the metacarpo-phalangeal (MCP) joints of the thumb (T), index (I), middle (M), ring (R), and little (L) digits during instructed movements of each of the 5 digits (in bold) are shown for a control and a stroke subject. Corresponding individuation indices of the control versus stroke subjects are as follows: thumb = 0.96 vs. 0.75; index = 0.87 vs. 0.45; middle = 0.84 vs. 0.56; ring = 0.84 vs. 0.44; little = 0.89 vs. 0.82. Stationarity indices are calculated for each non-instructed digit across trials of the instructed digits and are as follows: thumb = 0.98 vs. 0.77; index = 0.93 vs. 0.62; middle = 0.88 vs. 0.52; ring = 0.85 vs. 0.46; little = 0.88 vs. 0.39. Downward movements of the traces represent flexion, whereas upward movements represent extension.

contrast, regardless of which digit was instructed, the subject with stroke (3) moved noninstructed digits along with the instructed digit. The abnormality is particularly striking for the ring finger, for which the subject made almost equal amplitude movements with the neighboring middle and little fingers.

Individuation indices

Individuation indices reflect the degree to which a given instructed digit moves individually while the other digits remain as still as possible. The individuation indices of each instructed digit for the control subjects are plotted in Fig. 2A. Note that all control subjects were able to individuate their instructed digits with little between-digit and between-subject variability [mean across all digits = 0.87 ± 0.06 (SD)], although there is a visible downward trend from the thumb to the ring finger followed by a return upward for the little finger. The equivalent plot for patients with stroke is shown in Fig. 2B. Relative to the control subjects, the mean individuation indices for the stroke patients were lower and showed more intersubject variability (mean across all digits = 0.66 ± 0.14 ; stroke vs. control, $F_{(1,14)} = 35.615$, $P < 0.001$). Thus we found impaired individuation in patients with hemiparesis, as did Lang and Schieber (2003). However, in contrast to the findings of Lang and Schieber (2003), our stroke patients showed more uniform impairment across all digits with the same overall trend as the control subjects (digit \times group interaction, $P > 0.4$). One patient (1) had a particularly low individuation index for the thumb (0.35); however, elimination of this subject from the

statistical analyses did not change the results. A closer examination of Fig. 2B shows that five of eight patients (2, 4, 6, 7, and 8) had thumb individuation indices in the range of control subjects (7.5–9.5). However, four of eight patients (1, 2, 4, and 5) also had ring finger individuation in the range of control subjects, and patients 2 and 4 had both thumb and ring finger individuation indices in the range of control subjects. The three patients (1, 3, and 5) who showed impaired thumb individuation did not differ from the other five patients in the degree of hand motor impairment as measured by the FMS (shown in Table 1). Therefore we cannot conclude that thumb individuation is preferentially spared in patients with moderate hand motor impairment after stroke. Interestingly, two patients (4 and 6) with normal thumb individuation showed impaired little finger individuation, whereas two patients (1 and 3) with impaired thumb individuation showed normal little finger individuation.

Stationarity indices

Stationarity indices reflect the degree to which a digit remains still when it is noninstructed. The stationarity indices for the five digits in stroke and control subjects are plotted in Fig. 3. As seen in Fig. 3A, control subjects showed high stationarity of their noninstructed digits with little between-digit and between-subject variability (mean across all digits = 0.85 ± 0.06), although the middle finger was less stationary in subject 7. Stroke subjects (Fig. 3B) kept their noninstructed digits significantly less stationary than control subjects ($F_{(1,14)} =$

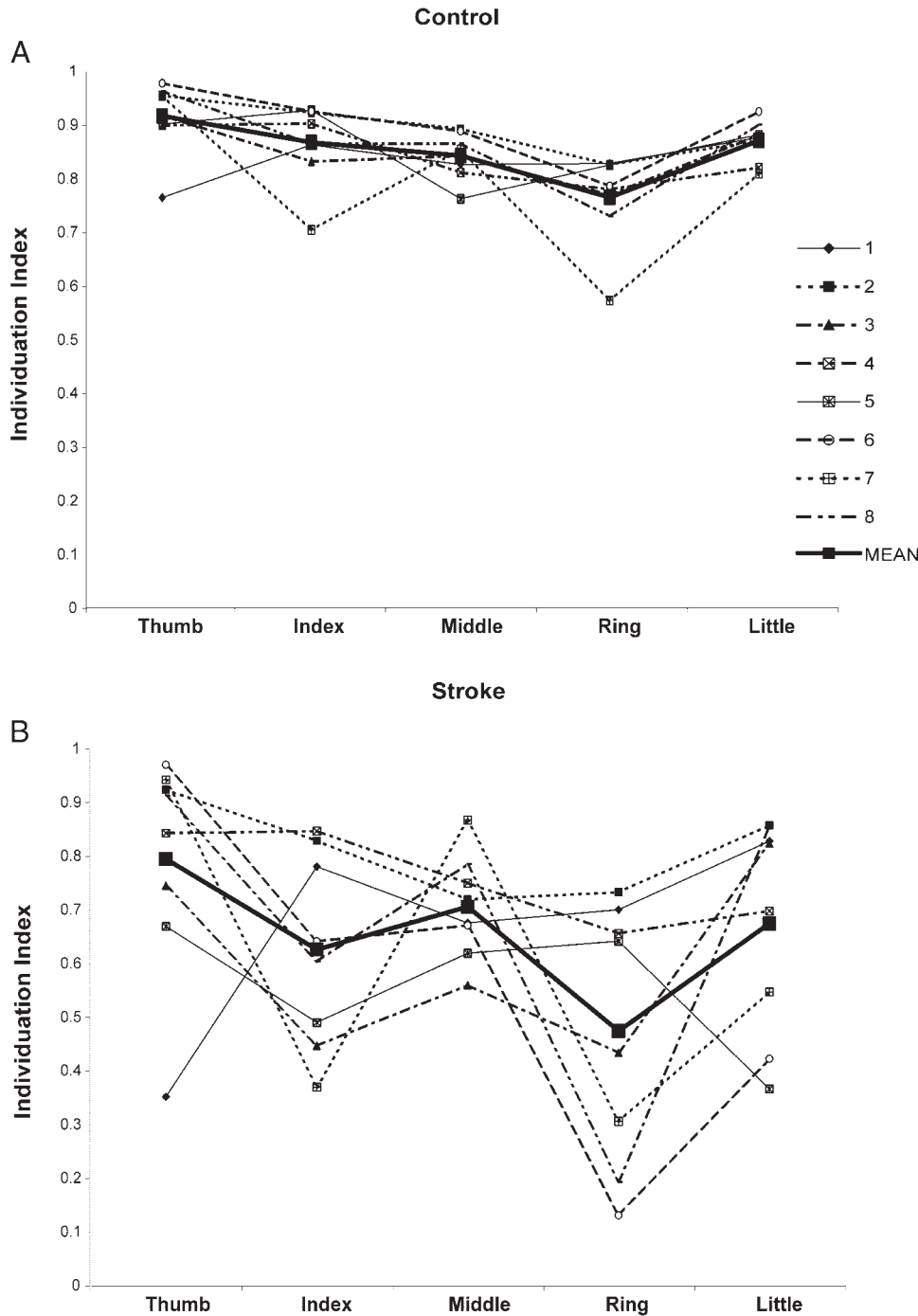


FIG. 2. Indivuation indices of all control (A) and stroke subjects (B) are shown. Thick line represents mean of all subjects. Control subjects have uniformly high indivuation indices across digits, whereas stroke subjects show large variability in the pattern of digit involvement.

26.978, $P < 0.001$) and showed large variability among the digits (mean across all digits = 0.63 ± 0.20). However, the digits were not affected equally in stroke patients and control subjects (digit \times group interaction, $F_{(4,56)} = 4.732$, $P < 0.002$). Post hoc pairwise comparisons confirmed that control subjects showed no differences in stationarity among the five digits; patients with stroke, however, showed that stationarity of the index, middle, ring, and little fingers was significantly lower than that of the thumb, and stationarity of the middle finger was significantly lower than that of the index and little fingers ($P < 0.05$). Stationarity of the thumb was not significantly different in stroke and control groups.

Movement excursions

We measured the absolute angular displacement of the MCP joints of the instructed digits at maximum flexion and extension and calculated the range of instructed digit angular excursion (displacement at flexion minus extension) to examine whether it could account for differences in digit independence in the two groups. The range of instructed digit excursion was not different between the stroke and control groups ($F_{(1,14)} = 1.017$, $P > 0.3$). Digit excursion did not correlate with the indivuation and stationarity indices ($P > 0.3$); therefore differences in digit independence between the groups cannot be attributed to differences in the range of digit excursions.

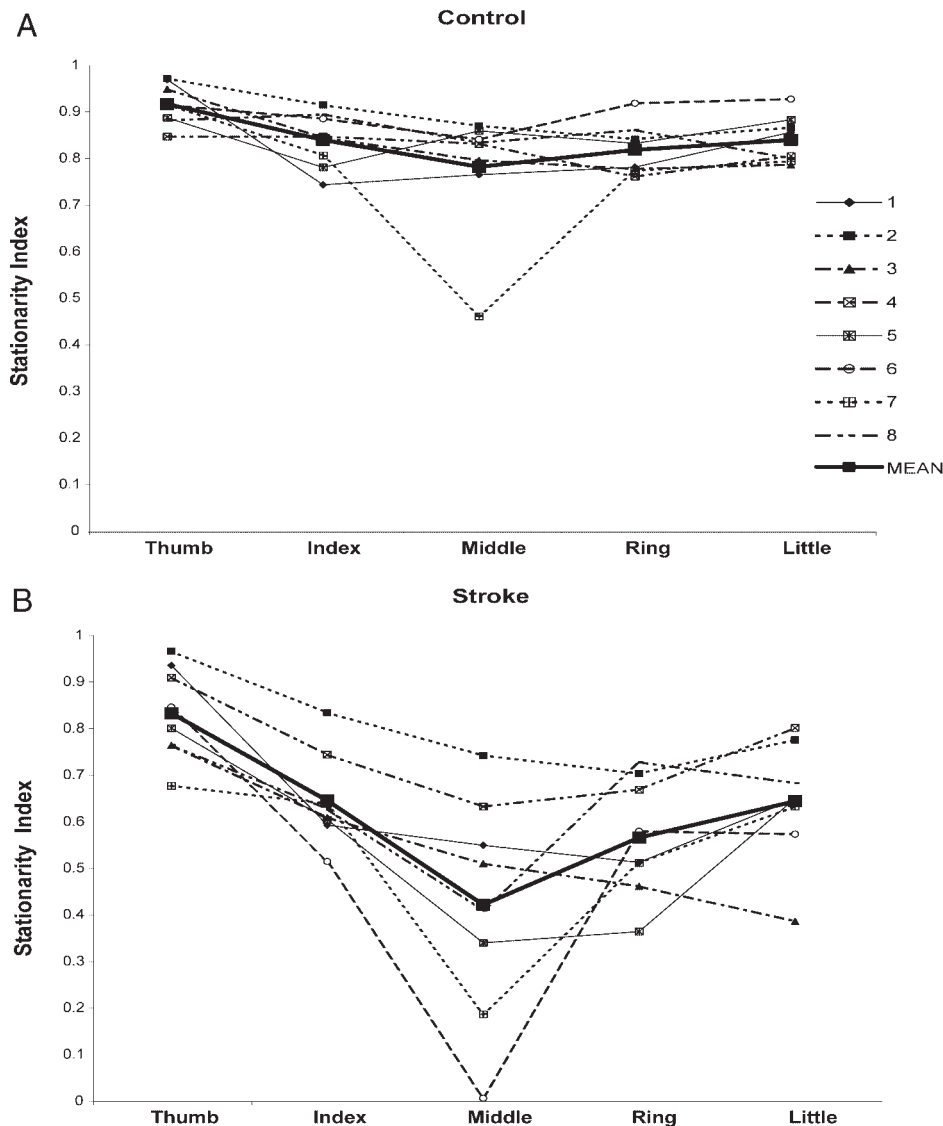


FIG. 3. Stationarity indices of all control (A) and stroke subjects (B) for the self-paced condition are shown. Thick line represents mean of all subjects. Control subjects have uniformly high stationarity indices, although the middle digit is least stationary. Stroke subjects show digit-dependent impairment in stationarity indices across all subjects: the thumb is least affected, whereas the middle digit is affected most.

However, although all subjects started their first flexion movement from a neutral (0°) MCP joint position, patients with stroke extended their digits 15° short of the neutral position they started from at maximum extension compared with control subjects (stroke = 15.56 ± 9.67 ; control = -0.37 ± 7.32 ; $F_{(1,14)} = 13.754$, $P < 0.002$). Stroke patients performed the subsequent flexion movements from this more flexed position (i.e., their baseline was now shifted toward flexion), and flexed their instructed digits 12° more than control subjects across all digits (stroke = 51.88 ± 9.22 ; control = 39.9 ± 10.6 ; $F_{(1,14)} = 5.794$, $P < 0.03$); this offset accounts for the similar range of instructed digit angular excursions between the stroke and control groups. Post hoc tests showed that extension of all the digits was similarly impaired, whereas the middle and little fingers were more flexed than the other digits in the stroke group ($P < 0.05$). The absolute joint displacement at maximum digit extension (but not flexion) correlated well with the average individuation indices ($r = -0.645$, $P < 0.04$) but moderately with the average stationarity indices ($r = -0.580$, but $P < 0.08$); negative correlations indicate lower indices in individuals with more flexed digits at maximum digit extension.

The frequency of digit movements was not different between stroke and control groups ($F_{(1,14)} = 0.809$, $P > 0.3$). However, frequency correlated significantly with both individuation ($r = 0.736$, $P < 0.037$) and stationarity indices ($r = 0.734$, $P < 0.038$) in stroke patients: subjects with higher indices moved faster, as would be expected.

Correlations between individuation, stationarity, and clinical measures

To understand the relationship between digit individuation and stationarity, we correlated the individuation and stationarity indices of all five digits. For a given digit, individuation and stationarity indices were not significantly correlated in either control subjects or stroke patients. However, in control subjects, the individuation and stationarity indices of adjacent digits (Table 2) were highly correlated. Stroke subjects revealed high correlations only between individuation of the index finger and stationarity of the thumb, individuation of the ring finger and stationarity of the middle finger, and individuation of the little finger and stationarity of the middle finger.

TABLE 2. Correlation between individuation and stationarity indices

Finger Pairs	Correlation*
Control	
I-thumb and S-index	0.790 (<0.02)
I-index and S-middle	0.946 (<0.001)
I-middle and S-index	0.715 (<0.046)
I-ring and S-middle	0.892 (<0.003)
I-little and S-ring	0.804 (<0.016)
Stroke	
I-index and S-thumb	0.936 (<0.001)
I-ring and S-middle	0.785 (<0.021)
I-little and S-middle	0.744 (<0.034)

*Values indicate Pearson's correlation coefficients (r). Significance of the correlations (P values) is in parentheses. I, individuation indices; S, stationarity indices.

Correlations of digit independence (represented by the average individuation and stationarity indices across all digits) with clinical measures are shown in Table 3. Individual digit individuation and stationarity indices correlated poorly with hand function as measured by the Purdue pegboard test and the WMFT (tasks 8–13). The two tests of hand function correlated moderately with each other ($r = -0.591$, $P < 0.12$); negative correlation indicates that patients who took longer to complete WMFT tasks scored lower on the Purdue pegboard test. Performance on individual fine motor tasks of the WMFT correlated moderately well with each other (tasks 8 and 10, $r = 0.619$, $P < 0.102$; tasks 8 and 12, $r = 0.737$, $P < 0.037$; tasks 9 and 10, $r = 0.679$, $P < 0.064$; tasks 9 and 11, $r = 0.589$, $P < 0.124$; tasks 10 and 11, $r = 0.554$, $P < 0.154$; tasks 11 and 13, $r = 0.725$, $P < 0.042$). Subjects with left and right hemiparesis did not differ significantly on any of the above variables.

DISCUSSION

In agreement with our hypothesis, we found that digit independence is impaired in subjects with FMS-defined hand motor impairment (score $\leq 25/33$ on the wrist and hand subcomponents) from a subcortical stroke. However, individuation was impaired in all the digits, including the thumb, whereas the impairment in stationarity was digit-dependent: the thumb showed high stationarity indices in contrast to the middle finger, which showed extremely low stationarity indices. Contrary to our hypothesis, however, the relationship between impairment in digit independence and hand function was not pronounced. This is particularly

TABLE 3. Correlation between clinical measures and finger independence

Clinical Measure	Individuation Indices*	Stationarity Indices*
Fugl-Meyer scale	0.500 (>0.21)	0.409 (>0.32)
Purdue pegboard test	0.182 (>0.66)	0.033 (>0.94)
WMFT (tasks 8–13)	-0.100 (>0.81)	-0.022 (>0.96)
MAS shoulder	-0.361 (>0.38)	-0.484 (>0.22)
MAS elbow	-0.012 (>0.98)	0.051 (>0.90)
MAS wrist	-0.034 (>0.94)	-0.048 (>0.91)

*Values indicate Pearson's correlation coefficients (r). Significance of the correlations (P values) is in parentheses. WMFT, Wolf motor function test; MAS, modified Ashworth scale.

surprising because our subjects showed impaired independence in all five digits.

Impaired individuation indices of all digits

Stroke patients in our study showed substantially impaired individuation of their digits. However, in contrast to the results of Lang and Schieber (2003), who showed spared individuation of the thumb and mildly impaired individuation of the index finger, we found uniform impairment of all the digits including the thumb. The difference in results may have been caused by slight differences in the methods used in our study compared with those of Lang and Schieber: 1) the baseline starting position of the cyclical flexion–extension movements of the instructed digit in our study was set at the 0° position of the MCP, PIP, and DIP joints, and subjects flexed their digits mainly from the MCP joints, although the PIP joints flexed passively when doing so (subjects in their study did not appear to be instructed to move from any one joint); and 2) we used only the MCP joint excursions to calculate the individuation and stationarity indices based on task requirement (whereas they included movement from the PIP and DIP joints as well). However, a subsequent analysis using PIP joint excursions to calculate individuation indices did not produce qualitatively different results, and Lang and Schieber (C. Lang, personal communication) also found that their results could be accounted for solely by MCP joint excursions. Thus we do not believe that the methodological differences account for the difference in results.

A more likely reason for the discrepancy in individuation indices between our study and that of Lang and Schieber (2003) is that our stroke patients had *uniformly* moderate hand motor impairment. While it is difficult to compare the subjects directly, Lang and Schieber (2003) studied a group of patients with subjectively defined mild residual hemiparesis, at least some of whom had minor hand deficits, which may have resulted in an overall finding of spared individuation of the thumb and index finger. Furthermore, as Lang and Schieber (2003) acknowledged, the greater biomechanical independence of the thumb may mask a true impairment in its independence. The inclusion criteria for our study were FMS wrist and hand scores $\leq 25/33$, history of a lacunar presentation, and a subcortical location for the stroke. Upper extremity FMS scores of motor impairment have been shown to reflect residual corticospinal function (Hendricks et al. 2003). In addition, all the patients in our study presented with a lacunar syndrome, and radiology reports confirmed lesion location to the corona radiata, internal capsule, and pons in six of eight patients, strongly suggesting that interruption of the corticospinal tract is the critical causal factor. We were unable to obtain copies of the patient's structural images and/or an official radiological report in two of eight patients. However, presentation with a lacunar syndrome predicts a subcortical lacune on imaging in about 80% of cases (Bamford 1995), and lesions confined to the putamen or globus pallidus do not typically cause hemiparesis; indeed, 80% of radiological deep subcortical infarcts are clinically silent (Tuszynski et al. 1989). Thus lacunar presentation and subcortical lesion location likely imply corticospinal damage. Hence it is conceivable that greater impairment in thumb individuation was caused by more extensive involvement of the corticospinal tract. However, it should be empha-

sized that a replication of this study in patients with mild hand motor impairment would be needed to confirm that the thumb is indeed spared in such patients. Furthermore, the main hypothesis of our study was psychophysical, not anatomical—patients with moderate hand motor impairment after a subcortical stroke, without cortical symptoms or proprioceptive loss by neurological examination, will have global impairments in digit independence, including the thumb and index finger. Future studies should correlate quantitative measures of finger independence with the precise anatomical extent of corticospinal damage.

Differential impairment of digit individuation and stationarity

A highly independent digit is defined by both high individuation and stationarity indices (Schieber 1991). Young healthy individuals (Hager-Ross and Schieber 2000), as well as the age-matched control subjects in this study, showed highly independent movements of each of the digits. However, the stroke patients in our study showed differential impairment of individuation and stationarity indices. Specifically, individuation of all five digits was affected equally, whereas stationarity indices showed a digit-dependent impairment: stationarity of the thumb was much less impaired than that of the other digits, whereas stationarity of the middle finger was much more impaired. This is in contrast to the results of Lang and Schieber (2003), who reported that individuation and stationarity were similarly affected, although they did not provide details of the stationarity indices. Digit individuation and stationarity place different demands on the neuromuscular control of the digits (Schieber 1995). During individuation of an instructed digit, digit flexion requires selective activation of finger flexors and simultaneous inhibition of that digit's antagonist extensor muscles, while digit extension requires activation of the extensors and simultaneous inhibition of that digit's antagonist flexor muscles (Bertolasi et al. 1998; Schieber 1995). In addition, the noninstructed digits must remain as still as possible. Strong correlation between adjacent individuation and stationarity indices in control subjects suggests that stabilization of the digit adjacent to the individuated digit may facilitate individuation. The stroke patients in our study were able to flex their instructed digits but were unable to fully extend them back to the baseline position. Extension was impaired in all the digits and the angular displacement at maximum digit extension correlated significantly with the individuation indices, while it showed a trend toward significance with the stationarity indices. Reduced activation of digit extensor muscles has been shown after stroke (Trombly 1989). A combination of coactivation of digit flexor and extensor muscles and decreased excitability of finger extensor muscles during voluntary movements in stroke patients has been shown to account for reduced extensor muscle activation (Kamper and Rymer 2001; Kamper et al. 2003). Furthermore, stroke patients exert greater effort to activate weak muscles, and such effort leads to additional nonselective muscle activation (Bhakta et al. 2001; Lang and Schieber 2004b), which may prevent the noninstructed digits from remaining still, thereby lowering the individuation indices further.

However, a noninstructed digit may remain stationary passively during instructed movements of another digit when it

has little biomechanical connectivity with that digit (Lang and Schieber 2004a). The thumb, for example, is moved by muscles that do not participate in movements of any other digit, therefore allowing for the better stationarity indices observed. Stationarity of digits that are connected by multi-tendoned muscles and ligaments, as are the index, middle, ring, and little fingers (Austin et al. 1989; Gonzalez et al. 1997; von Schroeder and Botte 1993; von Schroeder et al. 1990), require active muscle contractions to stabilize them (Lang and Schieber 2004a), placing greater demands on neuromuscular control, which the stroke patients might not have been able to meet. The stroke patients in our study also flexed their digits excessively. Overactivity in digit flexor muscles after stroke has been attributed to spasticity in finger flexor muscles (Kamper and Rymer 2000; Sampaio et al. 1997). Although we did not measure spasticity in the digits (only proximally), we did find that the middle and little fingers were significantly more flexed than the thumb. Increased flexion of the middle finger along with decreased extension (potentially caused by weakness in the multi-tendoned extensor digitorum communis muscle) may account for the especially low stationarity of this finger. In addition, unmeasured soft-tissue tightness (involving the web spaces) and subtle contractures in finger flexor muscles as a result of relative disuse of the chronically affected extremity (Gracies 2005a,b) may further limit stationarity by increasing the demands on neuromuscular control. This would also tend to affect the middle finger more than others. Strong correlations between middle finger stationarity and ring and little finger individuation in stroke patients suggests that impaired middle finger stationarity contributes to impaired individuation in the ring and little fingers. Thus decreased digit extension can account for impaired digit individuation, and decreased biomechanical stability caused by flexor overactivity and increased passive mechanical forces can account for the reduced stationarity observed in our patients. The differential pattern of impairment of individuation and stationarity indices provides an indication of the mechanism of impairment of digit independence poststroke.

Relationship between digit independence and hand function

Contrary to our expectation, digit independence did not correlate with measures of hand function (WMFT and Purdue pegboard test). The narrow range of motor ability in our patients, and the limited sample size, may account for the weak correlations. However, Lang and Schieber (2003) also showed only small to moderate functional correlations of digit independence with the Jebsen hand function test (which shares many of the components of the WMFT). Although hand postures required to match the size and shape of objects in the various tasks (see METHODS for description of tasks) may require independent movements of different digits to various degrees (Santello et al. 1998), the weak correlations observed suggest that digit independence did not significantly influence performance on these tasks. This could be because both the WMFT tasks and the Purdue pegboard test involve grasping objects (performance on these tasks correlated moderately well, see RESULTS). Grasping tasks are different from independent digit movements performed in our psychophysical task in at least two important ways. 1) Grasping tasks require not only control of digit movements to conform the fingers to the

shape and size of the object, but also control of fingertip forces to perform the task successfully. It has been shown that there are independent kinematic and dynamic learning components for reaching movements (Krakauer et al. 1999). Analogously, dissociation of digit individuation and performance on grasping tasks in our study might indicate that cortical control of digit independence is independent of cortical control of grasp (see Galea and Darian-Smith 1997; Lemon et al. 1995), even though both are dependent on corticospinal projections (Bortoff and Strick 1993; Lang and Schieber 2003; Lawrence and Kuypers 1968; Lemon 1993; Muir and Lemon 1983; Schieber 1999). Separate corticospinal control of grasp and finger independence would suggest a functional rather than topographic organization of the corticospinal tract. Such an organization is consistent with the fact that multiple cortical regions contribute to the corticospinal tract, that their axons travel separately in the internal capsule, and terminate with different patterns on spinal gray matter (Porter and Lemon 1993). A functional organization is also consistent with the fact that the corticospinal tract does not show intralimb somatotopy (Schieber 2001). Future studies are needed, however, to correlate psychophysical measures of these two tasks in humans with corticospinal damage to test this hypothesis. 2) Grasping requires synergistic opposition movements of the thumb with one or more of the other fingers, while the independent digit movements we tested required isolated nonsynergistic movements of individual digits. The lack of correlation between these tasks suggests differences in the neural control of synergistic and nonsynergistic finger movements. Functional imaging revealed stronger activation in nonprimary fronto-parietal areas and the cerebellum in nonsynergistic tasks (which involved thumb extension while the other fingers flexed) compared with synergistic tasks (involving flexion of all 5 digits) (Ehrsson et al. 2002), suggesting that nonsynergistic movements place greater demands on the neural control system. The same group also showed that power grip was associated with activity limited to the contralateral sensorimotor cortex, whereas precision grip, which involves synergistic but independent movements of the thumb and index finger, produced extensive activations of the sensorimotor, premotor, and parietal cortices in both hemispheres (Ehrsson et al. 2000). It is possible that the corticospinal tract is functionally organized such that contralateral sensorimotor projections related to grasp are more numerous than the widespread projections related to precision grip, which in turn number more than those needed for nonsynergistic independent finger movements. Any damage to the corticospinal tract would therefore be more likely to spare projections related to grasp over those required for independent finger movements. Thus patients may be able to perform grasping tasks more easily than expected given the impairment in digit independence.

Because most functional tasks involve different patterns of grasp, is it to be concluded that nonsynergistic digit independence tested in our study is not relevant to hand function? We do not think so. Functional hand use in humans also involves sophisticated activities that do not require grasp but do require one or more digits to move independently; for example, using sign language, typing, or playing a musical instrument. Studies on motor recovery after stroke often use tasks requiring independent movements of one or more digits (Cramer et al. 1999, 2003; Jang et al. 2003, 2004; McCombe Waller and Whitall

2004; Verleger et al. 2003), and training in isolated digit movements has been shown to lead to improved hand motor recovery after stroke (Butefisch et al. 1995). Thus we suspect that extant measures of hand function are not sensitive to the impairment in digit independence, at least within the narrow range of severity we tested. Therefore they do not address important components of hand function. The development of additional functional tasks that are designed to separately assess the effects of various impairments, such as digit independence and fingertip force coordination, may be more useful in directing and assessing therapeutic efforts.

In conclusion, in patients with FMS-defined moderate hand motor impairment from subcortical stroke, independence of all the digits including the thumb is impaired. However, the two aspects of digit independence—individuation and stationarity—are impaired differentially. Maximum digit extension correlated significantly with digit individuation, whereas decreased biomechanical stability of the digits and increased passive mechanical forces seemed to reduce stationarity. These results emphasize that impairment in the production of independent finger movements is an important component of the deficit in hand motor control after stroke and the degree of impairment is most likely a “dose response” representing the extent of involvement of the corticospinal tract. Lack of correlation of digit independence with tests of hand function emphasizing grasp suggests that corticospinal projections might be separated with respect to function rather than finger topography.

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