How do strength, sensation, spasticity and joint individuation relate to the reaching deficits of people with chronic hemiparesis?

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Summary
Hemiparetic subjects present with movement deficits including weakness, spasticity and an inability to isolate movement to one or a few joints. Voluntary attempts to move a single joint often result in excessive motion at adjacent joints. We investigated whether the inability to individuate joint movements is associated with deficits in functional reaching. Controls and hemiparetic subjects performed two different reaching movements and three individuated arm movements, all in the parasagittal plane. The reaching movements were a sagittal ‘reach up’ (shoulder flexion and elbow flexion) and ‘reach out’ (shoulder flexion and elbow extension). Joint individuation was assessed by getting each subject to perform an isolated flexion-extension movement at each of the shoulder, elbow and wrist joints. In addition, we measured strength, muscle tone and sensation using standard clinical instruments. Hemiparetic subjects showed varying degrees of impairment when performing reaching movements and individuated joint movements. Reaching impairments (hand path curvature, velocity) were worse in the reach out versus the reach up condition. Typical joint individuation abnormalities were excessive flexion of joints that should have been held fixed during movement of the instructed joint. Hemiparetic subjects tended to produce concurrent flexion motions of shoulder and elbow joints when attempting any movement, one explanation for why they were better at the ‘reach up’ than the ‘reach out’ task. Hierarchical regression analysis showed that impaired joint individuation explained most of the variance in the reach path curvature and end point error; strength explained most of the variance in reaching velocity. Sensation also contributed significantly, but spasticity and strength were not significant in the model. We conclude that the deficit in joint individuation reflects a fundamental motor control problem that largely explains some aspects of voluntary reaching deficits of hemiparetic subjects.

Keywords: movement; fractionation; hemiparesis; stroke; upper extremity

Introduction
A leading cause of disability after stroke is hemiparesis, with poor control of arm, hand and finger movements. As a result, hemiparetic subjects commonly have abnormal reaching movements. In a horizontal plane, reaching deficits include decreased hand velocity (Wing et al., 1990; Roby-Brami et al., 1997), abnormalities in the initial direction of instructed movements (Beer et al., 2000), increases in the curvature or smoothness of the reach path (Levin, 1996; Rohrer et al., 2002) and co-contraction of elbow flexor and extensor muscles (Wing et al., 1990). Studies of reaching in the sagittal plane report similar deficits in velocity and path curvature (Trombly, 1993; Archambault et al., 1999).

Another impairment following stroke is the loss of independent movements of joints or body parts. These types of movements historically have been described as movement synergies (Twitchell, 1951). Attempts at isolated motions (individuation) of one body part are accompanied by excessive, unintended motion of linked segments (Schieber and Poliakov, 1998; Wittenberg et al., 1998; Beer et al., 2000; Lang and Schieber, 2003). Poor individuation has been
quantified by measuring the finger movements of patients with hemiparesis. These studies have investigated specifically whether lesions of the motor cortex or corticospinal pathway affect individuation of finger movements (Schieber and Poliakov, 1998; Lang and Schieber, 2003). Lang and Schieber (2003) show that hemiparetic subjects’ voluntary attempts to move the fingers often result in excessive motion at adjacent fingers and that certain digits were more impaired than others. Deficits in finger individuation presumably would affect many functional activities such as typing or playing a musical instrument.

It is not known whether impairments in functional arm movements (e.g. reaching) are related to individuation deficits. Poor reaching control could be due to a combination of many factors including poor individuation of upper extremity joints, weakness, spasticity and/or sensory loss. Deficits in the individuation of upper extremity joints have not been evaluated specifically, although some studies show that hemiparetic subjects are unable to isolate muscle activity when making many arm movements. In one study of isometric upper limb control, Dewald et al. (1995) report a reduction in the number of possible muscle combinations (i.e. movement patterns) in the paretic limb of hemiparetic subjects, compared with controls. Similarly, other studies report that abnormal coupling of isometric elbow and shoulder torques in the paretic limb of hemiparetic subjects is the predominant abnormality affecting upper limb motor control (Beer et al., 1999; Dewald and Beer, 2001). The patterns that they describe are very similar to the kinds of ‘synergies’ that are often observed clinically in hemiparetic subjects. These abnormal torque couplings suggest that hemiparetic subjects may have a fundamental problem generating, for example, an elbow extensor torque when they have to actively hold the shoulder against gravity. In another recent study, hemiparetic subjects were shown to be impaired in the overall distance that they could reach when moving in many different (mostly forward) directions (Kamper et al., 2002). This limitation in reaching space further supports the idea that activation of anti-gravity muscles at the shoulder can reduce the ability to generate elbow extension torques that are needed to make a ‘reach out’, similar to what was described in isometric reaching studies. Based on these data, one might expect that some reaching movements would be more impaired than others depending largely upon the pattern of motion and torques required at the shoulder and elbow.

One purpose of this study was to determine whether the ability to individuate joint movements predicts deficits when reaching in two specific directions: up, requiring shoulder flexion with elbow flexion, and out, requiring shoulder flexion with elbow extension. We chose these reaching directions to determine if coupling a shoulder flexion motion with elbow extension is more difficult for hemiparetic subjects than simply flexing at both joints. A second purpose was to determine the relative contribution of individuation, strength, spasticity and sensation to reaching abnormalities in hemiparetic subjects. Parts of this work have been reported previously in abstract form (Zackowski et al., 2001).

Methods
Subjects
Eighteen hemiparetic subjects and 18 age- and gender-matched control subjects participated in this study. Individual subject information is given in Table 1. The mean age of the hemiparetic subjects (±SE) was 55.0 ± 2.4 and that for the control subjects was 54.6 ± 2.4 years. For the hemiparetic group, a diagnosis of cerebrovascular accident was required for participation in the study. This was confirmed by a neurological examination and MRI. Hemiparetic subjects were tested between 1 and 269 months post-cerebrovascular accident (32 ± 62 months, mean ± SD) and on the side contralateral to their lesion. Control subjects were matched accordingly.

All hemiparetic subjects met the following inclusion criteria: (i) absence of ataxia and/or cerebellar damage, measured by clinical observation and MRI/CT images; (ii) absence of hemispatial neglect as noted by a score of 52–54 on the BIT star cancellation test; (iii) ability to follow directions as determined by a score of ≤1 on a subset of questions taken from the National Institutes of Health Stroke Scale (Brott et al., 1989); (iv) active range of motion on the affected side of at least 15° in the shoulder and elbow; and (v) passive range of motion on the affected side at least 75% of normal in the shoulder, elbow, wrist and fingers, with minimal to no pain. The Institutional Review Board at Washington University School of Medicine approved the protocol for this study. Informed consent was obtained from all subjects prior to testing.

Paradigm
Subjects were evaluated while making reaching movements and attempting to isolate joint movements. We also assessed all subjects for spasticity, strength and sensation deficits. Subjects performed two sets of fast reaching movements to a target, a ‘reach out’, and a ‘reach up’. The target was a 40 mm Styrofoam ball suspended on a flexible wire in the sagittal plane (Fig. 1). Each subject was given an initial practice trial, and then 4–7 trials were recorded. For all trials, subjects were instructed to reach out and touch the target upon hearing a ‘go’ signal. The instruction was to reach as quickly as possible to touch anywhere on the target.

For the ‘reach out’, subjects were seated with their back supported and with the hand to be tested resting on a pillow in their lap (an ~90° angle at the elbow joint). The target was placed in a position that required the subject to reach using ~40° of shoulder flexion and 40° of elbow extension to touch the target (position 1, Fig. 1A). For the ‘reach up’, subjects were seated identically to the reach out condition. However, the target was placed in a position that required the subject to reach using ~40° of shoulder flexion and 40° of elbow flexion to touch the target (position 2, Fig. 1A).

All subjects also performed three upper extremity individuation movements; one initial practice trial was followed by 4–7 recorded trials for each type of movement. For ‘shoulder individuation’, subjects were seated with their back supported and their arm hanging down next to their body with the elbow extended (Fig. 1B). They were instructed to begin the movement upon hearing a ‘go’ signal and then carefully to raise their arm up to shoulder height, trying not to bend at their elbow or wrist. For ‘elbow individuation’, subjects...
were seated identically to the shoulder individuation movement and were instructed to bend their elbow carefully as far as possible, trying not to move at their shoulder or wrist. For ‘wrist individuation’, subjects were seated with their back supported, upper arm hanging down but with elbow flexed to 90° and their wrist flexed as far as they could comfortably hold it. Subjects were then instructed to extend their wrist carefully as far as possible, trying not to move at their shoulder or elbow.

Spasticity of the affected upper extremity was measured at the shoulder, elbow and wrist joints in the hemiparetic subjects using the MODIFIED Ashworth scale (see Table 1). For this measure, passive movements of flexion and extension of the shoulder, elbow and wrist are graded between 0 (no increase in muscle tone) to 4 (affected parts rigid in one position) (Bohannon and Smith, 1987). The modified Ashworth scale was designed to measure resistance to passive stretch, and is one of the most frequently used measures to grade spasticity (Bohannon and Smith, 1987; Gregson et al., 1999). It has been found to be a reliable and reproducible method of evaluating spasticity (Lee et al., 1989; Gregson et al., 1999). For this assessment, all subjects were positioned supine on a plinth.

The strength of the tested upper extremity was measured using a Microfet2 hand-held dynamometer. We measured strength of the shoulder, elbow and wrist flexor and extensor muscles (see Table 1). The strength testing protocol followed the protocol of Andrews et al. (1996), except that subjects were seated throughout the testing.

Fine touch sensation of the affected arm including the hand were tested.

**Data collection**

Kinematic signals were recorded from all subjects. Kinematic data for the reaching and individuation movements were collected in 3-D at 100 Hz, using an Optotrak motion measurement system (Northern Digital, Inc., Waterloo, Ontario, Canada). Infrared light-emitting diode markers were taped on the centre of the lateral surface of the index finger, head of the fifth metacarpal, wrist joint, elbow joint, shoulder joint and the target (Fig. 1).

**Analysis**

For reaching performance, we defined the start of movement as the time that the wrist velocity exceeded 5% of its peak. The end of the first reach was defined as the time and position at which the wrist velocity dropped to a minimum prior to subsequent corrective movements. Other measures of interest included: (i) peak wrist velocity; (ii) index end point error; and (iii) index finger path ratio. Peak wrist velocity was the maximum linear velocity reached by the wrist joint marker during this time. Index end point error was measured as the total distance between the tip of the index finger and the target at the end of the first reach movement. The index finger path ratio is a measure of the ‘straightness’ of the index finger path from the start of movement to touch of the target (Gilman et al., 1976). It is the ratio of the length of the path actually travelled to an ideal straight line between the start of movement and the position when the finger touches the target. A path ratio of 1 represents a straight path (normal), whereas a path ratio >1 represents an abnormally curved path. Hemiparetic subjects 08, 09 and 15 did not touch the target on every trial; in these cases, we chose the position of the index finger that was closest to the target as their end point.
For individuation performance, the relative motion of instructed versus non-instructed joints using a measure of the normalized joint excursion was determined. We calculated flexion and extension joint angles for the shoulder, elbow and wrist from the 3-D position data; this was necessary since motions were not always perfectly constrained to the parasagittal plane. We did not consider other motions (e.g. shoulder abduction) in this analysis. Joint excursion is defined as the range of motion a joint went through during each isolated movement (regardless of whether the joint was ‘instructed’ or ‘non-instructed’). The average joint excursion values were normalized by dividing the values by the excursion of that joint when it was the instructed joint. Thus, the normalized joint excursion is 1 when a joint is the instructed one and is usually <1 when it is a non-instructed joint. The normalized joint excursion was then used to derive the individuation index (Schieber, 1991). To quantify the degree to which non-instructed joints moved simultaneously with the instructed joints, methods initially developed by Schieber were modified (Schieber, 1991; Lang and Schieber, 2003).

The individuation index is a measure of how well a joint is able to move independently, i.e. without the other joints moving. The individuation index was calculated as 1 minus the average normalized joint excursion of the non-instructed joints, or:

\[
\text{II}_j = 1 - \left( \frac{1}{n} \sum_{i=1}^{n} |D_{ij}| \right)
\]

where \(\text{II}_j\) is the individuation index of the \(j\)th joint, \(D_{ij}\) is the normalized joint excursion of the \(i\)th joint when the \(j\)th joint is instructed, and \(n\) is the number of instructed joints (\(n = 3\)). One is subtracted from the sum of the normalized joint excursions in the numerator and from \(n\) in the denominator to remove the normalized joint excursion of the instructed joint itself. The individuation index will be close to 1 for an ideally individuated movement in which the instructed joint moves with no movement of non-instructed joints and closer to 0 when more non-instructed joint movements occur simultaneously with the instructed joint movement. The individuation index can be negative if the normalized joint excursion for the non-instructed joints is >1. This would only occur if, for example, the elbow flexed more when it was the non-instructed joint versus when it was the instructed joint. A joint individuation index was calculated separately for each of the three individuation movements (shoulder, elbow and wrist) and also averaged to obtain an average individuation index for each subject.

Spasticity, strength and fine touch sensation measures were also evaluated. For spasticity, individual MODIFIED Ashworth scale scores from shoulder flexion, elbow flexion and extension, and wrist flexion and extension were measured; the average value from across the three joints was used for analysis. For strength, values from the shoulder flexors, elbow flexors and wrist extensor muscles were chosen because they were the anti-gravity (agonist) muscles in all movements. The three muscle groups were then averaged and used in all subsequent analyses. For sensation, in each subject, four sites were assessed on the affected arm and given a score based on the smallest monofilament that could be sensed at that location: normal = 0 (i.e. the subject can feel monofilament, 2.83); diminished light touch = 1 (monofilament, 3.61); diminished protective sensation = 2 (monofilament, 4.31); loss of protective sensation = 3 (monofilament, 6.65); and unable to feel the largest monofilament = 4. The four numbers were then averaged; this average value was the sensation score for that subject and was used in all subsequent analyses.

Statistica software (StatSoft, Tulsa, OK) was used for all analyses. Separate, repeated measures analyses of variance (ANOVA) were used to test the reach movements, for differences due to group (control group versus hemiparetic group), condition (reach out versus reach up) and group \(\times\) condition interactions. Similarly, a repeated measure ANOVA was used to test the individuation movements for differences due to group (control versus hemiparetic), joint (shoulder, elbow and wrist) and group \(\times\) joint interactions. In cases where ANOVA revealed significant differences, post hoc comparisons were made using Tukey’s HSD test.

Pearson correlations were used to evaluate the relationships between individuation, spasticity, strength, sensation and months post-stroke in the hemiparetic subject group; a Bonferroni correction was also applied to adjust for multiple comparisons (Hayes, 1994). In addition, hierarchical regression analysis was used to test systematically whether strength, spasticity, sensation and/or individuation index best predicted the curvature of hand paths, end point error and peak velocity during reaching.

**Results**

**Reach performance**

All measures of reaching were abnormal in the hemiparetic group compared with controls. Hemiparetic subjects’ performance was also different in the reach out versus reach up
movements: when reaching up, reach paths were straighter and faster. Figure 2 shows plots of index finger paths and the corresponding joint angles during several trials of a reach up and a reach out movement. In each plot, the asterisk indicates the position/time of the end of the first phase of movement prior to corrective submovements. The asterisks therefore indicate end point error on the index path plots. In Fig. 2A, the index finger paths for a control subject are consistently directed straight toward the target and show little end point error (asterisk) for both types of reaches. Controls also produce smooth and consistent joint movements for both reach out (Fig. 2B) and up (Fig. 2C) movements. Two example subjects with hemiparesis are shown in Fig. 2D–I. Both subjects make straighter, less variable index paths when moving up versus out (Fig. 2D and G) and tended to undershoot the target more than controls in both conditions. Joint angles produced by the hemiparetic subjects were also more variable, with multiple reversals in direction, particularly for the reach out versus up condition (Fig. 2E and F, and H and I).

Figure 3 shows group mean bar graphs (±SE) for peak wrist velocity, index finger path ratios (curvature) and index end point errors for the reach out and up conditions. There was a significant effect of group on all measures, with hemiparetic subjects reaching more slowly, with greater path curvature and with larger end point errors compared with controls (Fig. 3A–C, all \( P < 0.01 \)). There was also a significant effect of condition in that reaching up was faster (\( P = 0.0001 \)) and straighter (\( P = 0.008 \)), but with slightly larger end point errors (\( P = 0.036 \)) compared with reaching out. In addition, there were significant interactions. Hemiparetic subjects improved the straightness of their reach when moving up versus out; this improvement was much greater than that of controls, who made straight
movements in both conditions (group × condition, \( P = 0.015 \)). Finally, hemiparetic subjects increased their speed when moving up versus out, but this improvement was not as great as that seen in the control group (group × condition, \( P = 0.006 \)).

**Upper extremity individuation**

Subjects in the hemiparetic group had varying ability to individuate shoulder, elbow or wrist movements. Figure 4 shows plots of shoulder, elbow and wrist joint angles during several trials of shoulder, elbow and wrist individuation in a representative control and two hemiparetic subjects. During shoulder individuation trials, the control subject in Fig. 4A flexed his shoulder ~73° and consistently added <8° of combined movement at the elbow and wrist joints. This subject’s individuation index was 0.97, indicating very good shoulder individuation. Similar patterns were observed for elbow and wrist individuation, resulting in individuation indices of 0.91 and 0.99, respectively.

Two example subjects with hemiparesis are shown in Fig. 4B and C; both had difficulty making individuated joint movements, although each shows a different pattern of joint movement. Subject 04 in Fig. 4B had a mild deficit in making individuated movements at the three joints tested and moved more slowly than controls. During attempted shoulder individuation (Fig. 4B, top), the shoulder was flexed 70°, in addition to 15° of elbow flexion and 20° of wrist extension; this resulted in an individuation index of 0.79. Similar patterns were observed for attempted individuation of elbow (Fig. 4B, middle) and wrist motions (Fig. 4B, bottom), resulting in individuation indices of 0.83 and 0.87, respectively. This subject always moved the most at the instructed joint, but typically had unwanted movement of the non-instructed joints.

Subject 08 had a severe inability to individuate movement of any joint and also moved slowly (Fig. 4C). This subject always moved most at the elbow, regardless of which of the three joints was the instructed one. When attempting to isolate shoulder movement (Fig. 4C, top), the shoulder was flexed 40° along with 65° of elbow motion and 20° of wrist motion, resulting in a very abnormal individuation index of ~0.29. This index was negative because the wrist actually moved more in this condition than it did when it was the instructed joint, and the elbow moved to a similar extent during this condition and when it was the instructed joint (see Methods, Equation 1). This subject was best at isolating elbow movement (Fig. 4C, middle), with an individuation index of 0.71. Wrist individuation was poor (0.53) because the wrist moved only 10°, while the elbow moved nearly 60° (Fig. 4C, bottom).

Figure 5 shows the individuation indices for all joints tested from subjects in the control and hemiparetic groups. Controls typically showed very good individuation indices (close to 1), with the best indices occurring at the wrist and shoulder and slightly lower indices at the elbow. The hemiparetic subjects’ indices were more variable, and often substantially lower than 1. This indicates that they were unable to move the instructed joint in isolation; instead, they had concomitant movements at the other joints of the arm. A few hemiparetic subjects had negative indices, most often during shoulder individuation. Negative indices were associated with the greatest abnormality; they indicate that one or more of the non-instructed joints (e.g. elbow or wrist) moved more during this condition (e.g. shoulder individuation) than when they were the instructed joints.

**Group means for the individuation index are shown in Fig. 6.** Note that controls perform best at the wrist and worst at the elbow. The hemiparetic group had significantly lower individuation indices for all three joints tested (all \( P < 0.05 \)), but followed the same pattern as controls. Hemiparetic subjects also had deficits actively moving all joints. Table 2 shows the active range of motion for each joint when it was the instructed joint. The hemiparetic group showed significantly reduced range at all joints (\( P < 0.01 \)), although the wrist was the most impaired in terms of active range of motion. Thus, in an absolute sense, the wrist was most impaired in its ability to actively move.

In addition to upper extremity individuation, hemiparetic subjects were each evaluated for spasticity, strength and sensation. Table 1 shows average individuation index, spasticity, strength and sensation measures, along with
months post-stroke for each subject. The individuation index in Table 1 is the average value across the three joints (shoulder, elbow and wrist); we did this to obtain a single index of severity. Likewise, average values of spasticity, strength and sensation measures were calculated. We then determined whether the average individuation index, spasticity score, strength, sensation and months post-stroke were correlated. Table 3 shows correlations for these five variables. Interestingly, we found a significant negative correlation between strength and spasticity ($r = -0.70, P = 0.001$); this shows that hemiparetic subjects who are weaker are also more spastic. In addition, strength was positively correlated with the individuation index. Though not statistically significant, this finding implies that strength may help individuation and that deficits such as reduced corticospinal tract drive may impair strength and individuation ability, rather than having independent effects. All other measures were poorly correlated with one another.
What impairments are related to reach performance?

It is not known how individuation, strength, spasticity or sensation impairments are related to functional movements such as a reach. We attempted to identify which of these impairments was most related to specific features of reaching performance of hemiparetic subjects. In a hierarchical regression analysis, reach path curvature was chosen as the dependent variable because it showed great sensitivity to differences between the control and hemiparetic groups and because it dissociated the results of the overall reaching behaviour better than end point error or velocity. Our analysis shows that the average individuation index explained the greatest portion of the variance in reach path (50%, $P = 0.0002$); sensation explained a smaller portion of the variance in reach path (33%, $P = 0.02$); and strength and spasticity were not as strongly related. In this analysis, strength explained an additional 17% ($P = 0.10$), and spasticity explained an additional 3% ($P = 0.52$) of the variance in reach path.

Although reach path curvature best characterized impaired reaching performance, we also evaluated whether the other measured parameters of end point error and peak velocity were more heavily influenced by strength, spasticity or loss of sensation than by individuation. To do this, we applied the same hierarchical regression analysis using peak velocity and end point error as dependent variables. The results show that peak reaching velocity was influenced most by poor strength (58%, $P = 0.005$); individuation index, spasticity and sensation were not significant in the model. In contrast, end point error, similar to reach path curvature, was most influenced by individuation index (54%, $P = 0.0007$); in addition, spasticity explained a smaller portion of the variance (40%, $P = 0.003$); strength and sensation were not strongly related.

It should also be noted that none of the measured reaching parameters were correlated with the amount of time since stroke. Specific correlation results include: reach path curvature, $r = -0.15$, $P = 0.56$; peak velocity, $r = -0.08$, $P = 0.74$; and end point error, $r = -0.14$, $P = 0.59$.

Discussion

Reaching

Historically, Brunnstrom, Fugl-Meyer, Twitchell and others have observed that hemiparetic subjects often move in...
synergies and typically have trouble using selective movement patterns (Twitchell, 1951; Brunnstrom, 1966; Fugl-Meyer et al., 1975). A synergy movement is defined here as movement of the upper extremity in a relatively fixed pattern when attempting a voluntary movement. Twitchell (1951) specifically noted that flexion movements of the upper extremity were the first voluntary movements to return following a cerebral lesion, and that voluntary movements typically resulted in a whole arm movement with the inability to isolate movements outside of this synergy motion.

More recently, studies have shown evidence that hemiparetic subjects activate specific combinations of muscle groups during isometric and planar movement tasks (Beer et al., 2000; Dewald and Beer, 2001; Lum, 2003). Lum et al. (2003) show an abnormally strong link between flexion of the shoulder and elbow in the paretic arm during an isometric task. They describe strength imbalances in the direction of shoulder and elbow flexion and the resulting synergy pattern. In a separate isometric study, Dewald and Beer (2001) characterized abnormal shoulder–elbow torques and show that an elbow flexion torque is a common secondary torque produced when generating shoulder activity. In a study relating isometric torque patterns to the disturbances in planar arm movements, Dewald et al. (2001) provide further evidence for an impaired capacity to generate certain muscle co-activation patterns in the impaired limb. Beer et al. (2000) show that hemiparetic patients retain the capacity to modulate the initial direction of a planar arm movement, although these movements were systematically misdirected. Their data suggest that this is due to abnormal spatial tuning of muscle activity specific to the elbow when initiating movements and

![Fig. 6](image_url) Mean individuation indices for shoulder, elbow and wrist joints. (A) Control group. (B) Hemiparetic group. Solid black circles, mean wrist individuation index ± SE; open triangles, mean elbow individuation index ± SE; grey squares, mean shoulder individuation index ± SE.

### Table 2: Upper extremity active range of motion of the instructed joint during individuation movements

<table>
<thead>
<tr>
<th></th>
<th>Control subjects</th>
<th>Hemiparetic subjects</th>
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<tr>
<td></td>
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</tr>
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<td>18</td>
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</table>

Mean: 65.03, 118.70, 102.15, 53.39, 91.09, 67.48
Mean (SD): 7.62, 14.67, 12.13, 18.85, 34.03, 37.52

Range of motion of the instructed joint, measured from start of movement to maximum angular excursion during the individuation movement.
results in impaired multijoint control. Overall, these studies point to a specific problem in coordinating appropriate torques at the shoulder and elbow leading to the use of synergy patterns during reaching movements.

In our study, we report differential impairments when subjects reach in two directions: up and out. Hemiparetic subjects make straighter (more normal) paths and reach faster when moving up. Reaching up requires flexion at both the shoulder and elbow, which would be easier for hemiparetic subjects to perform given that they produce a somewhat obligatory flexor pattern at these two joints. In contrast, reaching out requires shoulder flexion and elbow extension, so that subjects have to activate shoulder flexor muscles while relaxing elbow flexor muscles. This pattern appears to be more difficult for hemiparetic subjects to use, possibly due to an inability to break out of their flexor synergy. Another possibility is that upper extremity strength was a factor that caused the two types of reaches to look different. Presumably a reach out requires greater strength to control a lever arm that is getting longer as the reach progresses outward, whereas a reach up has less of a strength requirement because the lever arm is shorter. However, strength was not related to reaching path in our regression model.

### Individuation

The ability to isolate movement at specific joints is essential for many human behaviours. Few studies have directly examined individuation of joint movements. Hager-Ross and Schieber (2000) showed that when healthy subjects attempt to move a single finger, there is often some motion at adjacent fingers. Movements of the thumb, index finger and little finger typically were more highly individuated than were movements of the middle or ring fingers. They speculate that these differences could be due to long-term motor experiences of subjects, the organization of multitendoned finger muscles and/or differences in the central inputs to spinal motoneuron pools (Hager-Ross and Schieber, 2000). Studies of arm control have tested motions similar to our individuated movements (Almeida et al., 1995; Gribble and Ostry, 1999). They find that the non-moving joints are actively stabilized in a predictive manner throughout movement of a single joint. Stabilization is necessary in an individuated movement to offset the forces induced by biarticular muscles and/or to offset the rotational forces that arise due to the motions of linked joints (interaction torques). In this sense, joint individuation is a more global measure of reaching performance relative to measures such as strength, sensation or spasticity. We think that the ability to individuate reflects specific motor control problems essential to a reaching movement.

Control subjects in our study were adept at individuating all upper extremity joint movements, although they performed best at the wrist and worst at the elbow. Wrist individuation might have been best because the mass of the hand is smaller than that of the forearm or upper arm, therefore movement at the wrist requires the least stabilization of proximal joints. As a result, wrist motions produce only small interaction torques at proximal joints (Virji-Babul and Cooke, 1995). In addition, the cross-sectional area and moment arms of wrist muscles are relatively small and cannot influence movement at the elbow to any great extent (Loren et al., 1996). Wrist motions may have induced movement at the fingers; however, evaluation of movement at the fingers was not done in this study. It is unclear why the elbow was most difficult to individuate. One possibility is that elbow motion requires control of biarticular muscles, whereas shoulder motion theoretically could be done using mono-articular muscles. However, this explanation does not address the fact that individuated movements at either of these joints would require stabilization of the non-moving joints to offset interaction torques (Almeida et al., 1995; Bastian et al., 2000). Another possibility may be related to long-term motor experiences of these subjects. For example, in day to day activities, it might be more common to move the shoulder while holding the other arm joints steady and less common to move the elbow while holding the other arm joints steady.

Hemiparetic subjects individuated all joint motions much more poorly than controls. When attempting to move any joint, they typically produced unwanted flexion at the shoulder and elbow. In some cases, these subjects flexed more at the non-instructed versus the instructed joint. Based on the typical clinical presentation of subjects with hemiparesis (distal arm/hand worse than proximal), one might expect that the wrist would have the worst individuation index. This was not the case in our subjects. However, we did not test whether the fingers remained stationary during wrist motion, and it is possible that hemiparetic subjects would show more concurrent wrist–hand motion compared with controls. It should also be noted that hemiparetic subjects’ wrist joints showed the greatest reduction in active movement. Thus, in an absolute sense, the hemiparetic subjects were most impaired in moving the wrist. Finally, we did not study how well hemiparetic subjects produce the correct (instructed) movement at an individual joint (e.g. they may abduct when trying only to flex the shoulder). This was beyond the scope of this study, although it is an important issue for future work.

### Table 3 Correlations

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<table>
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<tbody>
<tr>
<td>Strength and spasticity</td>
<td>( r = -0.70^* )</td>
</tr>
<tr>
<td>Strength and individuation index</td>
<td>( r = 0.53 )</td>
</tr>
<tr>
<td>Strength and sensation</td>
<td>( r = -0.06 )</td>
</tr>
<tr>
<td>Strength and months post-stroke</td>
<td>( r = 0.12 )</td>
</tr>
<tr>
<td>Spasticity and individuation index</td>
<td>( r = -0.39 )</td>
</tr>
<tr>
<td>Spasticity and sensation</td>
<td>( r = -0.06 )</td>
</tr>
<tr>
<td>Spasticity and months post-stroke</td>
<td>( r = 0.02 )</td>
</tr>
<tr>
<td>Individuation index and sensation</td>
<td>( r = -0.03 )</td>
</tr>
<tr>
<td>Individuation index and months post-stroke</td>
<td>( r = 0.13 )</td>
</tr>
<tr>
<td>Sensation and months post-stroke</td>
<td>( r = -0.05 )</td>
</tr>
</tbody>
</table>

\(^{*} P = 0.001.\)
We found no correlation between the individuation index and spasticity; this would suggest that hyperactive stretch reflexes are not the cause of poor isolation of joint movement. In addition, we found poor correlations between the four impairments and months post-stroke, implying that hemiparetic subjects did not tend to improve their reaching ability simply with time since stroke. However, we did find a moderate correlation between the individuation index and strength. Strength deficits in this study could be caused by factors such as reduced corticospinal tract drive and also muscle atrophy. Hemiparetic subjects 09 and 15 are two of the three weakest subjects and have some of the poorest individuation indices (−0.81, and 0.36, respectively). However, this was not true for all subjects. Hemiparetic subject 02 did not follow this pattern (individuation index = 0.79); this subject was also extremely weak but was able to individuate better than subjects 09 and 15. Thus, strength might have affected individuation, but it was not the only influence.

**Parameters relating to reaching performance**

Motor function following stroke historically has been assessed using clinical observations (Twitchell, 1951). Fugl-Meyer et al. (1975) developed one of the first systematic means of evaluating motor function in hemiparetic subjects; this system characterizes the quality of movements using a rating scale. Few investigators have attempted to dissociate which of the parameter(s) may be contributing to these movement deficits. In this study, reach path curvature was identified as the variable that best describes reaching performance, since it was a sensitive indicator of differences between control and hemiparetic subjects. Our data show that reaching performance was not correlated with the amount of time since the stroke (i.e. subjects who had more time to relearn or compensate were not necessarily better at reaching). We then determined whether specific impairments, including joint individuation, strength, spasticity and sensation, explain reaching abnormalities in hemiparetic subjects. We found that individuation scores and sensation explained most of the variance in reaching path curvature in hemiparetic subjects. It should be noted that we assessed sensation using monofilaments, which would directly reflect fine touch but not proprioception. We think that it is likely that both sensory factors such as reduced corticospinal tract drive and also muscle atrophy. Hemiparetic subjects 09 and 15 are two of the three weakest subjects and have some of the poorest individuation indices (−0.81, and 0.36, respectively). However, this was not true for all subjects. Hemiparetic subject 02 did not follow this pattern (individuation index = 0.79); this subject was also extremely weak but was able to individuate better than subjects 09 and 15. Thus, strength might have affected individuation, but it was not the only influence.

**Conclusions**

Our data show that subjects with hemiparesis perform reaching motions directed upward faster and straighter than those directed outward. Hemiparetic subjects tended to produce concurrent flexion motions when attempting any movement, providing one explanation for why they were better at reaching up (requiring shoulder and elbow flexion) versus reaching out (requiring shoulder flexion and elbow extension). Our analyses show that joint individuation deficits are most correlated with abnormal reaching performance, followed by sensory deficits. We conclude that hemiparetic subjects show distinct deficits in joint individuation that reflect a fundamental motor control problem explaining some aspects of voluntary reaching deficits of hemiparetic subjects.

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