Compensatory Motor Control After Stroke: An Alternative Joint Strategy for Object-Dependent Shaping of Hand Posture

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[1]*Department of Rehabilitation Medicine, The Mount Sinai Medical Center;* [2]*Department of Biobehavioral Science, Teachers College;* [3]*Motor Performance Laboratory, Department of Neurology, College of Physicians and Surgeons, Columbia University, New York, New York; and* [4]*Department of Kinesiology and School of Biological and Health Systems Engineering, Arizona State University, Tempe, Arizona*

Raghavan P, Santello M, Gordon AM, Krakauer JW. Compensatory motor control after stroke: an alternative joint strategy for object-dependent shaping of hand posture. *J Neurophysiol* 103: 3034–3043, 2010. First published March 24, 2010; doi:10.1152/jn.00936.2009. Efficient grasping requires planned and accurate coordination of finger movements to approximate the shape of an object before contact. In healthy subjects, hand shaping is known to occur early in reach under predominantly feedforward control. In patients with hemiparesis after stroke, execution of coordinated digit motion during grasping is impaired as a result of damage to the corticospinal tract. The question addressed here is whether patients with hemiparesis are able to compensate for their execution deficit with a qualitatively different grasp strategy that still allows them to differentiate hand posture to object shape. Subjects grasped a rectangular, concave, and convex object while wearing an instrumented glove. Reach-to-grasp was divided into three phases based on wrist kinematics: reach acceleration (reach onset to peak horizontal wrist velocity), reach deceleration (peak horizontal wrist velocity to reach offset), and grasp (reach offset to lift-off). Patients showed reduced finger abduction, proximal interphalangeal joint (PIP) flexion, and metacarpophalangeal joint (MCP) extension at object grasp across all three shapes compared with controls; however, they were able to partially differentiate hand posture for the convex and concave shapes using a compensatory strategy that involved increased MCP flexion rather than the PIP flexion seen in controls. Interestingly, shape-specific hand postures did not unfold initially during reach acceleration as seen in controls, but instead evolved later during reach deceleration, which suggests increased reliance on sensory feedback. These results indicate that kinematic analysis can identify and quantify within-limb compensatory motor control strategies after stroke. From a clinical perspective, quantitative study of compensation is important to better understand the process of recovery from brain injury. From a motor control perspective, compensation can be considered a model for how joint redundancy is exploited to accomplish the task goal through redistribution of work across effectors.

INTRODUCTION

The ability to reach toward an object and grasp it is an essential human attribute. As the hand opens at the beginning of reach to grasp, healthy individuals shape their hand posture to approximate the size, shape, and use of an object, so that hand closure occurs in tight synchrony with approach of the target object for accurate grasp (Jeannerod 1984; Jeannerod and Biguer 1982; Paulignan et al. 1990). More recently it has been shown that hand posture is molded to object shape

throughout reach-to-grasp, suggesting that it is not fully specified at the end of hand opening (Santello and Soechting 1998). However, occlusion of vision immediately prior to (Santello et al. 2002) or after movement initiation (Winges et al. 2003) has no effect on the evolution of hand posture, which suggests that shaping involves a feedforward grip selection process that does not require on-line visual feedback. Nevertheless, when visual information about the object is unexpectedly altered during reach-to-grasp performed with continuous vision, hand posture is adjusted during the deceleration phase, suggesting that visual feedback can be used to improve matching between hand posture and object shape to optimize grasp (Ansuini et al. 2007; Castiello et al. 1992; Schettino et al. 2003). Thus in healthy individuals, hand shaping occurs feedforward during hand opening in the acceleration phase of reach, followed by feedback-dependent modulation during the deceleration phase.

In studies of reach-to-grasp, patients with stroke demonstrate slowed hand transport, prolonged terminal phase of reach-to-grasp, earlier and larger grip apertures, and circuitous hand paths (Lang et al. 2005, 2006; Nowak et al. 2007; Wenzelburger et al. 2005). Patients also show impaired coordination of fingertip forces during grasp and lift (Blennerhassett et al. 2006; Hermsdörfer et al. 2003; Nowak et al. 2003; Raghavan et al. 2006a); however, their grasp strategy has not been quantified. Identification and quantification of patients' hand posture at grasp would reveal whether they use an impaired version of the strategy used by controls or whether they use a qualitatively different "compensatory strategy" to complete the task. We define compensatory strategy as the (partial) recovery of a goal-directed coordinated movement with the affected limb using residual neural resources to control alternative muscles or joints. Thus compensation implies that there is some degree of effector redundancy that can be exploited to achieve task goals. Patients with stroke have been shown to use various compensatory strategies to improve function; for example, trunk flexion is used to compensate for inadequate reach (see Cirstea and Levin 2000; Levin et al. 2004; Michaelsen et al. 2004; Roby-Brami et al. 1997, 2003).

The purpose of the present study was to *1*) determine whether patients with mild hemiparesis adopt a qualitatively distinct compensatory strategy to shape their hand when they reach and grasp a rectangular, a concave, or a convex object; and *2*) determine whether the strategy is used feedforward during reach acceleration and/or emerges during reach deceleration. The rectangular, concave, and convex objects used were similar in size but have been shown to require sufficiently

different hand postures to produce measurably different excursions in finger abduction, metacarpophalangeal joints (MCPs), and proximal interphalangeal joints (PIPs) (Santello and Soechting 1998; Schettino et al. 2003; Winges et al. 2003). We applied discriminant analysis to quantify the extent to which object shapes were discriminated over the course of reach-to-grasp (Santello and Soechting 1998). Parts of this work were presented at the annual conference of the Society of Neuroscience in Atlanta 2006.

METHODS

Eight patients with mild right hemiparesis (five women and three men between the ages of 27 and 79 yr), who had the ability to reach and grasp objects and did not have deficits in other nonmotor domains, and eight age-matched (± 2 yr) control subjects participated in the study. All patients had sustained a single unilateral stroke ≥ 3 mo previously and 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 Fugl-Meyer Scale (FMS) (Fugl-Meyer et al. 1975). Hand function was assessed using the Wolf motor function test (WMFT; Wolf et al. 2001) and the Purdue pegboard test (Desrosiers et al. 1995). The clinical characteristics of the patients are shown in Table 1.

All subjects met the following inclusion criteria: *1*) right-hand dominant as confirmed by a laterality quotient of more than +80 on the 10-point Edinburgh Handedness Inventory (Oldfield 1971); *2*) ability to grasp and lift objects with the involved right hand; *3*) score of $\leq 25/33$ on the wrist and hand subcomponents of the FMS (Fugl-Meyer et al. 1975), suggesting impaired wrist and hand control; *4*) presentation with either a pure motor or a sensorimotor lacunar syndrome; *5*) score of >24 on the Folstein's Mini Mental Status examination (Cockrell and Folstein 1988), ruling out clinically significant cognitive dysfunction; *6*) ability to perceive the direction of passive displacements of the metacarpophalangeal (MCP) joints of all five digits with eyes closed, suggesting clinically intact joint position sense; *7*) intact visual perception on screening with the Block Design Test (Wechsler 1981); *8*) ability to recognize object shapes as per a verbal description of each shape; *9*) ability to bisect a straight line within 5% of the midpoint, ruling out clinically significant spatial neglect (Schenkenberg et al. 1980); *10*) ability to accurately demonstrate use of scissors, suggesting absence of ideomotor apraxia (O'Hare et al. 1999); *11*) subcortical location of stroke, verified by official radiology report and from viewing of brain magnetic resonance imaging, FLAIR (fluid-attenuated inversion recovery) sequence, by J. W. Krakauer (subjects with hemiparesis 3, 4, and 6), from official radiology reports (subjects with hemiparesis 2, 5, and 8), and from the subject's medical record (subjects with hemiparesis 1 and 7). 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 mo; or *4*) treatment with intrathecal baclofen. Patients 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.

Experimental protocol

Subjects sat in front of a height-adjustable table with their right upper arm aligned with the shoulder and the forearm parallel to the floor when the elbow was flexed to 90°. They wore an instrumented glove (CyberGlove; Immersion, San Jose, CA) on their right hand. At the start of each trial, the hand rested at a fixed location on the table, with the palm facing downward and the fingers making a loose fist. We ensured that starting hand posture was the same across trials for each subject by visual inspection and confirmed it by statistical comparison of initial joint angles both within and across the two groups. The object was placed on the table in front of the subjects at a distance of 75% of arm's length (range = 51–58 cm) and oriented perpendicular to their forearms. Objects of three different shapes—rectangular, concave, and convex—but similar dimensions were used because they have been shown to require distinct hand postures that evolve over the course of reach-to-grasp (Santello and Soechting 1998; Schettino et al. 2003; Winges et al. 2003). The order of presentation of the objects was counterbalanced across subjects. Since an object may be grasped in a number of different ways, we maximized the possibility that hand posture would reflect object shape by instructing subjects to perform the task in the following standardized manner: *1*) reach toward the object with their affected right hand (or corresponding hand in age-matched controls) at their preferred speed following an auditory cue; *2*) grasp the object using the whole hand, with the thumb on the planar surface and the four fingers spread out along the shaped surface of the object (Fig. 1*A*); and *3*) lift it after all digits made contact with the object. The task was first demonstrated by the investigator and then the subjects performed one or two trials to demonstrate understanding of the instructions. Seven blocked trials

TABLE 1. *Clinical characteristics of subjects with hemiparesis*

Patient/Side[a]	Age, yr/Gender[b]	Lesion Location[c]	TSS[d]	MAS[e]	FMS[f] W and H/30	FMS[f] UE/66	Purdue Pegboard[g]	WMFT[h] 8 to 13	WMFT[h] 15
1R	27F	L basal ganglia and IC	36	1, 1 +, 1	24	48	2.4	10.2	6.3
2R	34M	L putamen-capsular hge[i]	109	0, 1 +, 0	20	56	5.2	10.0	5.8
3R	54F	L PL IC	3	0, 0, 1	16	44	4.4	6.5	4.0
4R	75F	L PL IC and thalamus	69	0, 0, 1	18	46	7.2	4.8	3.7
5R	79F	L IC	37	0, 1 +, 0	20	40	1.6	12.5	7.2
6R	66F	L IC	7	0, 0, 0	25	55	10.6	4.6	3.7
7R	59M	L IC	29	0, 2, 1+	21	44	3.2	9.1	5.3
8R	57M	L IC	5	1, 1 +, 1	22	46	4.8	7.8	5.2

[a] Side of hemiparesis; [b] M, male, F, female; [c] all lesions refer to infarcts, except in patient 2: L, left, BG, basal ganglia, IC, internal capsule, PLIC, posterior limb of the internal capsule; [d] TSS, time since stroke, in months; [e]MAS, Modified Ashworth Scale, with scores across the involved shoulder, elbow, and wrist joints; [f]FMS, Fugl-Meyer Scale, with scores of the wrist and hand out of a maximum of 30 and those of the total upper extremity out of a maximum of 66; [g]Purdue pegboard scores represent the average number of pegs inserted in 30 s over five trials; [h]WMFT, Wolf Motor Function Test, where scores represent the average time taken, in seconds, to complete tasks 8–13 involving fine motor skills versus all 15 tasks; [i]hge, hemorrhage.

A

B Discriminant space

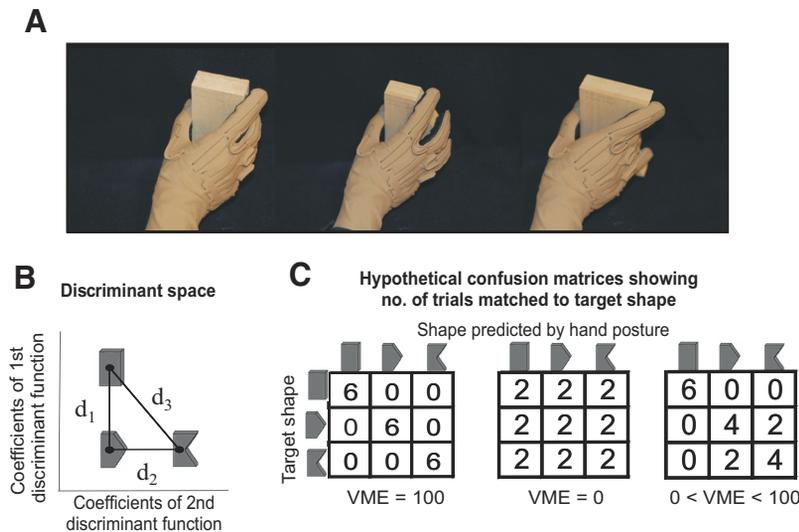**C** Hypothetical confusion matrices showing no. of trials matched to target shape

FIG. 1. Subjects grasped each object using the whole hand with the thumb on the planar surface and the 4 fingers spread out along and conformed to the shaped surface of the object (*A*). The extent to which hand posture discriminated the 3 shapes was quantified by the visuomotor efficiency (VME) index. First discriminant analysis was performed to determine whether the hand postures for the 3 shapes were reliably different from each other, by allocating each trial to the shape to which it corresponded most closely in discriminant space, i.e., the space formed by the discriminant functions (*B*). To detect any overlap in the hand postures for the 3 shapes, the results from the discriminant analyses were used to construct a confusion matrix that summarized the extent to which the hand posture on each trial correctly predicted the shape of the grasped object. Each entry in this matrix represents the number of trials for which the target shape (*rows*) was predicted by hand posture (*columns*) (*C*). If the subject's hand posture matched the target shape at each trial, all entries would be on the diagonal.

per object shape (21 trials) were recorded and subjects were given adequate rest breaks to prevent fatigue.

Data analysis

Wrist position was recorded using an electromagnetic position sensor (Polhemus, Colchester, VT) and its output was sampled at 120 Hz. The onset and offset of reach were determined by time at 10% of peak horizontal wrist velocity because this value was found to consistently capture the beginning and end of wrist movement across all subjects. Time at object lift-off determined termination of reach-to-grasp. The duration of the reach-to-grasp movement was defined as the time between reach onset and object lift-off and was normalized to 100% for comparison across subjects in the two groups. The normalization procedure was justified because the temporal evolution of reach-to-grasp in healthy individuals has been shown to be independent of reach speed (Santello and Soechting 1998; Schettino et al. 2003; Winges et al. 2003). The normalized reach-to-grasp duration was divided into three phases: *reach acceleration* (reach onset to time at peak horizontal wrist velocity), *reach deceleration* (time at peak horizontal wrist velocity to reach offset), and *grasp* (reach offset to lift-off). The duration of the three phases was proportionally the same in subjects with hemiparesis and controls (see RESULTS). Hand posture was recorded by 14 bend sensors embedded in the instrumented glove. These sensors corresponded to the MCP and PIP joints of the four fingers, the angles of MCP joint abduction (ABD) between adjacent fingers (index-middle, middle-ring, and ring-small), the MCP, and interphalangeal (IP) joints of the thumb, as well as the angle of thumb rotation (ROT) about an axis passing through the trapeziometacarpal joint of the thumb and index MCP joint. Flexion and abduction were defined as positive; the MCP and PIP angles were defined as 0° when the finger was straight and in the plane of the palm. At the thumb, positive values of thumb rotation denoted internal rotation. The spatial resolution of the CyberGlove was 0.1°. The glove's calibration was verified for each subject prior to data collection by comparing the joint angle output from the glove for specific hand postures (for example, flat hand posture requiring 0° of MCP and PIP extension and flexed hand posture requiring 90° of MCP and PIP flexion), with the anatomical joint angle measured using a handheld goniometer.

MEASUREMENT OF FINGER JOINT EXCURSIONS AT GRASP. Abduction, PIP, and MCP excursions of the index, middle, and ring fingers differ for rectangular, concave, and convex objects (Santello et al. 1998; Schettino et al. 2003) (see Fig. 1*B*). To characterize the grasp impairment in patients compared with controls, we examined the difference in the magnitude of finger abduction, PIP, and MCP across

the index, middle, and ring fingers for each shape at the end of grasp. To determine which joints were modulated most with respect to object shape at grasp, we calculated the difference in joint excursions for the concave and convex shapes (concave–convex difference), two shapes that have been shown to elicit reliably different hand postures (Schettino et al. 2003). In a prior study in healthy subjects (Santello and Soechting 1998), maximal differences between concave and convex shapes across the index, middle, and ring fingers were 5–10° in the MCP joints and 10–15° in the PIP joints at the end of grasp. The existence of a qualitatively different grasp in patients would be inferred by showing that the maximum concave–convex difference, in the 5–10° range, occurred at different joints compared with controls.

DISCRIMINATION OF HAND POSTURE TO OBJECT SHAPE. The Visuo-Motor Efficiency (VME) index quantifies the consistency with which hand posture discriminates the three shapes across trials (Santello et al. 1998). It is computed by a three-step process using cumulative joint position data from each of the 14 joints itemized earlier (see *Data analysis*) for the three shapes. *1*) Discriminant analysis (Johnson and Wichern 1992) was first performed to determine whether the hand postures for the three shapes were reliably different from each other, as described previously (Santello and Soechting 1998). In brief, this analysis computes discriminant functions that are linear combinations of joint angles that maximize the ratio of between-group variance to within-group variance; here each group consisted of joint position data from seven trials toward each shape (21 trials). Thus the value of the discriminant function reflects minimum joint angle variability across trials within each shape and maximum joint angle variability across trials between the three shapes. We verified that the within-shape joint angle variability was similar in controls and patients by examining the SDs across all joints for each shape at the end of each of the three phases of reach-to-grasp between the two groups (see RESULTS). After group means were computed, each trial was allocated to the target shape to which it corresponded most closely in discriminant space, i.e., the space formed by the discriminant functions (Fig. 1*B*). The normalized coefficients of the discriminant functions were later examined to determine which joints contributed most to the variance between shapes in patients versus controls. *2*) To detect any overlap in hand postures for the three shapes, results from the discriminant analyses were used to construct a confusion matrix (Johnson and Wichern 1992; Sakitt 1980), which summarized the extent to which the hand posture on each trial correctly predicted the shape of the grasped object. Each entry in this matrix represents the number of trials for which the target shape (rows) was predicted by hand posture (columns) (Fig. 1*C*). If the subject's hand posture matched the target shape for each trial, all entries would be on the diagonal. *3*) To define
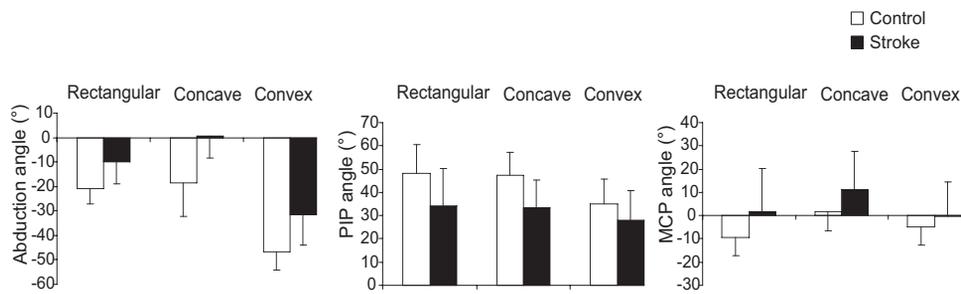
FIG. 2. The average (±SD) abduction, proximal interphalangeal joint (PIP), and metacarpophalangeal joint (MCP) angles of the index, middle, and ring fingers for the rectangular, concave, and convex shapes at the end of grasp in controls (white bars) and patients with hemiparesis (black bars) are shown. Negative numbers represent abduction and extension and positive numbers represent flexion. Note that patients showed reduced abduction and PIP flexion, but increased MCP flexion compared with controls.

the extent to which the hand posture reflected the object's shape, the entries from the confusion matrix were further analyzed by computing the ratio between the information transmitted by the hand posture and the maximum possible amount of information that could be transmitted, i.e., three hand shapes associated with the three object shapes (Sakitt 1980; Santello and Soechting 1998); this ratio is the VME (Fig. 1C). Since the VME was computed using all the measured joints of each digit at every 5% interval of the reach-to-grasp movement, it succinctly summarized information about the degree to which hand posture discriminated object shape over the course of reach-to-grasp. To determine whether hand posture was discriminated feedforward during reach acceleration and/or emerged during reach deceleration we calculated the slope of the VME using data at each 5% interval of reach-to-grasp for the acceleration (reach onset to peak wrist velocity), deceleration (peak wrist velocity to reach offset), and grasp (reach offset to lift-off) phases.

Statistical analysis

Repeated measures ANOVA (RM-ANOVA) using a priori contrasts were performed on the following primary variables: 1) Joint execution strategy was analyzed by joint (average abduction, PIP, and MCP angles of the index, middle, and ring fingers) × shape (rectangular, convex, concave) × group (control, stroke) ANOVA; the concave–convex difference across joints indicated a difference in shaping strategy. 2) Discrimination of hand posture to object shape over the course of reach-to-grasp was analyzed by phase (acceleration, deceleration, and grasp) × group ANOVA on the change in VME (slope) during each phase. Secondary variables were then analyzed using RM-ANOVA to support the conclusions from the primary analyses and included 1) timing of the three phases of reach-to-grasp, 2) joint range of motion, 3) timing of peak joint extension, and 4) within-shape joint angle variability across all the joints (SDs) for each shape in controls versus patients. Relationships between execution of grasp and clinical measures were analyzed with Pearson's correlation tests. Data from one control subject was excluded from statistical analysis because joint trajectories revealed an excessive

delay (>3SD) between object contact and lift-off unlike that in other controls. Thus results from seven controls and eight subjects with hemiparesis are reported. The P value for the primary variables and correlation analyses was set at <0.05, after adjustment for multiple comparisons using Keppel's modified Bonferroni correction (Keppel 1991; Raghavan et al. 2006a). The P value for the secondary variables was set at <0.05.

RESULTS

Grasp execution was impaired in patients

Patients with hemiparesis had a motor deficit in their affected hand based on their FMS scores and reduced performance on the Purdue pegboard test and WMFT (Table 1). They took significantly longer to perform the reach-to-grasp movement compared with controls [control = 1.78 ± 0.33 s, stroke = 2.95 ± 1.02 s, group difference, $F_{(1,13)} = 8.238$, $P = 0.013$], although the proportional duration of reach acceleration (reach onset to time at peak horizontal wrist velocity), reach deceleration (time at peak horizontal wrist velocity to reach offset), and grasp (reach offset to lift-off) were comparable in both groups [phase × group, $F_{(2,26)} = 0.188$, $P = 0.830$]. All subjects formed a loose fist at initiation of reach-to-grasp and the average magnitude of abduction and flexion at the PIPs and MCPs of the index, middle, and ring fingers was similar across the three shapes in both groups [joint × group, $F_{(2,26)} = 1.015$, $P = 0.376$]. At the end of the grasp phase (i.e., at lift-off) patients showed significantly reduced finger abduction, PIP flexion, and MCP extension across the index, middle, and ring fingers compared with controls (Fig. 2) for all three object shapes [joint × group, $F_{(2,26)} = 3.921$, $P = 0.032$]. Thus patients demonstrated an obvious quantitative deficit in grasp execution. When extending the fingers from a flexed position of the hand at movement onset (Table 2, peak flexion) to peak extension, patients extended their PIPs slightly more (closer to 0 deg) and

TABLE 2. *Finger range of motion*

Joint	Peak Flexion, deg		Peak Extension, deg		Range, deg	
	Control	Stroke	Control	Stroke	Control	Stroke
PIP						
Index	50.8 ± 18.2	42.8 ± 20.7	27.5 ± 11.0	16.20 ± 12.8	23.3 ± 14.5	26.6 ± 10.5
Middle	60.5 ± 16.4	56.5 ± 16.8	29.4 ± 14.5	18.80 ± 12.4	31.1 ± 14.7	37.7 ± 10.0
Ring	59.5 ± 15.7	61.3 ± 14.9	28.2 ± 12.1	17.20 ± 10.4	31.3 ± 24.3	44.1 ± 14.4
MCP						
Index	38.9 ± 17.5	37.3 ± 11.3	-3.5 ± 8.6	-4.60 ± 9.2	42.5 ± 11.3	41.9 ± 16.8
Middle	42.9 ± 20.9	45.4 ± 8.3	-3.7 ± 5.8	0.17 ± 8.8	46.6 ± 19.4	45.2 ± 13.1
Ring	36.2 ± 14.2	45.5 ± 9.4	-2.9 ± 3.9	1.40 ± 9.2	39.1 ± 12.7	44.1 ± 15.5

Values are average ± SD for peak flexion, peak extension, and total average range of motion (flexion minus extension) at the proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joints of the index, middle, and ring fingers in controls and patients. Note that the range of PIP extension is slightly larger, whereas that of MCP extension is slightly reduced in patients; however, there were no significant differences in range of motion at the PIPs or MCPs between the two groups.

extended their MCPs slightly less than controls (Table 2), but the range of PIP and MCP excursion was similar in the two groups [group difference, $F_{(1,13)} = 0.500$, $P = 0.492$]. The timing of peak PIP/MCP extension in normalized reach-to-grasp time was also similar in both groups [controls = $45.6 \pm 2.6\%$, stroke = $44.1 \pm 6.0\%$, group difference, $F_{(1,13)} = 0.386$, $P = 0.543$].

Patients and controls used different joints to modulate hand posture to object shape at grasp

We then asked whether patients used a different set of joints compared with controls to shape their hand to the rectangular, concave, and convex objects at object lift-off. We reasoned that if the joints that showed the largest difference between the concave and convex shapes differed between patients and controls, it would suggest a qualitative change in shaping strategy in the patients. Figure 3 shows representative trajectories of the abductors, PIPs, and MCPs from one control subject and one patient in normalized time while reaching-to-grasp a rectangular, concave, and convex object. The control subject (#4) showed largest modulation in finger abduction

across the three shapes. PIP excursions of the middle digit were also modulated, whereas MCP excursions were similar across all three shapes. The patient (#5) also showed largest modulation in finger abduction. However, PIP excursions remained similar across the three shapes, whereas MCP excursions were varied instead. To quantify these differences in joint excursions, we calculated the concave–convex difference at the end of grasp using the average abduction, PIP, and MCP angles of the index, middle, and ring fingers. Figure 4 shows that the concave–convex difference was similar for finger abduction, but showed opposite patterns for the PIPs and MCPs in the two groups: the concave–convex difference was greater at the PIPs in controls, whereas it was greater at the MCPs in patients [joint $\times$ group, PIPs vs. MCPs, $F_{(1,13)} = 7.108$, $P = 0.019$]. Therefore although the two groups modulated abduction angles in a similar fashion, controls appeared to mainly use their PIPs to conform the hand to object geometry, whereas the patients used their MCPs to do so. Thus the patients differentiated their hand posture to object shape at grasp using a qualitatively different joint strategy compared with controls.
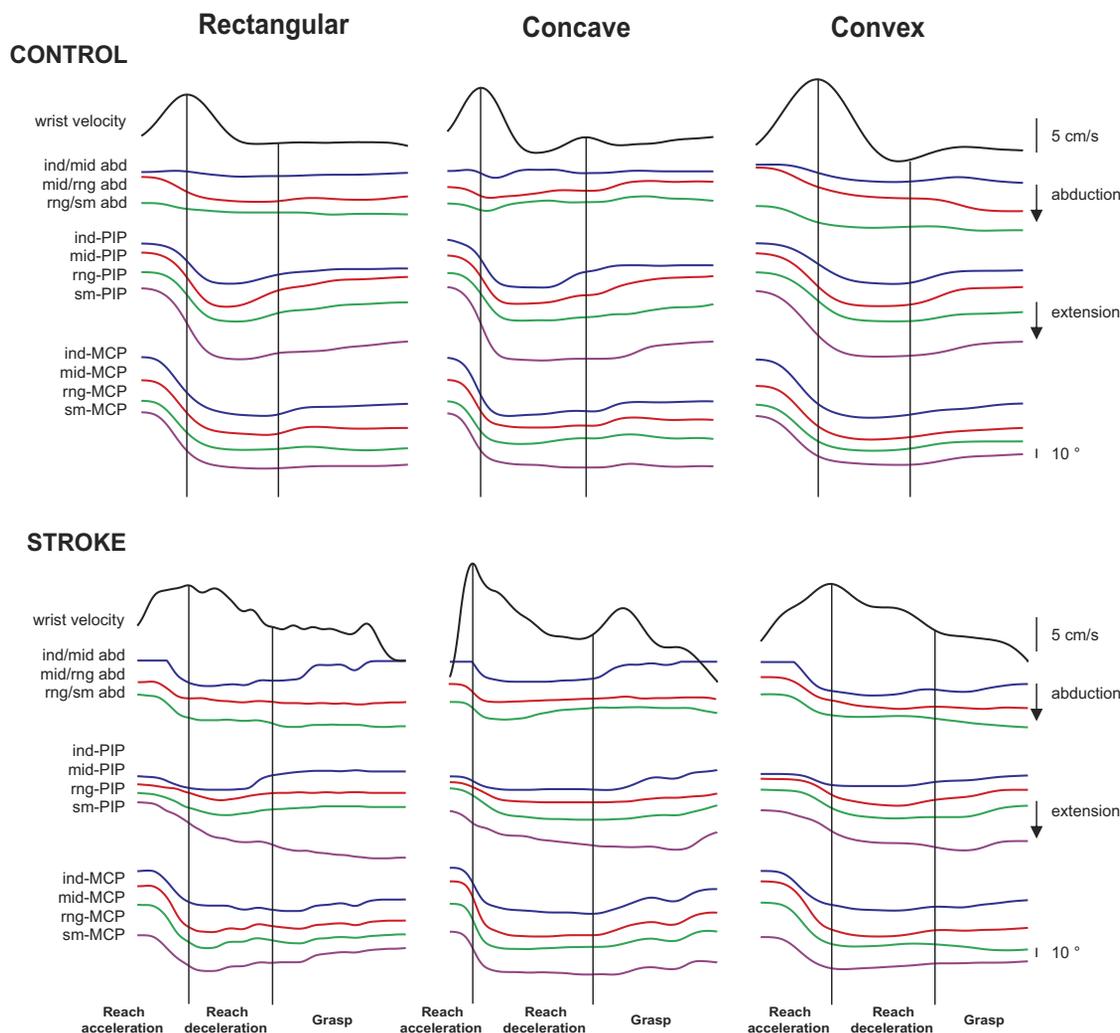

FIG. 3. Representative joint data at grasp from one control and one patient is shown. The data are normalized to the duration of reach-to-grasp. The 2 lines demarcate the 3 phases of the movement based on wrist velocity. Note that the control subject (#4) differentiated the 3 shapes mostly by varying the abduction angles. The PIP excursions of the middle digit also differentiated the concave and convex shapes, but MCP excursions were more similar across all 3 shapes. The patient (#5) was also able to vary the abduction angles across the 3 shapes. The PIP excursions were more similar across the 3 shapes, whereas the MCP excursions appeared to vary instead.
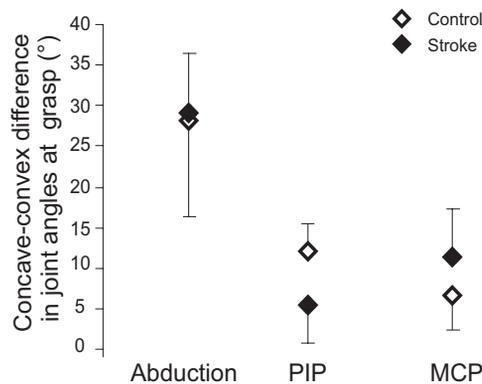
FIG. 4. The difference in average magnitudes ($\pm$SD) of finger abduction, PIP and MCP excursions across the index, middle, and ring fingers for the concave and convex shapes in the 2 groups are shown. While the 2 subject groups modulated abduction angles to object geometry in a similar fashion, controls varied their PIP joints more at grasp, whereas patients varied their MCP joints more.

Evolution of hand shaping and its relationship to joint strategy

Although we were able to show that the largest concave–convex difference was expressed at different joints in controls and patients (i.e., the MCPs and PIPs, respectively), this finding does not tell us how well the hand differentiated between the three shapes. In other words, were the patients able to differentiate object shape as well as controls with their altered strategy? In addition, the differences in joint angles at grasp do not tell us how the shape of the hand evolved over the course of reach-to-grasp. To determine whether the patients were able to effectively differentiate hand posture according to object shape over the course of reach-to-grasp, we computed the VME using all 14 joints sampled (see METHODS). The VME specifically quantifies the consistency with which the three shapes are discriminated across trials by calculating discriminant functions that reflect minimum joint angle variability across trials within each shape and maximum joint angle variability across trials between the three shapes. We verified that the within-shape joint angle variability was similar in controls and patients by examining the SDs across all joints for each shape at the end of each of the three phases of reach-to-grasp [phase $\times$ shape $\times$ group, $F_{(4,52)} = 0.609$, $P = 0.658$]. Computation of the VME served two purposes: *1*) it provided a succinct measure of the quality of shape discrimination regardless of the joint strategy used and *2*) it enabled us to examine the evolution of shape-specific hand posture over the course of reach-to-grasp. The utility of the VME can be understood intuitively by imagining a patient who could adopt three distinct hand postures for the three shapes as consistently as controls even though the postures are not as efficient for grasp.

Figure 5 shows the average VME in controls and patients over the course of reach-to-grasp. Note that, overall, patients had a lower VME than controls [group difference, $F_{(1,13)} = 8.440$, $P = 0.012$], which suggests less effective shape differentiation compared to controls. Importantly, however, there was a difference in the pattern of evolution of the VME during the reach acceleration and deceleration phases in the two groups: it increased rapidly in controls during reach acceleration (delta = 48.6%), but barely increased in patients (delta = 3.2%), whereas it increased only modestly in controls (delta =

10.2%) during reach deceleration, but increased markedly in patients (delta = 41.7%) [phase $\times$ group, acceleration vs. deceleration slope, $F_{(1,13)} = 11.706$, $P = 0.005$]. The VME at reach onset was comparable in both groups (34.8 vs. 37.0%). During the grasp phase, controls continued to show a small increase in their VME (delta = 4.5%), whereas patients showed a small decrease (delta = -2.1%). Thus in stark contrast to controls, patients did not discriminate their hand posture consistently across trials during reach acceleration, but did so much more consistently during reach deceleration.

Next we asked whether finger abduction, PIP, and MCP angles contributed differently to the VME in controls and patients. Based on the difference in joint strategy noted in the concave–convex difference at the end of grasp, we reasoned that if patients truly used an alternative, compensatory MCP strategy, the MCPs would be the main contributors to the VME in patients versus the PIPs in controls. This was investigated by examining the magnitude of the joint weighting coefficients for the largest discriminant functions obtained in the computation of the VME. The discriminant functions are linear combinations of joint angles that account for the greatest variance in hand posture across the three shapes. In both controls and patients the first discriminant function accounted for >80% and the second discriminant function contributed to roughly 19% of the variance in hand posture. Figure 6 shows area plots of the absolute value (all values were converted to positive to examine the magnitude) of the normalized coefficients of finger abduction, PIP, and MCP angles that contributed to the first and second discriminant functions in each control subject and patient (each subject is represented by a different color) at the end of reach deceleration, the time at which both groups attain a VME close to their maximum (see Fig. 5). Note that the total height of the plot is similar for the abduction angles but higher for the PIPs in controls versus the MCPs in patients. This provides qualitative support for our conclusion that in contrast to controls, the VME increase in patients with stroke was driven by an MCP strategy during reach deceleration.
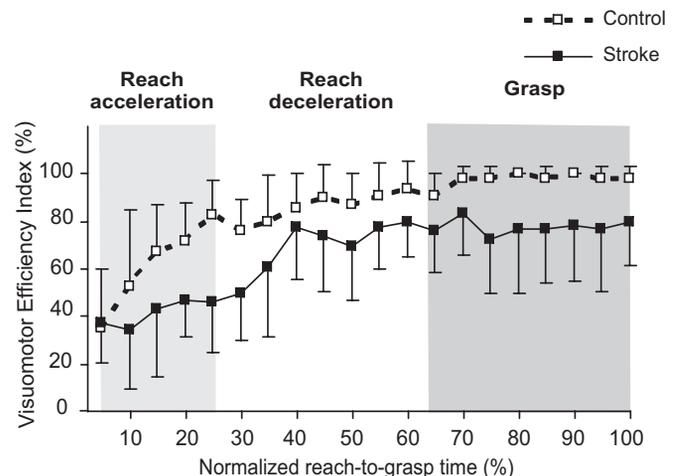

FIG. 5. The average VME ($\pm$SD) at every 5% interval and the slopes of the VME during reach acceleration, deceleration, and grasp phases of reach-to-grasp are shown. Note that controls showed a steep increase in the slope during reach acceleration, which flattened off during reach deceleration and grasp. In contrast, patients showed a flat VME slope during reach acceleration, which became steeper during reach deceleration and flattened off during grasp.
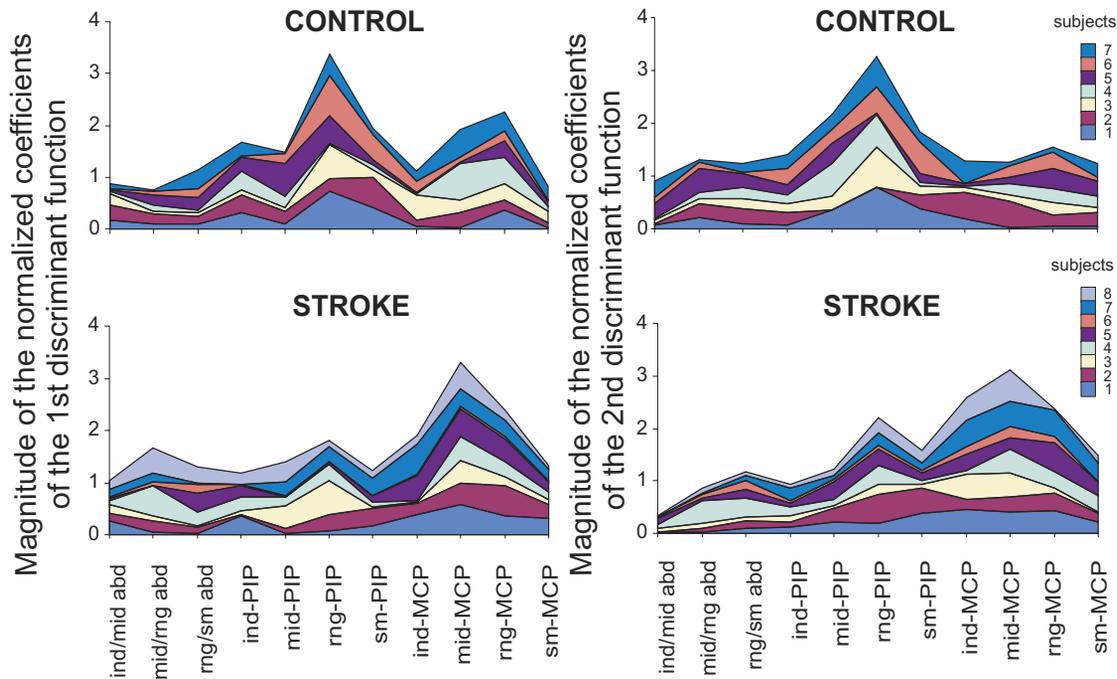
FIG. 6. Area plots of the magnitude of the normalized coefficients (all values converted to positive) of the finger abduction, PIP, and MCP angles of the 1st and 2nd discriminant functions for each control subject and patient (represented by the individual colors) at the end of reach deceleration are shown. Note that the total height of the plot is similar for the abduction angles but higher for the PIPs in controls vs. the MCPs in patients. This provides qualitative support for our conclusion that the VME increase during reach deceleration in patients with stroke was driven by an MCP strategy.

Relationship between clinical impairment and joint strategy

If we were correct in our conclusion that patients did not use their PIPs due to their primary impairment and used their MCPs as a secondary compensatory strategy, then patients with greater impairment would show reduced PIP flexion but increased MCP flexion. To test this, we correlated the average abduction, PIP, and MCP angles of the index, middle, and ring fingers at grasp for the default rectangular shape (shown in Fig. 2) with each patient's FMS scores. We chose the default shape because we were not interested in shape-specific modulation but likely differences in joint strategy across patients. As predicted, patients with lower FMS scores (greater impairment) showed reduced finger abduction ($r = -0.762$, $P = 0.028$), and PIP flexion ($r = 0.748$, $P = 0.033$), but increased MCP flexion ($r = -0.783$, $P = 0.022$) (Fig. 7). These correlation results suggest 1) that the stroke had an effect on control of finger abduction, PIP flexion, and MCP extension; and 2) that the MCP flexion strategy for shaping of hand posture was compensatory in response to impairment.

DISCUSSION

In this study we quantified the grasp strategy adopted by patients with mild hemiparesis in the context of a reach-to-

grasp task with three different object shapes. We also examined how their strategy evolved over the course of the reach trajectory. All patients had a left subcortical stroke and could perceive object geometry, sense finger movements, and grasp and lift objects (see inclusion criteria in METHODS). We chose to study patients with mild hemiparesis because we surmised that higher-level control deficits are more easily detected when they are not masked by severe weakness. We found that patients were able to adopt qualitatively different hand postures with respect to object shape at the end of grasp, but did so with a strategy that involved modulation of MCP flexion (MCP strategy) rather than modulation of PIP flexion (PIP strategy) seen in controls. However, patients used their MCP strategy during reach deceleration rather than during reach acceleration.

A compensatory grasp strategy after stroke

The patients in this study were clearly impaired in their affected hand, as noted by their scores on the FMS. Kinematic analysis revealed that they prolonged their reach-to-grasp time and showed reduced finger abduction, PIP flexion, and MCP extension at the end of grasp compared with controls. Although
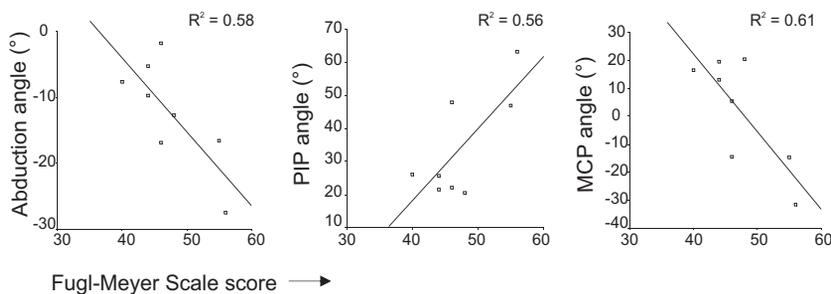

FIG. 7. Correlations between the Fugl-Meyer Scale (FMS) scores and the average index, middle, and ring finger abduction, PIP, and MCP angles for the default rectangular shape at grasp are shown. Patients with lower FMS scores (greater impairment) showed reduced finger abduction and PIP flexion, but increased MCP flexion. These results suggest that individuals with greater levels of impairment compensated by switching over to the MCP strategy.

we did not impose any temporal constraints, patients were instructed to grasp the object in a clearly specified manner, within the limits of their execution deficit, using the whole hand with the thumb on the planar surface and the four fingers spread out along the shaped surface of the object (Fig. 1*A*); the patients did not generate the same pattern of joint angles at the end of movement as that generated in controls. However, they were able to differentiate their hand posture according to object shape at the end of grasp, but did so with a different set of joints, and less effectively compared with controls, as shown by the concave–convex difference and the VME, respectively. In addition, correlations between the FMS scores and joint angles at grasp further support our conclusion that patients were impaired in control of PIP flexion and therefore modulated hand shape by varying MCP flexion across the three shapes. We call this qualitatively different approach a "compensatory strategy." Truly recovered movements are generated by commands to the same muscles as were used before the injury, implying unmasking of undamaged preexisting cortico-cortical connections (Jacobs and Donoghue 1991), by a process similar to skill learning (Plautz et al. 2000). In contrast, compensation is the use of alternative muscles to accomplish the task goal and appears to arise through normal learning mechanisms, presumably arising from plasticity in remaining intact tissue (Metz et al. 2005). Patients with hemiparesis after stroke have been shown to use various compensatory strategies for reaching (Michaelsen et al. 2004; Roby-Brami et al. 1997, 2003), but this is the first time to our knowledge that a compensatory strategy has been described for grasping in patients with hemiparesis.

What were the patients compensating for?

The PIP strategy may be optimal for appropriate force production on contact with an object (Venkadesan and Valero-Cuevas 2008). Patients may have used the MCP strategy rather than the PIP strategy because *1*) deficits in execution at the PIPs somehow precluded flexing or extending them through the required range at the appropriate time and/or *2*) patients had difficulty controlling independent movements at the PIPs. Our data revealed that PIP flexion at movement initiation, the range of PIP excursions over the course of reach-to-grasp, and the relative time taken to open the hand were similar in patients and controls. Patients actually extended their PIPs more than controls during hand opening, suggesting that although there does not appear to be a deficit in PIP execution with regard to average excursions, they may have had difficulty controlling PIP flexion during digit extension, particularly for individual digits. However, we did not test for the ability to individuate PIPs and patients did not use PIP flexion to shape their hand posture at the end of grasp. Our findings are consistent with studies of hand shaping using maximum grip aperture, in which adults with hemiparesis were found to use a slightly larger grip aperture compared with controls (Michaelsen et al. 2009), although the timing of maximum grip aperture was preserved (Lang et al. 2005; Michaelsen et al. 2004). Previous studies have shown that patients with mild hemiparesis, such as the subjects in this study, are impaired in their ability to control independent finger movements (Lang and Schieber 2003; Raghavan et al. 2006b), although the

tasks did not directly address differential control at the PIPs and MCPs.

More fundamentally the MCP strategy is likely a compensatory strategy at the muscle level. Recent work suggests that even "simple" finger flexion movements require time-critical orchestration of all the muscles moving a finger (Venkadesan and Valero-Cuevas 2008) and are sensitive to task constraints (Cianchetti and Valero-Cuevas 2010). Biomechanical analyses of fingertip force (Valero-Cuevas et al. 1998) and finger motion (Kamper et al. 2002) also suggest that simple finger movements require complex coordination of excursions and forces across all muscles (Venkadesan and Valero-Cuevas 2009). Given the multiarticular nature of all finger muscles, the control of individual finger joints is progressively more sensitive to muscle dysfunction in a proximal to distal gradient. This is because control of a given distal joint requires meeting mechanical constraints at all joints proximal to it—but not necessarily vice versa because distal joints are actuated by progressively fewer tendons. Thus coordinating rotations at the PIPs requires precise coordination among all extrinsic and intrinsic hand muscles and this control may be particularly vulnerable to dysfunction poststroke.

The VME is useful because it captures the ability to differentiate hand posture to object shape independent of the quality of execution. The VME value could have been the same for both the PIP and MCP strategies, even though the PIP strategy is better for actual grasp. Similarly, the temporal evolution of the VME in the two groups could have been similar despite differences in the magnitude of the VME. The two main findings pertaining to the VME were that *1*) the value at grasp was lower in the patients than that in controls and *2*) the VME changed predominantly during reach acceleration in controls and during reach deceleration in patients. The lower VME for the patients is perhaps unsurprising; it would only make sense to adopt a shape-differentiation strategy that would allow effective grasp and the MCPs may be inherently more limited in their capacity for modulation compared with the PIPs. The lack of change in VME during reach acceleration suggests that the MCP strategy was not adopted as yet. This is hard to explain based on a primary execution deficit because the hand was maximally open at the same point in the reach trajectory and the joints moved through a similar range as seen in controls. In addition, although control of individual digit motion at the MCPs was likely impaired (Raghavan et al. 2006b), the patients were able to individuate the digits sufficiently to shape the hand using the MCPs during reach deceleration. Further, there is no evidence that control of digit motion depends on the position of the hand in the reach trajectory. Another possibility for the lack of change in VME during reach acceleration is that the patients were impaired in feedforward planning (Raghavan et al. 2006a) of hand posture (affecting the PIPs and MCPs) and so needed to rely on feedback later in the movement to adopt the MCP strategy. Although a complete differentiation between execution and planning deficits is beyond the scope of this study, an interesting experiment to address this question would be to splint the PIPs in controls and then see whether they adopt an MCP strategy and, if so, when. If controls could indeed start to shape the MCPs during the acceleration phase then it would suggest a planning deficit in the patients.

Shaping of hand posture during reach deceleration

Continuous vision of the hand and object is not required for shaping hand posture in healthy individuals (Schettino et al. 2003; Winges et al. 2003). However, visual feedback does play a role in increasing grasp efficiency in the absence of adequate anticipatory control in children (Smyth et al. 2004), when task goals demand increased terminal accuracy (Ansuini et al. 2006) or when the accuracy of the transportation component is degraded, such as during fast movements and/or when there is lack of visual control (Jeannerod 1988). Although blind individuals demonstrate a basic anticipatory strategy, they use kinesthetic feedback through multiple openings and closings of the hand to increase grasp precision (Castiello et al. 1993). Since the subjects with hemiparesis in this study performed the reach-to-grasp movements at their preferred speed, had intact proprioception, and no visual deficits on screening, we propose that they relied on feedback-mediated adjustments of hand posture to adopt their MCP strategy (Fikes et al. 1994). It is possible that with an extended opportunity to practice patients would begin to use the MCP strategy earlier in the movement. This idea is consistent with the finding that feedforward movements can be learned through feedback adjustments in healthy individuals (Bhushan and Shadmehr 1999).

Compensation and the problem of movement coordination

In this study we showed that patients with hemiparesis use a compensatory strategy with opposite patterns of PIP and MCP excursions at the end of grasp compared with controls, which allowed partial discrimination of hand posture to object shape. However, the altered grasp strategy was not apparent at the onset of reach-to-grasp, perhaps indicative of impaired feedforward control, but emerged later in the deceleration phase of reach, perhaps through use of visual feedback. The finding that patients with mild hemiparesis can differentiate hand posture to object shape using an alternative grasp strategy provides a good example of compensatory motor control after stroke. It is interesting to consider compensation after stroke as a special case of the broader problem in motor control of coordinating multiple effectors to work together to achieve a task goal (Diedrichsen et al. 2009). Specifically, the problem of coordination concerns the question of how work is distributed across multiple effectors (muscles, joints, limbs) when there is more than one way to accomplish the task goal. There is debate as to how this redundancy or degrees-of-freedom problem is solved in healthy controls, with some positing internal neural and anatomical constraints often called "synergies" (for a recent review see Tresch and Jarc 2009), whereas others suggest that the specific weighting across effectors is the consequence of an optimization process based on a cost function made up of the goal and the effort/energy required to achieve it (for a recent review see Diedrichsen et al. 2009). In this latter framework, stroke may lead to a change in the cost function, for example, individuating the PIPs may take too much effort or be associated with increased variability; the MCP strategy may be the result of reoptimization in the setting of a new cost function.

Identification and quantification of compensatory strategies in patients with hemiparesis is very important from the standpoint of rehabilitation because it allows a therapist to determine whether the strategy should be discouraged or encouraged

depending on the feasibility of patients attaining their premorbid normal grasp strategy. The implication is that in some patients a compensatory strategy is a habit acquired from falling into a local optimum and they need to be trained out of it, whereas for other patients the compensatory strategy may indeed be the new global optimum.

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