Title

Finger strength, individuation, and their interaction: Relationship to hand function and corticospinal tract injury after stroke.

Journal
Clinical neurophysiology : official journal of the International Federation of Clinical Neurophysiology, 129(4)

ISSN
1872-8952

Authors
Wolbrecht, Eric T
Rowe, Justin B
Chan, Vicky
et al.

Publication Date
2018-04-03

Peer reviewed

Published in final edited form as:
Clin Neurophysiol. 2018 April ; 129(4): 797–808. doi:10.1016/j.clinph.2018.01.057.

Finger Strength, Individuation, and their Interaction: Relationship to Hand Function and Corticospinal Tract Injury after Stroke

Eric T. Wolbrecht[1], **Justin B. Rowe**[2], **Vicky Chan**[3], **Morgan L. Ingemanson**[4], **Steven C. Cramer**[3,4,6], and **David J. Reinkensmeyer**[2,4,5,6]

[1]Department of Mech. Engineering, University of Idaho

[2]Department of Biomedical Engineering, University of California at Irvine

[3]Department of Neurology, University of California at Irvine

[4]Department of Anatomy and Neurobiology, University of California at Irvine

[5]Department of Mechanical and Aerospace Engineering, University of California at Irvine

[6]Department of Physical Medicine and Rehabilitation, University of California at Irvine

Abstract

Objective—The goal of this study was to determine the relative contributions of finger weakness and reduced finger individuation to reduced hand function after stroke, and their association with corticospinal tract (CST) injury.

Methods—We measured individuated and synergistic maximum voluntary contractions (MVCs) of the index and middle fingers, in both flexion and extension, of 26 individuals with a chronic stroke using a robotic exoskeleton. We quantified finger strength and individuation, and defined a novel metric that combines them – "multifinger capacity". We used stepwise linear regression to identify which measure best predicted hand function (Box and Blocks Test, Nine Hole Peg Test) and arm impairment (the Upper Extremity Fugl-Meyer Test).

Results—Compared to metrics of strength or individuation, capacity survived the stepwise regression as the strongest predictor of hand function and arm impairment. Capacity was also most strongly related to presence or absence of lesion overlap with the CST.

Conclusions—Reduced strength and individuation combine to shrink the space of achievable finger torques, and it is the resulting size of this space – the multifinger capacity – that is of elevated importance for predicting loss of hand function.

corresponding author, ewolbrec@uidaho.edu.

Conflict of Interest Statement
David J. Reinkensmeyer has a financial interest in Hocoma A.G. and Flint Rehabilitation Devices, LLC, companies that develop and sell rehabilitation devices. The terms of these arrangements have been reviewed and approved by the University of California, Irvine, in accordance with its conflict of interest policies. The remaining authors declare that they have no competing interests.

Significance—Multi-finger capacity may be an important target for rehabilitative hand training.

Keywords

Finger individuation; finger strength; multi-finger strength; stroke; neurorehabilitation; hand function; corticospinal tract (CST) injury

1. Introduction

Many activities of daily living require dexterous use of the fingers, such as opening a door, buttoning a shirt, and holding a fork. Such activities often become more effortful and slower after a stroke, and sometimes impossible to achieve with the hemiparetic hand. Thus, approximately 50% of the 700,000 individuals who survive a stroke each year in the U.S. have persistent upper extremity impairment (Dobkin, 1996; Heller et al., 1987; Ma et al., 2014; Warabi et al., 1990). Understanding the pathophysiological mechanisms that cause reduced hand function is essential for targeting stroke therapies.

Two of the most common and prominent deficits after a stroke are weakness and loss of independent control of the fingers. Weakness is usually more severe distally (Gandevia, 1993), and grip strength is one of the best predictors of functional deficit after stroke (Bohannon et al., 1991; Canning et al., 2004; Dobkin, 1996; Harris and Eng, 2007; Heller et al., 1987; Lang and Beebe, 2007; Ma et al., 2014; Warabi et al., 1990). Weakness appears to arise primarily due to an inability to activate motoneuronal pools (Kamper et al., 2003; Kamper et al., 2006), although other factors, including abnormal muscle coactivation (Kamper and Rymer, 2001) and muscle atrophy may also play a role (Triandafilou and Kamper, 2012). Grip strength has been reported to depend on the integrity of the corticospinal tract, as are other aspects of hand impairment and hand function (Cho et al., 2007; Lindenberg et al., 2010; Nouri and Cramer, 2011; Riley et al., 2011; Rosso et al., 2013; Xu et al., 2015; Zhu et al., 2010). Amplitude of the motor evoked potential (measured from hand muscle activity arising from transcranial, magnetic brain stimulation) is also significantly correlated with grip strength following stroke (Brouwer and Schryburt-Brown, 2006; Lindberg et al., 2012; Thickbroom et al., 2002).

Less is known about the loss of independent control of the fingers. Studies to date have typically focused on developing quantitative measures of synergy, i.e., loss of individuation in people with stroke. For example, one metric of finger individuation, the individuation index (Lang and Schieber, 2003), quantifies how much non-intended fingers move during an attempted, isolated, movement with another finger. People with a stroke demonstrate reduced finger individuation measured with this index (Lang and Schieber, 2003; Schieber et al., 2009) or similar metrics (Raghavan et al., 2006). Some studies have measured isometric force generation instead of free movement of the fingers after stroke, and likewise found “finger enslaving” (Li et al., 2003), reduced force independence (Kim et al., 2014), or increased frequency of generation of unwanted finger movements (Térémetz et al., 2015), all indicative of reduced finger individuation.

It has been hypothesized based on primate lesion/inactivation studies that the CST is a primary mediator of finger individuation (Lawrence and Kuypers, 1968; Schieber and

Poliakov, 1998). In humans, however, this hypothesis is not well tested. Some studies have limited subject populations to those with damage to the CST or primary motor cortex and demonstrated reduced finger individuation (Lang and Schieber, 2003; Lang and Schieber, 2004). But, to our knowledge few attempts have been made to determine if the presence or absence of CST damage correlates with loss of finger individuation.

Critically, in contrast to the well-known contribution of hand strength, the contribution of reduced finger individuation to hand function also remains unclear at present. One study did not find correlation between finger individuation and clinical tests of hand function (Raghavan et al., 2006). Another found that measures of finger individuation based on unwanted extra finger movements correlated with the Action Research Arm Test (ARAT) and the Moberg Pick-Up Test scores (Térémetz et al., 2015).

Understanding the relative contributions of finger strength and individuation to hand function is essential for optimal development and application of stroke therapies, and for clarifying which of these factors should be targeted during rehabilitation. For example, robotic and sensor-based devices are being proposed to target training of finger independence (Adamovich et al., 2009; Dovat et al., 2010; Friedman et al., 2014; Thielbar et al., 2014), but this approach makes most sense if finger individuation plays a leading role in causing loss of hand function. In this paper, we investigated the impact of stroke on both finger strength and individuation, as well as on a novel metric of their combined effect on multifinger force production. We also estimated lesion load of the CST to determine if it correlates with these impairments, and used stepwise linear regression to identify which of these measures best predicted hand function.

2. Methods

2.1. Subjects

Twenty-six individuals with a history of a single stroke were recruited to participate in a parent study (Rowe et al., 2017) that used the FINGER robotic exoskeleton device (Figure 1, (Taheri et al., 2014)) for robot-assisted hand therapy. Four additional subjects completed the parent study, but their data were not analyzed because the torques they generated were very small and noisy, due to the severity of their impairment. All of the participants provided informed consent following a protocol approved by the local Institutional Review Board. The study was registered on Clinical-Trials.gov (NCT02048826).

2.2. Clinical Tests of Hand Function

Besides the Box and Blocks Test, subjects completed the Nine-Hole Peg Test to measure finger function. The tests were administered by a single, blinded, and experienced physical therapist two-weeks prior to a three-week training period with the FINGER robot. The therapist also assessed the Fugl-Meyer Test of the Upper Extremity (See et al., 2013), an impairment-based measure that judges the ability to control arm joints independently and ranges from 0 (no arm movement) to 66 (normal arm movement function). All three clinical assessments were repeated at the conclusion of the three-week training period; results reported here are averages from the two separate assessments. Scores from the Box and

Blocks and Nine-Hole Peg tests were normalized to the performance of the unimpaired arms of the subjects, giving a range of 0–1 for those tests.

2.3. Quantification of Corticospinal Tract Injury

High-resolution T1-weighted and T2 FLAIR (fluid- attenuated inversion recovery) images were acquired using a 3.0T Philips (Best, the Netherlands) Achieva system. Using MRIcron software (http://www.mccauslandcenter.sc.edu/mricro/mricron), each patient's infarct was outlined by hand on the T1-weighted MRI image, informed by the T2 FLAIR image as described previously (Burke et al., 2014). Stroke masks were transformed into MNI (Montreal Neurological Institute) standard stereotaxic space using FSL (Functional Magnetic Resonance Imaging of the Brain Software Library). Stroke masks for patients with right-sided lesions were flipped about the midsagittal plane onto the left hemisphere, to allow direct comparison between patients.

Because fiber tracking with diffusion tensor imaging can be problematic in brain regions affected by stroke, injury to the CST for each patient was quantified by examining the extent to which the stroke infarct overlapped with a template CST generated from healthy controls (Burke et al., 2014; Burke Quinlan et al., 2015; Nouri and Cramer, 2011; Riley et al., 2011). To simulate damage to groups of axons, the template CST was divided into 16 separate longitudinal subsections using a standard canonical template. The number of subsections was determined from a prior report (Riley et al., 2011) which found that dividing the CST into 16 subsections provided the strongest correlations with behavioral status in patients with stroke. For each subject, the binary stroke mask was overlapped onto each CST subsection. The percentage of CST injury was calculated from the summed number of subsections damaged more than 5% (percentage also based on Riley et al. (2011)) divided by the total number of subsections, which was then converted to a percentage. To determine percent damage, the lesions were manually outlined and binarized using validated methods previously reported (Burke et al., 2014). CST injury for subjects with infarcts below the level of the thalamus were omitted from relevant statistical analyses.

2.4. The FINGER Robotic Exoskeleton

The FINGER robot consists of two stacked single-degree-of-freedom 8-bar mechanisms for guiding the index and middle fingers through a naturalistic grasping motion (Taheri et al., 2014; Taheri et al., 2012). FINGER can assist in flexion and extension of index and middle fingers independently or together. During the grasping motion, the metacarpophalangeal (MCP) joint can move from full extension to 60 degrees of flexion. Each mechanism connects to the middle and proximal phalanx of the finger through small load cells (Futek LSB200 miniature s-beam load cells) located on the dorsal surface of the finger (see Figure 1). FINGER is actuated by two brushless linear actuators (Dunkermotoren Servotube STA116-168-S-S03C). The combination of these low-friction actuators and precision low-friction mechanisms makes FINGER highly backdriveable and directly force controllable.

2.5. Robot Tests of Finger Strength and Individuation

The parent study (Rowe et al., 2017) included three weeks of robot-assisted finger training, with three, one-hour sessions per week. During movement training with FINGER the subjects played a musical computer game similar to Guitar Hero (Taheri et al., 2012). While playing the game, they attempted to move their index and middle fingers (both individually or together) to meet streaming musical notes at a specific place and time on the computer screen. Varying levels of robotic assistance were provided to the subjects during gameplay, based on the rate at which they successfully met the notes, following the algorithm described in (Taheri et al., 2014). Further details of the musical computer game and parent study can be found in (Rowe et al., 2017).

In addition to playing the musical computer game, subjects also completed a weekly robotic test designed to quantify finger movement ability. Here, we analyzed a maximum voluntary contraction (MVC) test for measuring finger flexion and extension strength. This test was administered two weeks prior to the three-week training period, at the start of each week of training, and at the conclusion of the training period, for a total of five tests. Each subject also completed these tests once with their unimpaired hand, in order to provide data for normalizing the impaired hand performance.

During the MVC test, the FINGER robot held the index and middle fingers fixed (at an MCP angle of approximately 30 degrees) by simulating a stiff, damped spring. Participants were instructed to "Flex as hard as you can" against the robot: first their index finger alone ("*flex index*"), followed by their middle finger alone ("*flex middle*"), and finally both middle and index fingers at the same time ("*flex both*"). They then repeated this sequence for finger extension. They typically held the flexion or extension for 2–5 seconds, and typically there were 5–10 seconds between the events, which were always performed in the same sequence. An example showing MVC tests in flexion is shown in Figure 2.

2.6. Data Collection and Analysis

Data from all four load cells (two per finger) and the FINGER position sensors were recorded at 1000 Hz during all experiments. Based on the kinematic and mechanical design of FINGER, the measured force on the proximal phalanx (f_p) and middle phalanx (f_m) of each finger were mapped to the equivalent proximal interphalangeal (PIP) torque (τ_{PIP}) and MCP torque (τ_{MCP}), according to

$$\begin{bmatrix} \tau_{\text{PIP}} \\ \tau_{\text{MCP}} \end{bmatrix} = \begin{bmatrix} 0 & r_m \cos(\theta_A) \\ r_p & r_m \cos(\theta_A) + l_p \cos(\theta_B) \end{bmatrix} \begin{bmatrix} f_p \\ f_m \end{bmatrix}, \quad (1)$$

where r_p is distance from the MCP joint to the proximal phalanx force sensor, r_m is the distance from the PIP joint to the middle phalanx force sensor, and l_p is the length of the proximal phalanx. The angle of the middle phalanx force, f_p, is always normal to the dorsal surface. This is not the case with middle phalanx force sensor, where the angle relative to the dorsal surface normal, θ_A, changes during motion. The angle θ_B is the angle of f_m relative to f_p. These two angles, θ_A and θ_B, are determined as a function of actuator position according to the kinematics of the 8-bar mechanism (Taheri et al., 2014).

The calculated MCP torque includes contributions from the forces measured at both the middle and proximal phalanx and thus provides a more complete measure of finger strength during finger flexion than the PIP torque and is our focus here. Unfiltered time-series MCP torque data (Figure 2) were used to identify each flexion event (*flex index, flex middle, flex both*). Bias torques from tone, determined from the intervals between the events, were subtracted from the MCP torque data. Extension torques were much smaller and difficult to identify, and thus not parsed out of the time series. Kinematic and kinetic data were smoothed using a 50th-order windowed linear-phase finite-impulse-response digital filter with cut-off frequency f_c = 100 Hz. Time series with clear outlier data were either trimmed or omitted; for example when flexion events were either missing or could not be clearly identified or when there was clear confusion on the part of the subjects regarding when and how to move their middle and index fingers.

2.7. Quantification of Finger Strength and Individuation from Multifinger Capacity Plots

For the primary analyses below, MCP torque data were combined from all MVC tests across all evaluations from each of the 26 subjects. Plotting index and middle finger torques on the x and y axes, respectively, provided a means to visualize and quantify finger strength and individuation (left side of Figure 3). We term such a plot a “multifinger capacity plot” (or “capacity plot”). A convex hull can be fit such that it circumscribes the torque data (right side of Figure 3). Analysis of the convex hull boundary provides metrics of both strength and individuation, including the total area, which combines both.

To define individuation and strength, a pie-wedge shape (named a “circular sector” in plane geometry) was fit to the convex hull boundary. The radius of the circular sector, which represents an average of strength across the two fingers, was defined as the average of the maximum distances from the origin along three directions: the x-axis, the y-axis, and the $y = x$ direction. To define individuation from a multifinger capacity plot, first note that full individuation ability ($I = 1$) would result in a 90° sector (i.e. a quarter pie wedge), and zero individuation would result in a 0° sector. Thus, individuation can be found from the convex hull area A and the radius r:

$$I = \left(\frac{4}{\pi}\right)\frac{A}{r^2} \quad (2)$$

Examples of circular sectors fit to flexion and extension hulls for both their unimpaired and impaired sides are shown in the right side of Figure 3. Here, we define flexion capacity and extension capacity as the area of the circular sectors in flexion and extension, respectively, as they represent a combined capacity of finger individuation and strength. Below we often report strength and capacity of the impaired hand normalized to the values of unimpaired hand, in which case we identify the measure as “normalized” and report the measure without units. We did not normalize individuation, since individuation scores (e.g. 0 or 1) have interpretations that normalization would obscure. It should be noted that individuation values greater than 1 are possible when MCP torques of opposite signs are recorded from the two fingers (resulting in torque vectors in quadrants II and IV of the multi-finger capacity plots). This appears to be a “leveraging” strategy, in which the subject “pushes off” with one finger to maximize the torque produced by the other finger.

2.8. Statistics and Stepwise Linear Regression

To compare measures of strength, individuation, or capacity, we used paired t-tests across the 26 subjects. To evaluate data normality, we used normal probability plots and the Anderson-Darling test. The %CST injury data showed significant departure from normality, so we used Spearman's method for correlation analysis. For our three response variables (Fugl-Meyer score, Box and Blocks score, and Nine Hole Peg Test score), only the Nine Hole Peg Test score data displayed non-normality due to a floor effect for 9 of 26 subjects who scored zero; when we removed those subjects, Nine Hole Peg Test score data passed normality, and the regression values did not change substantially; capacity was still the strongest predictor (see below). For simplicity and consistency, we report the values for all subjects, as for the other measures, and we used Pearson's method for all correlation analysis. For each clinical outcome, we used stepwise linear regression to identify the simplest model with the strongest predictive power. Table 1 lists the six predictor variables (strength, individuation, and capacity in both flexion and extension) and the three response variables (Fugl-Meyer score, Box and Blocks score, and Nine Hole Peg Test score) considered. All predictor variables were normalized to the unimpaired hand. Linear, quadratic, and cross terms were considered during the stepwise linear regression, which was performed in the forward direction using five different criteria for each (sum-of-squared error, Akaike information, Bayesian information, R^2, and Adj. R^2). The forward direction was chosen because no clear model hypothesis existed and the simplest model was preferred.

3. Results

All subjects had experienced a single, unilateral stroke at least six months before the study, were between 18–73 years old, and were able to score a minimum of three blocks on the Box and Blocks test (see Table 2, (Mathiowetz et al., 1985)). Of the 26 subjects, 54% had hypertension, 54% had hypercholesterolemia, 19% had diabetes mellitus, and 15% had atrial fibrillation. The stroke affected the right arm in 11 and the left arm in 15. Subjects were a median of 19.4 [interquartile range (IQR) 11 – 49] months post-stroke at time of study enrollment. Across subjects, infarct locations varied, including hemispheric and brainstem, affected the cerebral cortex in 15, and had median volume of 5.3 cc [IQR 1.5 – 38.5]. Table 2 shows the demographics and baseline Box and Blocks and Fugl-Meyer scores of the 26 individuals with a stroke who participated in the study. All participants had at least some minimal hand function, defined as ability to lift at least three blocks in the Box and Blocks Test.

3.1. Multifinger Capacity Plots: Visualizing Finger Strength, Individuation, and Capacity

We first present a new way to visualize hand impairment after stroke, "Multifinger capacity plots", which graph index and middle finger torques generated during MVC tests against each other, overlaying tests of each finger in isolation and together (Figure 4). These plots provide a way to simultaneously visualize finger strength (radius of the approximating convex hull) and individuation ability (angular width of the hull). As can be seen, for the 26 individuals with a stroke studied here, flexion torques (hulls in the upper right quadrants) were in general much larger than extension torques (hulls in the lower left quadrants), both before and after stroke (Figure 4). The hulls were more shrunken for fingers that were weaker, and were also often more narrowed so that they looked like cigars, rather than round balloons. The narrowing reflected the inability of these fingers to independently generate torques; the fingers operated in tandem, synergistically generating torque together. In sum, multifinger capacity plots depict the torque generation resource the hands have to work with to achieve manipulative function. The convex hull area is a combined metric of strength and individuation that quantifies this resource, and we will refer to this measure as "capacity".

To validate analyses based on multifinger capacity plots, we tested if the measures of finger strength and individuation derived from these plots correlated with previously used metrics for strength and individuation. Finger flexion strength correlated with pinch grip strength (3-jaw chuck, $p = 0.001$, $R^2 = 0.353$) and lateral pinch strength (lateral/key pinch, $p = 0.004$, $R^2 = 0.295$) obtained with a dynamometer. Finger individuation strongly correlated with the Individuation Index used in previous studies ($p < 0.001$, $R^2 = 0.81$) (Lang and Schieber, 2003; Schieber, 1991), which we calculated from torque path distances of the *flex index* and *flex middle* events of the MVC tests, rather than angular path distances, since the measurements were isometric.

3.2. Finger Strength, Finger Individuation, and their Relationship

Based on analysis of the multifinger capacity plots, finger flexion strength was significantly greater than finger extension strength (MCP torque) both for the impaired hand (2.17 ± 0.93 N-m compared to 0.46 ± 0.18 N-m, $p < 0.001$) and the unimpaired hand (2.69 ± 0.64 N-m compared to 0.74 ± 0.27 N-m, $p < 0.001$). The ratio of flexion to extension strength was 5.06 ± 2.23 for the paretic hand, compared to 3.97 ± 1.46 for the non-paretic, a significant difference ($p = 0.042$). Relative to the unimpaired hand of each participant, the average finger flexion strength was 0.82 ± 0.32, while the average finger extension strength was 0.66 ± 0.28, a significant difference ($p = 0.029$). Normalized finger flexion and extension torques were nearly correlated (Figure 5 left, $p = 0.118$, $R^2 = 0.099$).

Average flexion individuation for the impaired hand was 0.80 ± 0.27 and extension individuation was 1.12 ± 0.30, a significant difference ($p < 0.001$). The two were weakly correlated ($p = 0.028$, $R^2 = 0.186$).

To test the hypothesis that finger weakness and loss of individuation arise from a common mechanism after stroke, we evaluated their correlation for this population of participants with a wide variety of lesion locations and sizes. Flexion strength, normalized to the unimpaired hand, was positively correlated with flexion individuation (Figure 5 right, $p = 0.009$, $R^2 = 0.249$). Normalized extension strength was not, however, correlated with finger extension individuation (Figure 5 right, $p = 0.52$, $R^2 = 0.017$). Thus, finger strength and individuation were related, but only for flexion.

3.3. Relationship to Lesion Overlap with the CST

We quantified CST injury for each participant as the percentage of overlap between the infarct and a healthy control template CST. Six subjects had infarcts below the level of the thalamus, for which the template tract was not available. Of the remaining subjects, three had no lesion overlap with the CST and 17 had an overlap of the CST ranging from 6.25% to

100%. As a first analysis, we divided the participants into three groups: % CST = 0, % CST > 0, and, for completeness, lesion below thalamus (i.e. CST overlap unknown). For the flexion capacity metric, the % CST = 0 injury group was significantly different from the % CST > 0 group ($p < 0.001$), as well as the below thalamus group ($p = 0.003$) (see Figure 6 Left). Thus, for injuries above the level of the thalamus, lesions that overlapped the CST impaired finger capacity compared to those that did not. For the strength and individuation metrics, repeating the same group comparisons did not always produce significant results, although the comparison trended toward significance (flexion strength: $p = 0.040$ for % CST > 0 and $p = 0.064$ for below thalamus, individuation: $p = 0.072$ for % CST > 0 and $p = 0.146$ for below thalamus). In sum, CST injury best corresponded to reduced capacity.

For all three flexion metrics, the below Thalamus and % CST > 0 groups were not significantly different ($p = 1$). None of the groups were significantly different for the extension metrics.

Next, we assessed whether the percentage of CST injury (rather than the presence or absence of CST injury, as in the previous paragraph) correlated with strength, individuation, and capacity in both flexion and extension (for 6 total correlations). Because the % CST injury data was not normally distributed, we used Spearman's rank correlation (Spearman's ρ) for significance analysis. When all injuries above the thalamus were included (% CST ≥ 0), all three flexion metrics (strength, individuation, and capacity) correlated with % CST injury (Figure 6 Right, and Table 3). We also repeated this analysis for the 17 subjects in the % CST > 0 group due to the clear separation between this group and the % CST = 0 group. In this case, none of the three metrics correlated with % CST injury in flexion or extension (Table 3). Thus, while presence or absence of CST injury predicted reduced finger flexion capacity, percentage of CST injury did not correlate with amount of reduction of finger capacity, strength, or individuation (when at least some CST injury was present). CST injury was thus best considered as a binary, rather than graded, predictor of flexion capacity.

3.4. Relationship to Clinical Measures of Hand Impairment and Function

We first assessed to what extent strength (normalized to the unimpaired hand for these analyses), individuation, and capacity (normalized to the unimpaired hand for these analyses) correlated with the Upper Extremity Fugl-Meyer score. We again individually tested these three measures for flexion and extension, for six total correlations (Table 3). For finger flexion, all three measures were positively correlated with the Fugl-Meyer score, with flexion capacity correlated the most strongly (Figure 7). Extension capacity correlated more strongly than strength with the Fugl-Meyer score; extension individuation did not correlate significantly (Table 3).

Next, we analyzed relationship of strength, individuation, and capacity to hand function measured using well-established clinical tests that required rapidly manipulating small objects. Flexion capacity positively correlated the most strongly to both the Box and Blocks score and Nine Hole Peg Test score (Figure 7, Table 3). The other two metrics (individuation and strength) were also positively correlated in the flexion direction. In the extension direction, only capacity correlated significantly with hand function, measured with the Box and Blocks score. In general, the capacity metric accounted for higher variance in the correlations with the impairment and function measures (average R^2 = 0.27 across six functional correlations in Table 3), followed by strength (average R^2 = 0.23) then individuation (average R^2 = 0.15). In addition, the capacity metric correlations were more significant, in terms of p-values, for all six functional correlations (Table 3).

In 10 of the total 15 applications of stepwise linear regression, the resulting model was 1 + FC (normalized flexion capacity, Table 4). The remaining models (some of which are also shown in Table 4) were either minimally more predictive, although the model 1 + (FC)(EC) that added additional complexity through a cross-term combining flexion and extension capacity was more predictive than 1 + FC in terms of effect size R^2. Each resulting model included flexion capacity as a term in the model.

4. Discussion

Loss of finger strength and loss of finger individuation are two motor impairments thought to diminish hand function after stroke. The results of this study suggest that multifinger capacity, which represents the combined effect of strength and individuation, explains more of the inter-subject variance in hand function than either alone. Further validation of the capacity metric came from the finding that it was also significantly related to presence or absence of lesion overlap with the corticospinal tract. We discuss now the implications of this work, as well as limitations and directions for future research.

Why is finger capacity more related to hand function than strength or individuation alone?

Previous studies of the determinants of hand function after stroke have often focused on measuring force production of all fingers working together. One key such study found that it was the inability to activate motor neuronal pools, rather than muscle atrophy, increased passive stiffness, or spasticity, that limited force production (Kamper et al., 2006). Many studies have found that this activation inability, manifested as power grip weakness, is one of the best predictors of functional upper extremity deficit after stroke (Bohannon et al., 1991; Canning et al., 2004; Dobkin, 1996; Harris and Eng, 2007; Heller et al., 1987; Lang and Beebe, 2007; Ma et al., 2014; Warabi et al., 1990).

In contrast, studies that have focused on the role of individuation in hand function are limited and equivocal. One study did not find correlation between finger individuation and clinical tests of hand function (Raghavan et al., 2006). Another found that measures of finger individuation based on unwanted extra finger movements correlated with the Action Research Arm Test and the Moberg Pick-Up Test scores (Térémetz et al., 2015). Another recent report found a strong correlation between both strength and individuation with the Fugl-Meyer score as well as a functional hand score, the ARAT, with similar strengths of correlation for strength and individuation (Xu et al., 2017).

Consistent with these findings that individuation affects hand function, recent studies examining the ability to coordinate hand muscles after stroke support the concept that increased multiple-muscle coupling contributes significantly to hand impairment after stroke. For example, greater hand impairment was associated with greater muscle coactivation in a recent study of hand muscle EMG synergies after stroke (Lee et al., 2013).

Flexor coupling between the thumb and fingers was also found to contribute to undesired thumb movement after stroke, likely impacting hand function (Kamper et al., 2014).

To our knowledge, multifinger capacity, calculated as the area of torque space traced out during individuated and synergistic multi-finger MVCs, does not have a direct comparison in existing literature. This measure assesses the overall finger capacity for generating torques individually and independently, in flexion or extension. We hypothesize that capacity mattered particularly for the type of hand function we studied here – gripping blocks and pegs. One must have enough individuation ability to position the fingers in a way that allows one to grip such small objects, and then be able to exert enough force to maintain the grip on the object.

It is interesting to note that finger capacity is the mathematical product of strength and individuation. The stepwise linear regression procedure considered models that contained the sum of strength and individuation, as well, but it is their product that survived the stepwise selection process. Their product has a geometric interpretation, which is the area of the multifinger capacity plot, which can be understood as the area of the space of achievable flexor finger torques, a key resource for hand function. From the capacity point of view, strength and individuation are very similar. Both require the motor system to generate a balanced pattern of multiple-muscle activity such that a desired force outcome is met. Both work to expand the workspace of achievable finger torques.

Do impairments of finger strength and individuation arise from a common anatomical injury?

In the flexion direction, finger strength correlated strongly with finger individuation, confirming the conjecture that stroke affects both with at least some commonality. In fact, strength and individuation showed comparable correlations to Fugl-Meyer, Box and Blocks, and Nine Hole Peg scores. This is somewhat unexpected, given some previous research suggesting that CST injury affects fine motor control more than strength (Jang, 2009). Analysis of the extension strength and individuation data did not typically provide significant correlations.

Xu et al. (2017) recently reported a nonlinear relationship between strength and individuation after stroke. Initially after a stroke, strength and individuation were strongly correlated for most patients – i.e. the relationship was fairly linear. Then, a year later, patients whose hand strength exceeded 60% of the ipsilesional side (now over half of the individuals) exhibited individuation near maximum that was uncorrelated with strength. This saturation of individuation without full recovery of strength produced a nonlinear relationship. We did not observe a saturation in individuation for the chronic stroke participants studied here, even though they had a wide range of strength recovery. In particular, in the flexion direction, individuation positively and linearly correlated with strength (Fig. 5 right). In the extension direction, strength and individuation were not correlated. The difference with Xu may be due to the apparatus, visual feedback provided, or data analysis techniques for estimating individuation and strength being different. Differences in stroke populations studied can affect results, too, and so this difference may also be due to relatively fewer participants in the present study (N = 26) versus theirs (N =

54) obscuring the relationship. For now, the most robust result, observed in both studies, is that strength and individuation are strongly correlated, at least until individuation is nearly fully recovered. This suggests they arise from a common source.

Is the source injury to the CST? Xu et al. (2017) found different time courses and patterns of variability in strength and individuation. They also found that individuation correlated more with CST injury than strength. These observations led them to speculate that strength recovery, along with some individuation, can be attributed to descending systems other than the CST, whereas individuation relies more on the CST. This interpretation is difficult to test with our data, since we measured at only the chronic stage of recovery. We also found comparable correlations between strength, individuation, and capacity with CST injury, when considering all above-thalamus injuries together (% CST ≥ 0). That is, the three correlations had comparable strength, making it difficult to associate CST injury with one individual metric. Again, the most robust conclusion at this point is that CST injury is involved in both strength and individuation deficits.

In the cases where the injury was above the level of the thalamus, subjects whose injuries overlapped the CST (% CST > 0) exhibited significantly greater impairment compared to those whose injuries did not (% CST = 0). We note that it is this difference that drove the correlation found in the % CST ≥ 0 cases, rather than a strong correlation among only the CST > 0 cases. Therefore, while the results from this study support previous studies showing that amount of injury CST overlap predicts motor impairment and functional ability (Pineiro et al., 2000; Sterr et al., 2014; Sterr et al., 2010; Zhu et al., 2010), they suggest that this correlation may be driven by a binary pattern, in which % CST = 0 spares function, and, in contrast, % CST > 0 produces relatively lower but variable and non-graded levels of impairment. It is possible this binary pattern is an artifact of the subsection technique we used to quantify CST injury, which, among other possible shortcomings, does not account for CST somatopy.

The lack of independent control of the fingers, manifested as the “cigar-shaped” torque traces for the most impaired participants, can be understood as a form of abnormal muscle synergy or abnormal muscular coupling. A flexion synergy has been quantified for the upper extremity, manifesting as unwanted activation coupling between shoulder abductor elbow flexor muscles (Ellis et al., 2016). The flexion synergy has been suggested to arise as a result of dependence on more diffusely innervating motor pathways, such as the reticulospinal tract, following CST damage (Ellis et al., 2012). The present data are consistent with the idea that a reliance on more diffusely innervating motor pathways could cause the abnormal coupling between the index and middle fingers.

Relative impairment in finger extension versus flexion and relationship to hand function

Previous studies have found that stroke affects finger extension strength more than flexion strength on average (Conrad and Kamper, 2012). The results of this study support this observation, finding that normalized finger flexion strength after stroke was larger (0.82) than normalized finger extension strength (0.66). Looked at another way, the ratio of flexion to extension strength in the paretic hand (5.1) was significantly larger than the non-paretic hand (4.0), again consistent with the concept that extension was relatively more affected. It is worthwhile to note, however, that extension will always appear weak in an absolute sense because, even before a stroke, finger flexion strength is four times stronger than extension strength.

To our knowledge, we measured individuation ability for both finger flexion and extension after stroke for the first time. Average individuation was significantly less in the flexion direction (0.8) than extension direction (1.1). Thus, in contrast to strength, stroke appears to affect finger flexion individuation more than finger extension individuation. The reason is unknown, but this finding suggests that the neural subsystems that control flexion and extension are somewhat separable. A caveat is that the signal-to-noise ratio of the extensors was low compared to flexors, and this may have affected the extension individuation measure.

Flexion capacity survived the stepwise linear regression analysis most frequently when testing for a parsimonious predictor of hand function (Table 3), explaining 30–40% of the variance in the hand function assessments. However, adding extension capacity to the modeled explained an additional ~15% of the variance. In light of the specific population studied here (i.e. people who could open their hand a small amount), it may be that if individuals preserve some finger extension ability, finger flexion metrics are relatively more important for predicting function, although finger extension still plays a role.

Limitations and future directions

Limitations of this study are as follows. The study had a limited sample size and should be verified with a larger population. We only included individuals with at least a small amount of hand function, and caution should be exerted in comparing this study to other studies that included participants with more serve loss of hand function. We relied on the participants to accurately interpret the instructions to move one or the other finger. If, in practice, they never actually attempted to isolate their finger movements, it could have made the capacity appear smaller than actual; we consider this possibility unlikely as the instructions were simple and clear. Another caveat already mentioned was that extension torques were small and variable, and thus caution should be applied in interpreting lack of significant correlation of function or anatomical injury with any of the measures of extension ability. Another aspect of the study is that we averaged measurements of finger force production taken over a three week study of robotic therapy, and this may have increased measurement variance if the measures changed significantly over time. Preliminary analysis suggests they did not change, suggesting, for example, that individuation is difficult to improve after stroke, but future work will examine this issue. Other possible sources of variance were: we always measured flexion before extension (and isolated movement before synergistic movement); possible fatigue encountered during the multiple MVCs at each weekly test; and variability in level of preserved finger sensation (Rowe et al., 2017). Finally, we only studied one type of hand function, which involved picking and placing small objects (i.e. blocks and pegs). However, the fact that the capacity metric also best predicted a more general upper extremity impairment measure (the Fugl-Meyer test), affords some confidence that it reflects more general aspects of hand function.

As for future directions, this study focused on MCP torques generated by the middle and index fingers, both individually and together, during maximum voluntary contraction tests. Multifinger capacity plots could be created not only for isometric force production, but for dynamic movement of the fingers, when force production deficits become even more exaggerated (Conrad and Kamper, 2012). Further, although the current study was conducted using the FINGER robotic device, which is a capable of evaluating the performance of the index and middle fingers, this approach may be applied to data collected from other devices and may be extended to include other digits of the hand, albeit without the ease of visualization provided by the two degree-of-freedom case.

The previous point highlights another limitation, which is lack of strength, individuation, and capacity metrics for the thumb. The thumb has been shown to be a strong predictor of arm function (Lang et al., 2003) even though thumb individuation ability after stroke remains unclear (Raghaven et al., 2006). The participants used the thumb for the functional tests measured here, and adding measures of thumb movement into models may increase their predictive power.

Finally, in considering therapeutic targets, this study suggests that rehabilitative hand training should seek to improve both strength and individuation. If one could simultaneously improve both, one theoretically would have a multiplicative effect on improving multifinger capacity and thus hand function. An interesting question is, since strength and individuation are correlated, at least in flexion as we found here, will training one improve the other, or should they be independently targeted? Further, extensor individuation may not be as important to target as extension strength.

Acknowledgments

Steven C. Cramer serves or has served as a consultant for GlaxoSmithKline, RAND Corporation, Dart Neuroscience, and MicroTransponder, and is a cofounder of personalRN. He acknowledges support from K24 HD074722 and UL1 TR000153.

This project was supported by NIH-R01HD062744 from the National Center for Medical Rehabilitation Research at the National Institute of Child Health and Human Development, and the National Center for Research Resources and the National Center for Advancing Translational Sciences, National Institutes of Health, through Grant UL1 TR000153.

References

Adamovich SV, Fluet GG, Mathai A, Qiu Q, Lewis J, Merians AS. Design of a complex virtual reality simulation to train finger motion for persons with hemiparesis: a proof of concept study. J Neuroeng and Rehabil. 2009; 6(1):28. [PubMed: 19615045]

Bohannon RW, Warren ME, Cogman KA. Motor variables correlated with the hand-to-mouth maneuver in stroke patients. Arch Phys Med Rehabil. 1991; 72(9):682–684. [PubMed: 1859265]

Brouwer BJ, Schryburt-Brown K. Hand function and motor cortical output poststroke: are they related? Arch Phys Med Rehabil. 2006; 87(5):627–634. [PubMed: 16635624]

Burke E, Dodakian L, See J, McKenzie A, Riley JD, Le V, Cramer SC. A multimodal approach to understanding motor impairment and disability after stroke. J Neurol. 2014; 261(6):1178–1186. [PubMed: 24728337]

Burke Quinlan E, Dodakian L, See J, McKenzie A, Le V, Wojnowicz M, Shahbaba B, Cramer SC. Neural function, injury, and stroke subtype predict treatment gains after stroke. Ann Neurol. 2015; 77(1):132–145. [PubMed: 25382315]

Canning CG, Ada L, Adams R, O'Dwyer NJ. Loss of strength contributes more to physical disability after stroke than loss of dexterity. Clin Rehabil. 2004; 18(3):300–308. [PubMed: 15137561]

Cho S-H, Kim DG, Kim D-S, Kim Y-H, Lee C-H, Jang SH. Motor outcome according to the integrity of the corticospinal tract determined by diffusion tensor tractography in the early stage of corona radiata infarct. Neurosci Lett. 2007; 426(2):123–127. [PubMed: 17897782]

Conrad MO, Kamper DG. Isokinetic strength and power deficits in the hand following stroke. Clin Neurophysiol. 2012; 123(6):1200–1206. [PubMed: 22055766]

Dobkin, BH. Neurologic Rehabilitation. Vol. 47. F.A. Davis Company; Philadelphia: 1996.

Dovat L, Lambercy O, Salman B, Johnson V, Milner T, Gassert R, Burdet E, Leong TC. A technique to train finger coordination and independence after stroke. Disabil Rehabil Assist Technol. 2010; 5(4):279–287. [PubMed: 20370489]

Ellis MD, Drogos J, Carmona C, Keller T, Dewald JP. Neck rotation modulates flexion synergy torques, indicating an ipsilateral reticulospinal source for impairment in stroke. J Neurophysiol. 2012; 108(11):3096–3104. [PubMed: 22956793]

Ellis MD, Lan Y, Yao J, Dewald JPA. Robotic quantification of upper extremity loss of independent joint control or flexion synergy in individuals with hemiparetic stroke: a review of paradigms addressing the effects of shoulder abduction loading. J Neuroeng Rehabil. 2016; 13:95. [PubMed: 27794362]

Friedman N, Chan V, Reinkensmeyer AN, Beroukhim A, Zambrano GJ, Bachman M, Reinkensmeyer DJ. Retraining and assessing hand movement after stroke using the MusicGlove: comparison with conventional hand therapy and isometric grip training. J Neuroeng Rehabil. 2014; 11:76. [PubMed: 24885076]

Gandevia, SC. Spasticity: Mechanisms and Management. Springer-Verlag; Berlin: 1993. Strength changes in hemiparesis: Measurements and mechanisms; p. 111-122.

Harris JE, Eng JJ. Paretic upper-limb strength best explains arm activity in people with stroke. Phys Ther. 2007; 87(11):88–97. [PubMed: 17179441]

Heller A, Wade D, Wood VA, Sunderland A, Hewer RL, Ward E. Arm function after stroke: measurement and recovery over the first three months. J Neurol Neurosurg Psychiatry. 1987; 50(6):714–719. [PubMed: 3612152]

Jang SH. The role of the corticospinal tract in motor recovery in patients with a stroke: a review. NeuroRehabilitation. 2009; 24(3):285–290. [PubMed: 19458437]

Kamper D, Harvey R, Suresh S, Rymer W. Relative contributions of neural mechanisms versus muscle mechanics in promoting finger extension deficits following stroke. Muscle Nerve. 2003; 28(3): 309–318. [PubMed: 12929190]

Kamper D, Rymer W. Impairment of voluntary control of finger motion following stroke: role of inappropriate muscle coactivation. Muscle Nerve. 2001; 24(5):673–681. [PubMed: 11317278]

Kamper DG, Fischer HC, Conrad MO, Towles JD, Rymer WZ, Triandafilou KM. Finger-thumb coupling contributes to exaggerated thumb flexion in stroke survivors. J Neurophysiol. 2014; 111(12):2665–2674. [PubMed: 24671534]

Kamper DG, Fischer HC, Cruz EG, Rymer WZ. Weakness is the primary contributor to finger impairment in chronic stroke. Arch Phys Med and Rehabil. 2006; 87(9):1262–1269. [PubMed: 16935065]

Kim Y, Kim W-S, Yoon B. The effect of stroke on motor selectivity for force control in single-and multi-finger force production tasks. NeuroRehabilitation. 2014; 34(3):429–435. [PubMed: 24473243]

Lang CE, Beebe JA. Relating movement control at 9 upper extremity segments to loss of hand function in people with chronic hemiparesis. Neurorehabil Neural Repair. 2007; 21(3):279–91. [PubMed: 17353458]

Lang CE, Schieber MH. Differential impairment of individuated finger movements in humans after damage to the motor cortex or the corticospinal tract. J Neurophysiol. 2003; 90(2):1160–1170. [PubMed: 12660350]

Lang CE, Schieber MH. Reduced muscle selectivity during individuated finger movements in humans after damage to the motor cortex or corticospinal tract. J Neurophysiol. 2004; 91(4):1722–34. [PubMed: 14668295]

Lawrence DG, Kuypers HGJM. The functional organization of the motor cortex in monkeys. I. The effects of bilateral pyramidal lesions. Brain. 1968; 91(1):1–14. [PubMed: 4966862]

Lee SW, Triandafilou K, Lock BA, Kamper DG. Impairment in task-specific modulation of muscle coordination correlates with the severity of hand impairment following stroke. PloS One. 2013; 8(7):e68745.doi: 10.1371/journal.pone.0068745 [PubMed: 23874745]

Li S, Latash ML, Yue GH, Siemionow V, Sahgal V. The effects of stroke and age on finger interaction in multi-finger force production tasks. Clin Neurophysiol. 2003; 114(9):1646–1655. [PubMed: 12948793]

Lindberg PG, Roche N, Robertson J, Roby-Brami A, Bussel B, Maier MA. Affected and unaffected quantitative aspects of grip force control in hemiparetic patients after stroke. Brain Res. 2012; 1452:96–107. [PubMed: 22464180]

Lindenberg R, Renga V, Zhu L, Betzler F, Alsop D, Schlaug G. Structural integrity of corticospinal motor fibers predicts motor impairment in chronic stroke. Neurology. 2010; 74(4):280–287. [PubMed: 20101033]

Ma VY, Chan L, Carruthers KJ. Incidence, prevalence, costs, and impact on disability of common conditions requiring rehabilitation in the United States: stroke, spinal cord injury, traumatic brain injury, multiple sclerosis, osteoarthritis, rheumatoid arthritis, limb loss, and back pain. Arch Phys Med and Rehabil. 2014; 95(5):986–995. [PubMed: 24462839]

Mathiowetz V, Volland G, Kashman N, Weber K. Adult norms for the Box and Block Test of manual dexterity. Am J Occup Ther. 1985; 39(6):386–391. [PubMed: 3160243]

Nouri S, Cramer SC. Anatomy and physiology predict response to motor cortex stimulation after stroke. Neurology. 2011; 77(11):1076–1083. [PubMed: 21880996]

Pineiro R, Pendlebury S, Smith S, Flitney D, Blamire A, Styles P, Matthews P. Relating MRI changes to motor deficit after ischemic stroke by segmentation of functional motor pathways. Stroke. 2000; 31(3):672–679. [PubMed: 10700503]

Raghavan P, Petra E, Krakauer JW, Gordon AM. Patterns of impairment in digit independence after subcortical stroke. J Neurophysiol. 2006; 95(1):369–78. [PubMed: 16207778]

Riley JD, Le V, Der-Yeghiaian L, See J, Newton JM, Ward NS, Cramer SC. Anatomy of stroke injury predicts gains from therapy. Stroke. 2011; 42(2):421–426. [PubMed: 21164128]

Rosso C, Valabregue R, Attal Y, Vargas P, Gaudron M, Baronnet F, Bertasi E, Humbert F, Peskine A, Perlbarg V. Contribution of corticospinal tract and functional connectivity in hand motor impairment after stroke. PloS One. 2013; 8(9)

Rowe JB, Chan V, Ingemanson ML, Cramer SC, Wolbrecht ET, Reinkensmeyer DJ. Robotic assistance for training finger movement using a Hebbian model: A randomized controlled trial. Neurorehabil Neural Repair. 2017; 31(8):769–780. [PubMed: 28803535]

Schieber MH. Individuated finger movements of rhesus monkeys: a means of quantifying the independence of the digits. J Neurophysiol. 1991; 65(6):1381–1391. [PubMed: 1875247]

Schieber, MH., Lang, C., Reilly, K., McNulty, P., Sirigu, A. Progress in Motor Control. Springer; 2009. Selective activation of human finger muscles after stroke or amputation; p. 559-575.

Schieber MH, Poliakov AV. Partial inactivation of the primary motor cortex hand area: effects on individuated finger movements. J Neurosci. 1998; 18(21):9038–9054. [PubMed: 9787008]

See J, Dodakian L, Chou C, Chan V, McKenzie A, Reinkensmeyer DJ, Cramer SC. A standardized approach to the Fugl-Meyer assessment and its implications for clinical trials. Neurorehabil Neural Repair. 2013; 27(8):732–741. [PubMed: 23774125]

Sterr A, Dean PJ, Szameitat AJ, Conforto AB, Shen S. Corticospinal tract integrity and lesion volume play different roles in chronic hemiparesis and its improvement through motor practice. Neurorehabil Neural Repair. 2014; 28(4):335–343. [PubMed: 24334657]

Sterr A, Shen S, Szameitat AJ, Herron KA. The role of corticospinal tract damage in chronic motor recovery and neurorehabilitation: a pilot study. Neurorehabil Neural Repair. 2010; 24(5):413–419. [PubMed: 20516488]

Taheri H, Rowe JB, Gardner D, Chan V, Gray K, Bower C, Reinkensmeyer DJ, Wolbrecht ET. Design and preliminary evaluation of the FINGER rehabilitation robot: controlling challenge and quantifying finger individuation during musical computer game play. J Neuroeng Rehabil. 2014; 11:10.doi: 10.1186/1743-0003-11-10 [PubMed: 24495432]

Taheri H, Rowe JB, Gardner D, Chan V, Reinkensmeyer DJ, Wolbrecht ET. Robot-assisted Guitar Hero for finger rehabilitation after stroke. Conf. Proc. IEEE Eng Med Biol Soc. 2012:3911–3917. [PubMed: 23366783]

Térémetz M, Colle F, Hamdoun S, Maier MA, Lindberg PG. A novel method for the quantification of key components of manual dexterity after stroke. J Neuroeng Rehabil. 2015; 12:64.doi: 10.1186/s12984-015-0054-0 [PubMed: 26233571]

Thickbroom GW, Byrnes ML, Archer SA, Mastaglia FL. Motor outcome after subcortical stroke: MEPs correlate with hand strength but not dexterity. Clin Neurophysiol. 2002; 113(12):2025–2029. [PubMed: 12464343]

Thielbar KO, Lord TJ, Fischer HC, Lazzaro EC, Barth KC, Stoykov ME. Training finger individuation with a mechatronic-virtual reality system leads to improved fine motor control post-stroke. J Neuroeng Rehabil. 2014; 11:171.doi: 10.1186/1743-0003-11-171 [PubMed: 25542201]

Triandafilou KM, Kamper DG. Investigation of hand muscle atrophy in stroke survivors. Clin Biomech. 2012; 27(3):268–272.

Warabi T, Inoue K, Noda H, Murakami S. Recovery of voluntary movement in hemiplegic patients: Correlation with degenerative shrinkage of the cerebral peduncles in CT images. Brain. 1990; 113(1):177–189. [PubMed: 2302531]

Xu J, Ejaz N, Hertler B, Branscheidt M, Widmer M, Faria AV, Harran M, Cortes JC, Kim N, Celnik PA, Kitago T, Luft A, Krakauer JW, Diedrichsen J. Separable systems for finger strength and control after stroke. J Neurophysiol. 2017; 118(2):1151–1163. [PubMed: 28566461]

Xu, J., Haith, AM., Krakauer, JW. Motor control of the hand before and after stroke. In: Kansaku, K.Cohen, LC., Birbaumer, N., editors. Clinical Systems Neuroscience. Springer; Japan: 2015. p. 271-289.

Zhu LL, Lindenberg R, Alexander MP, Schlaug G. Lesion load of the corticospinal tract predicts motor impairment in chronic stroke. Stroke. 2010; 41(5):910–915. [PubMed: 20378864]

Author Manuscript

Author Manuscript

Author Manuscript

Highlights

- It is unclear if reduced finger strength or individuation limits hand function more after stroke.
- Multi-finger capacity is a novel metric of the combined effect of finger strength and individuation.
- Multi-finger capacity predicts hand function better than strength or individuation alone.

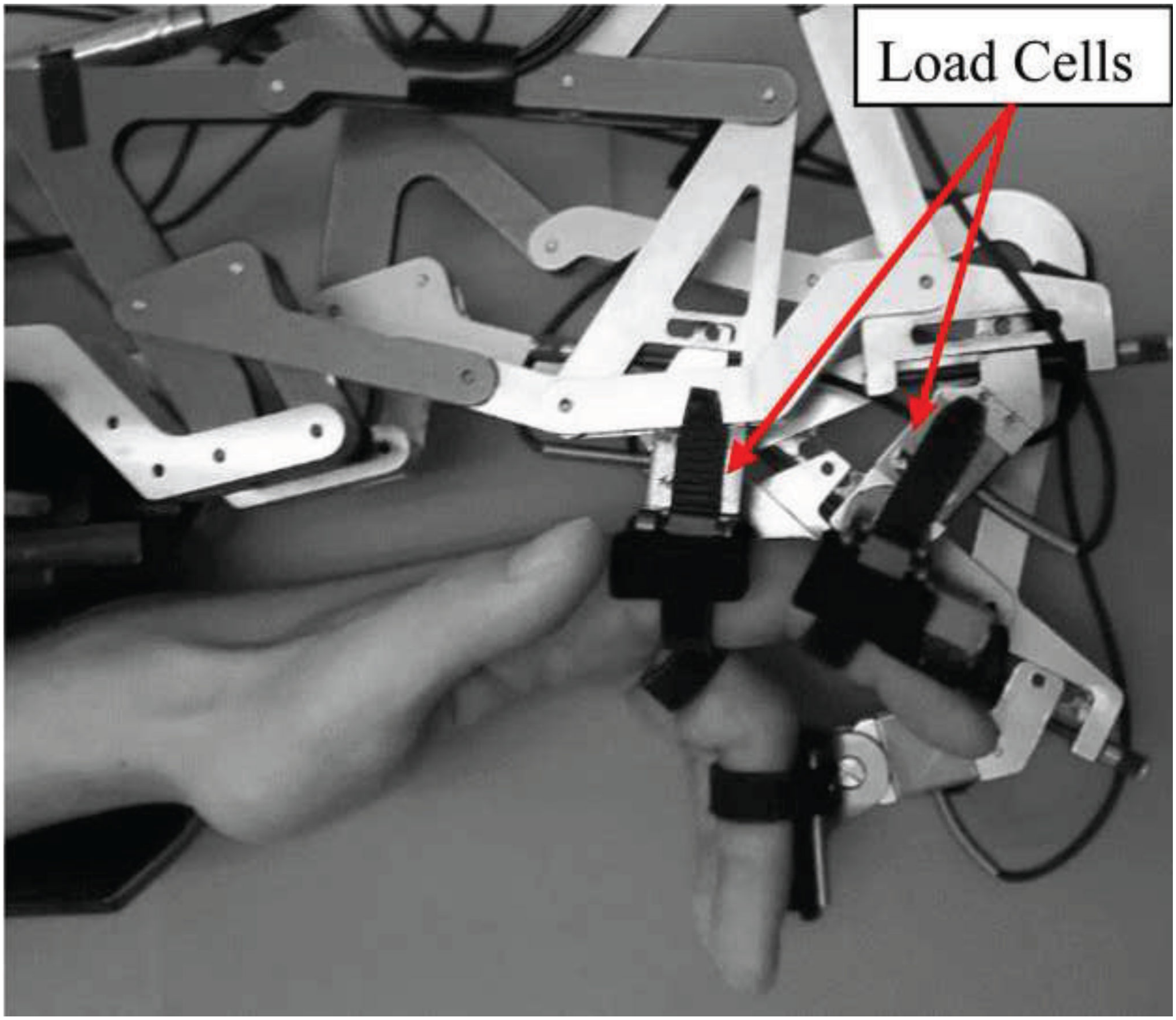


Figure 1.

The FINGER robotic movement therapy device. FINGER allows subjects to move their index and middle fingers through a naturalistic curling motion, and can assist or resist this movement. Two force sensors on each finger are used to calculate joint torques during movement or while the robot holds the fingers in an isometric position.

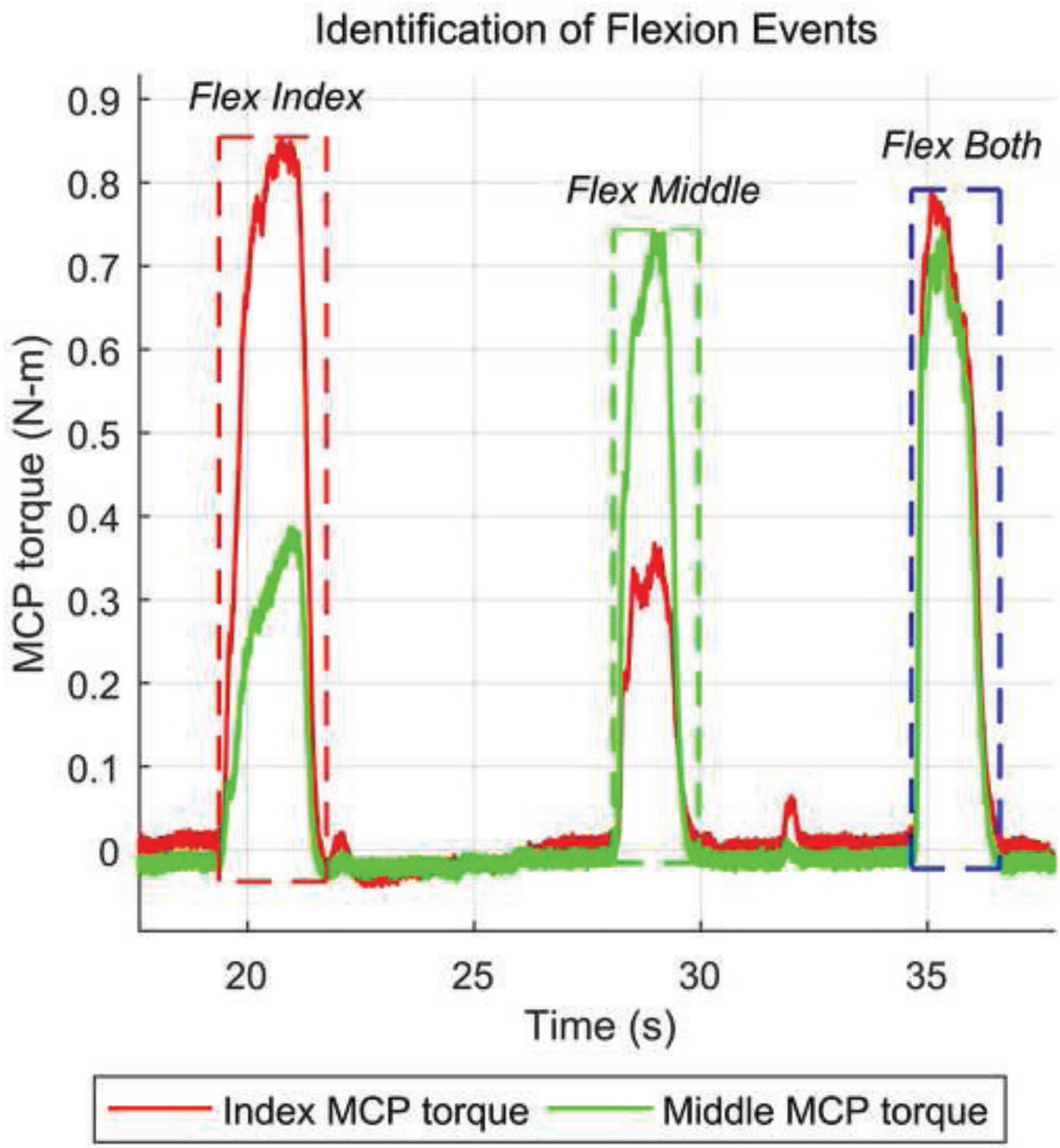


Figure 2.
Example finger torques measured by the robot. Subjects were instructed to flex their fingers against the stationary robot in the following order: index, middle, both together. The solid red and green lines are the flexion MCP torques generated by the subject with their index and middle fingers, respectively. Red, green, and blue dashed boxes identify the flex index, flex middle, and flex both flexion events.

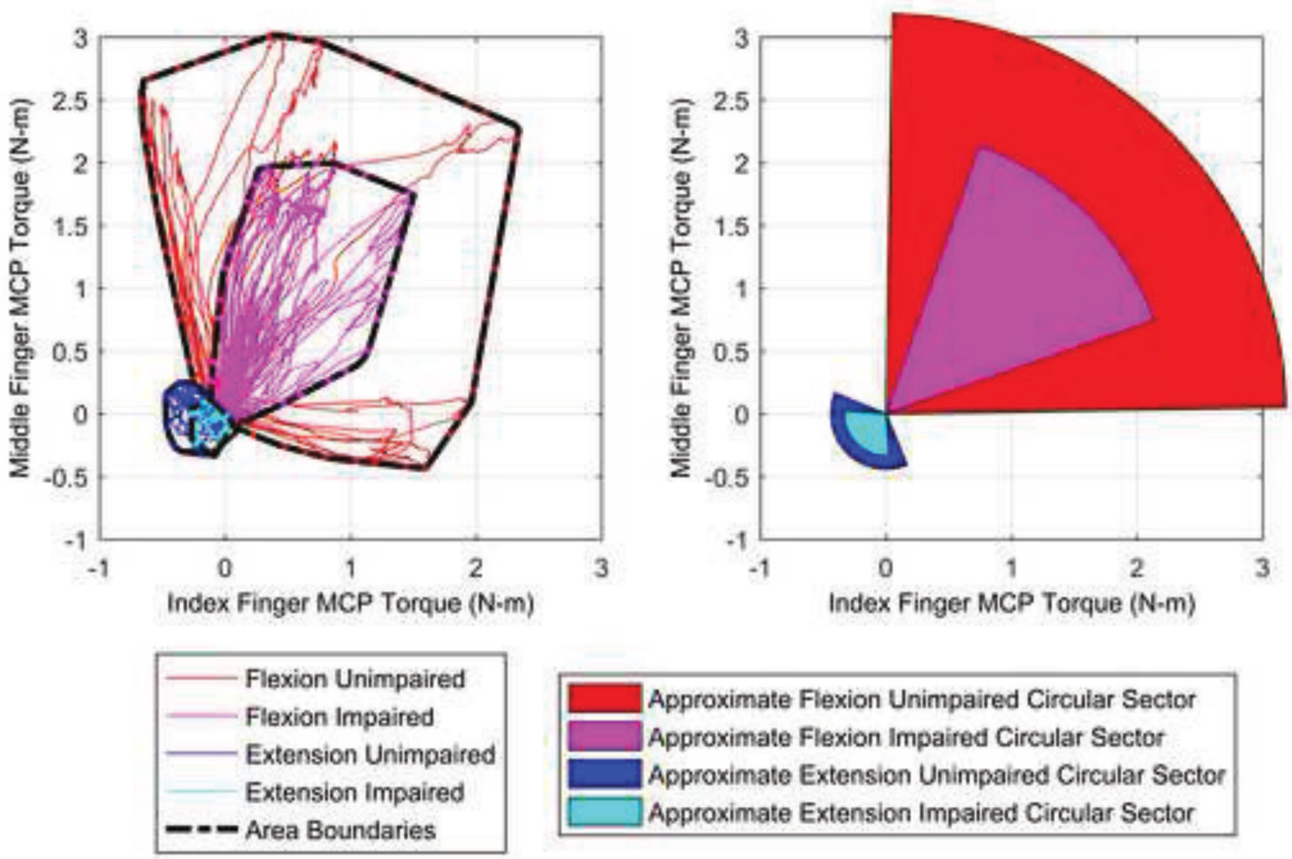


Figure 3.

LEFT: An example multi-finger capacity plot of a subject's MVC test performance. Results from a single subject's unimpaired (flexion in red and extension in blue) and impaired hand (flexion in magenta and extension in cyan) are shown. Convex hulls fit to these four torque traces are shown with striped lines; and the area of these convex hulls indicate flexion capacity and extension capacity. RIGHT: Individuation is indicated by the angle of the circular sector fit to each hull area, increasing from 0 to 1 as the sector angle increase from zero to 90°. Average strength is indicated by the radius of the sector. In this case, the subject's impaired side has reduced strength and individuation in both flexion and extension.

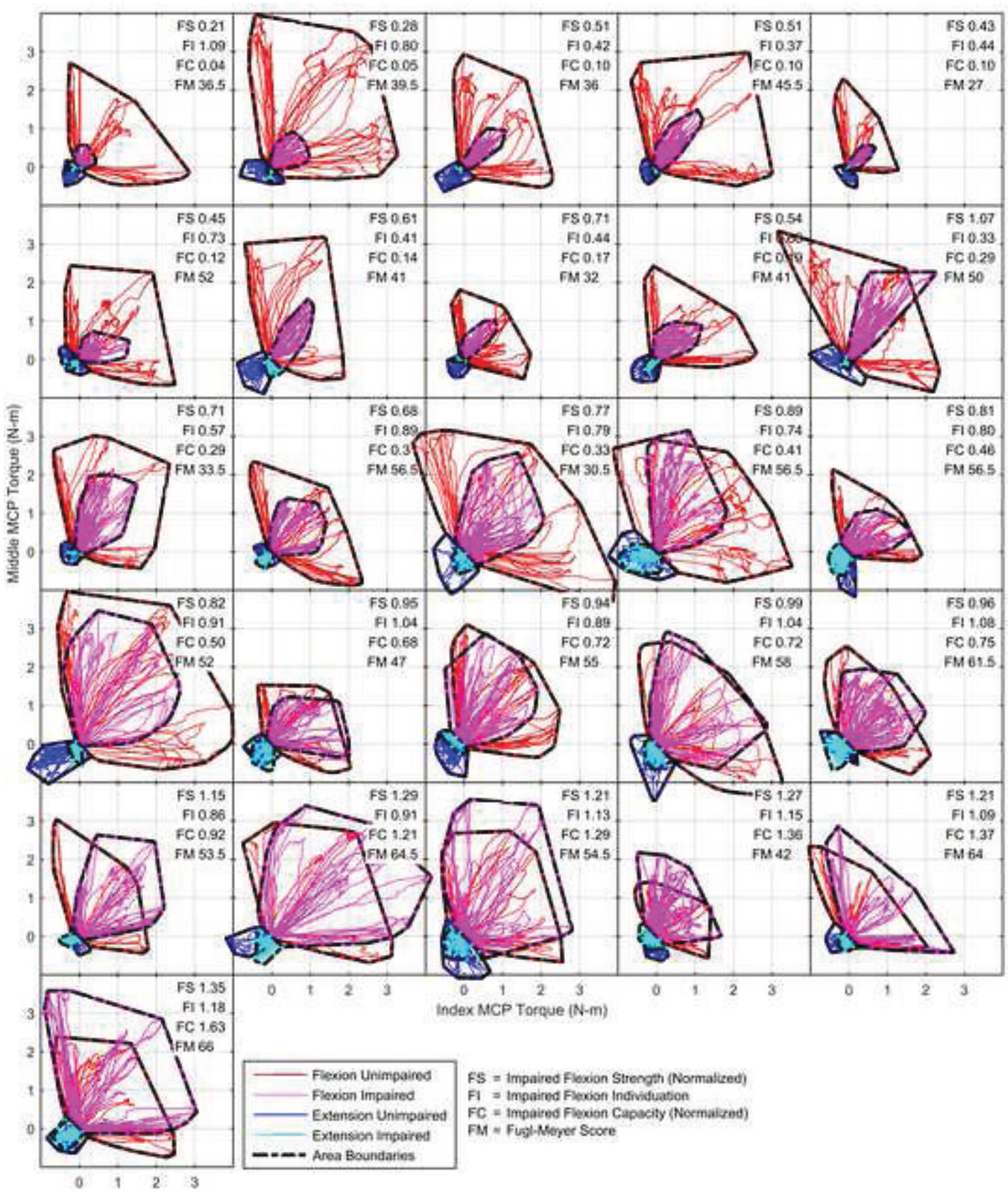
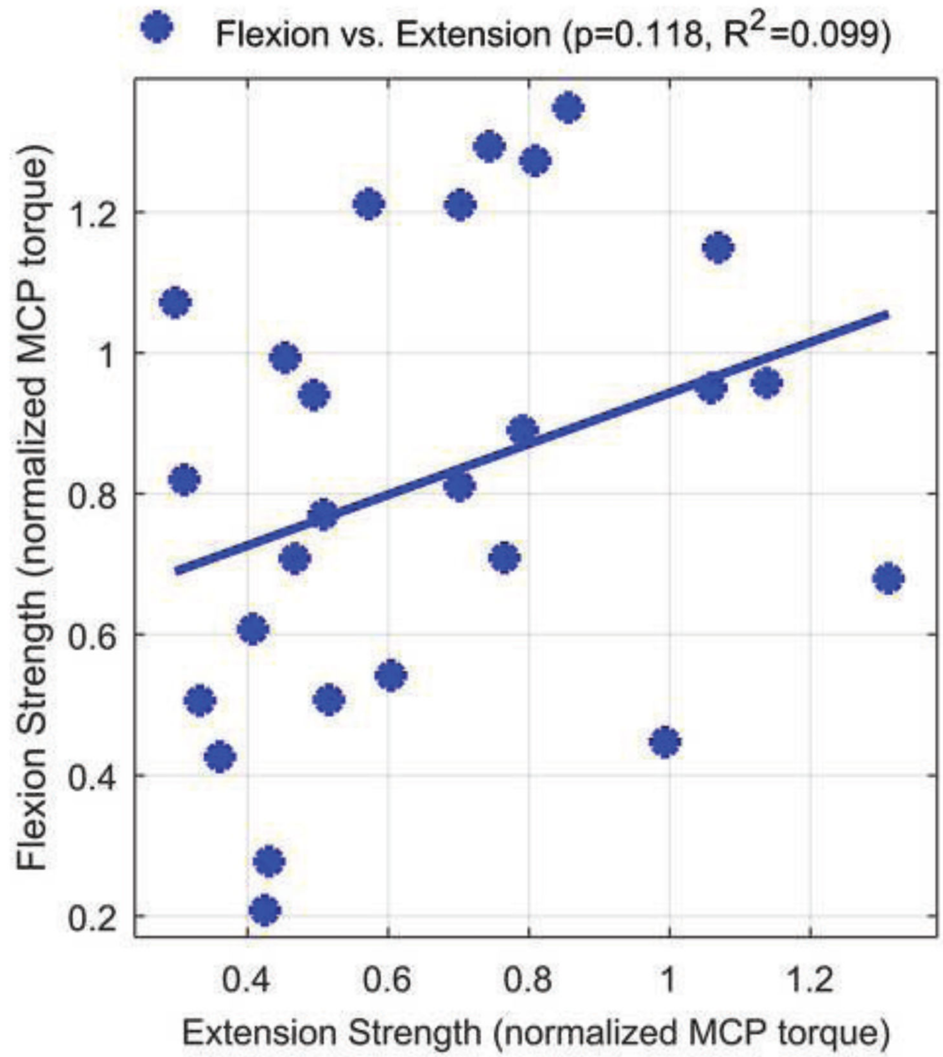


Figure 4.

Multi-finger capacity plots for all subjects (N=26) shown in order of increasing normalized impaired flexion capacity (FC). MCP torques for the index and middle fingers are plotted on the x and y axes, respectively, providing a way to simultaneously visualize and quantify finger strength (distance from origin), individuation ability (ability to move along the x and y axes independently), and capacity (the product of strength and individuation). Flexion scores for strength (FS), individuation (FI), and capacity (FC) are shown in the top right corner of each plot, followed by Fugl-Meyer (FM) score. Results are shown for both flexion (1st quadrant) and extension (3rd quadrant) and both subject's unimpaired and impaired hands. For the unimpaired hand, flexion is shown in red and extension in blue. For the impaired hand, flexion is shown in magenta and extension in cyan. The convex hull boundaries of these four torque traces are shown with a striped line of the same color. By plotting both unimpaired and impaired hands, we can readily see how stroke affects flexion strength (radius from origin), flexion individuation (angle of sector) and flexion capacity (convex hull area).

Left



Flexion vs. Extension (p=0.118, R2=0.099)
Flexion Strength (normalized MCP torque)
1.2
1
0.8
0.6
0.4
0.2
0.4
0.6
0.8
1
1.2
Extension Strength (normalized MCP torque)

Right

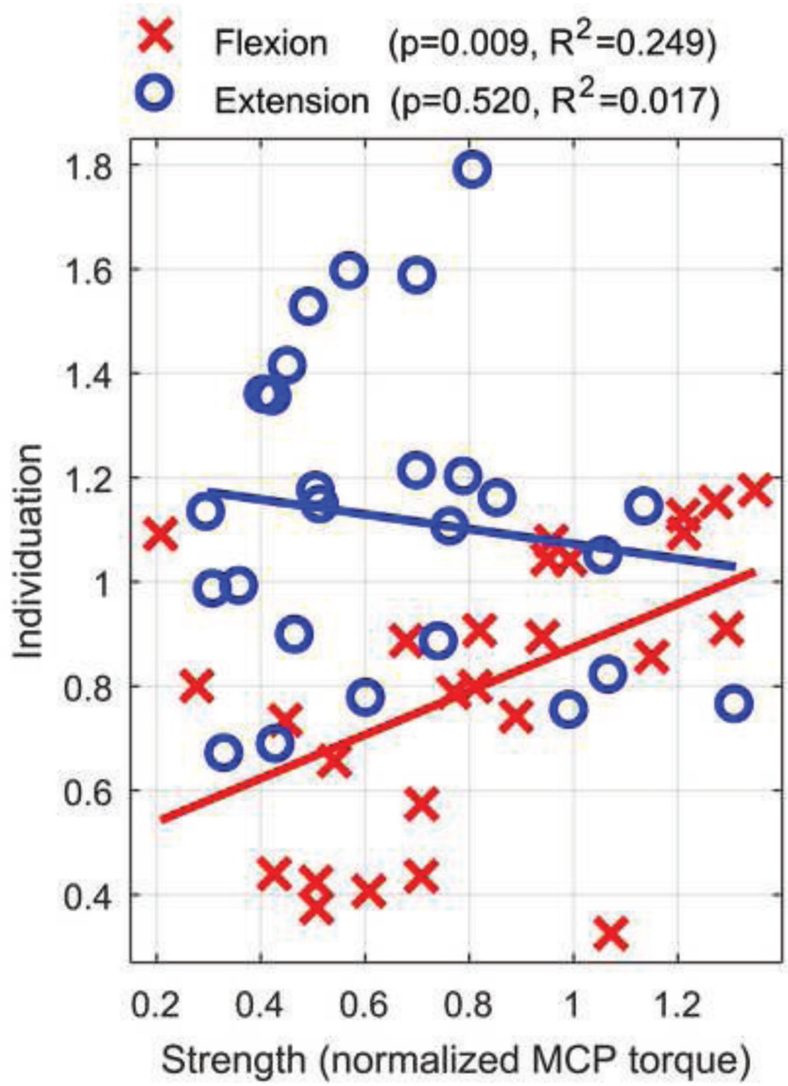
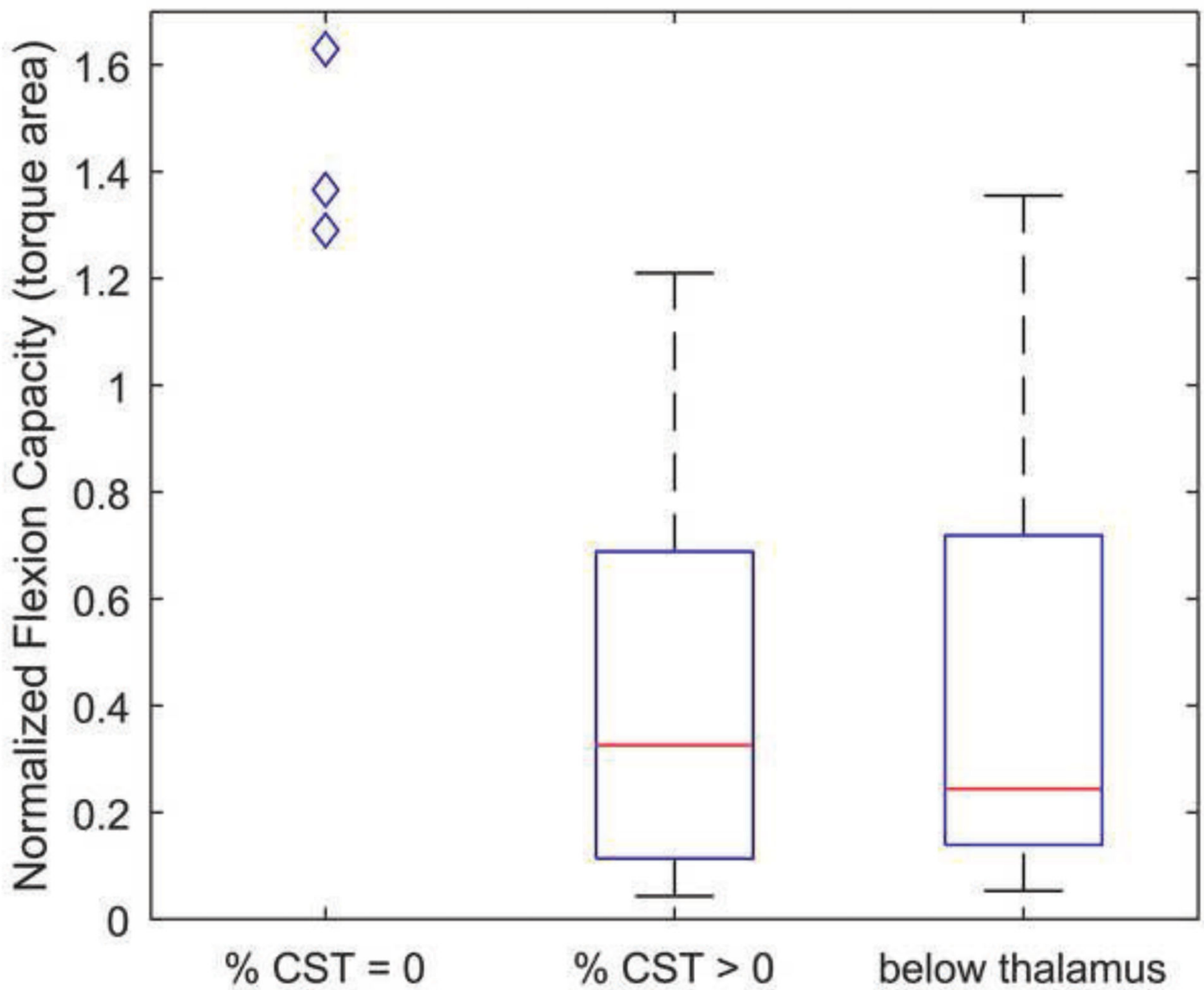


Figure 5.

LEFT: Flexion strength (MCP torque of the impaired hand normalized to that of the unimpaired hand) versus extension strength (also MCP torque normalized to the unimpaired hand). RIGHT: Strength (normalized MCP torque) versus individuation for both flexion and extension of the impaired hand.

Left


Normalized Flexion Capacity (torque area)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
% CST = 0
% CST > 0
below thalamus

Right

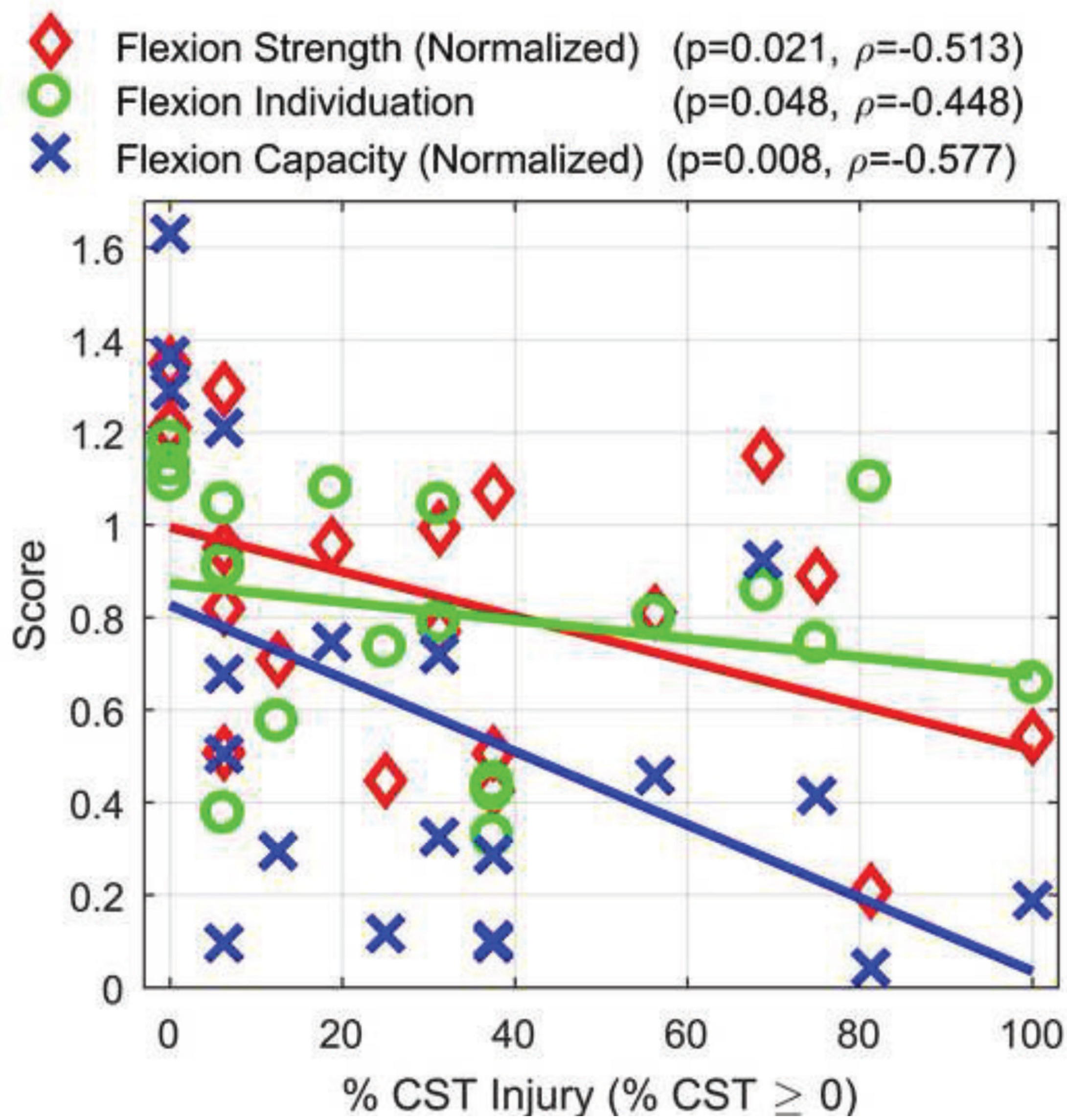
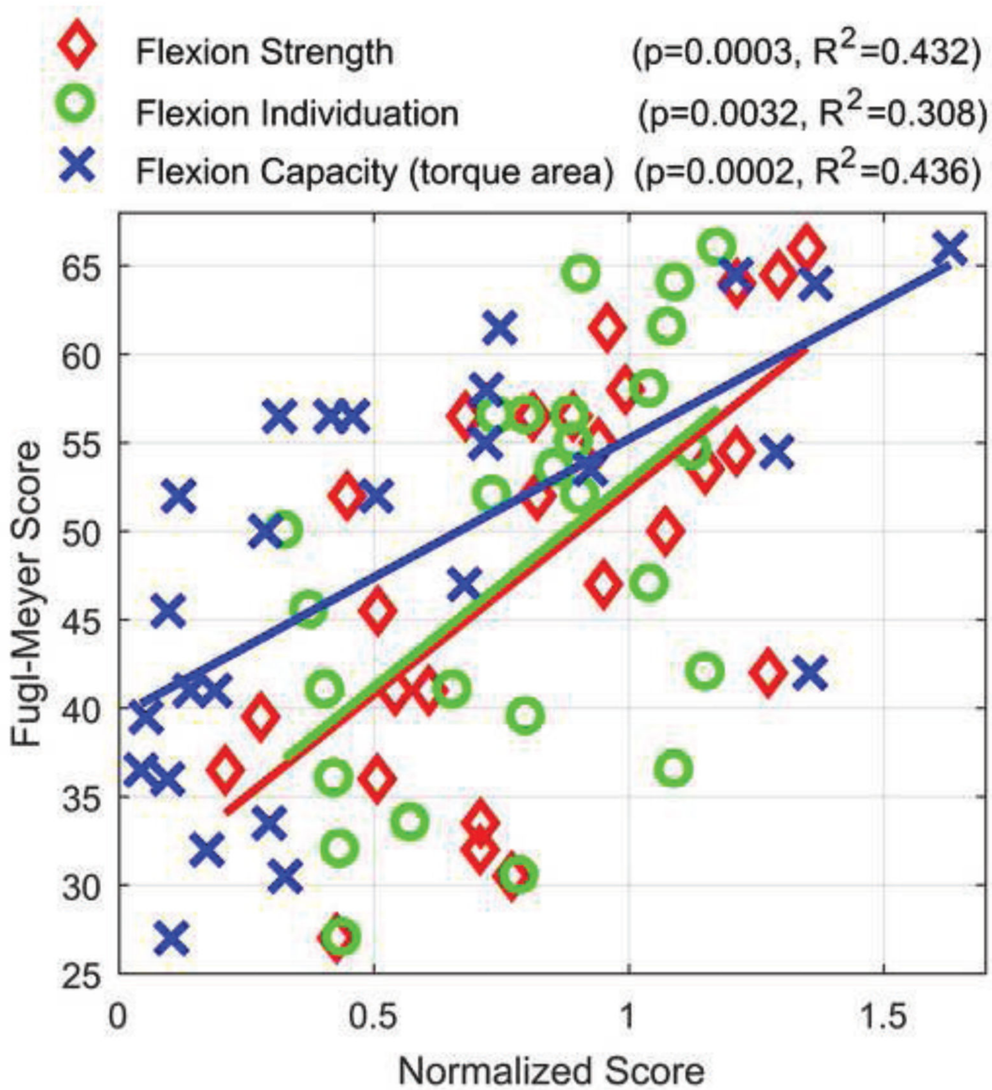


Figure 6.

LEFT: Box plots for injury groups below thalamus (injury below the level of the thalamus, N = 6), % CST > 0 (% CST overlap greater than zero, N = 17), and % CST = 0 (% CST overlap equal to zero, N = 3). RIGHT: Correlations for flexion strength (normalized to unimpaired hand), individuation, and capacity (normalized to unimpaired hand) vs. % CST overlap for injuries above the thalamus (% CST ≥ 0, N = 20).

Left


Flexion Strength (p=0.0003, R2=0.432)
Flexion Individuation (p=0.0032, R2=0.308)
Flexion Capacity (torque area) (p=0.0002, R2=0.436)
Fugl-Meyer Score
65
60
55
50
45
40
35
30
25
0
0.5
1
1.5
Normalized Score

Right

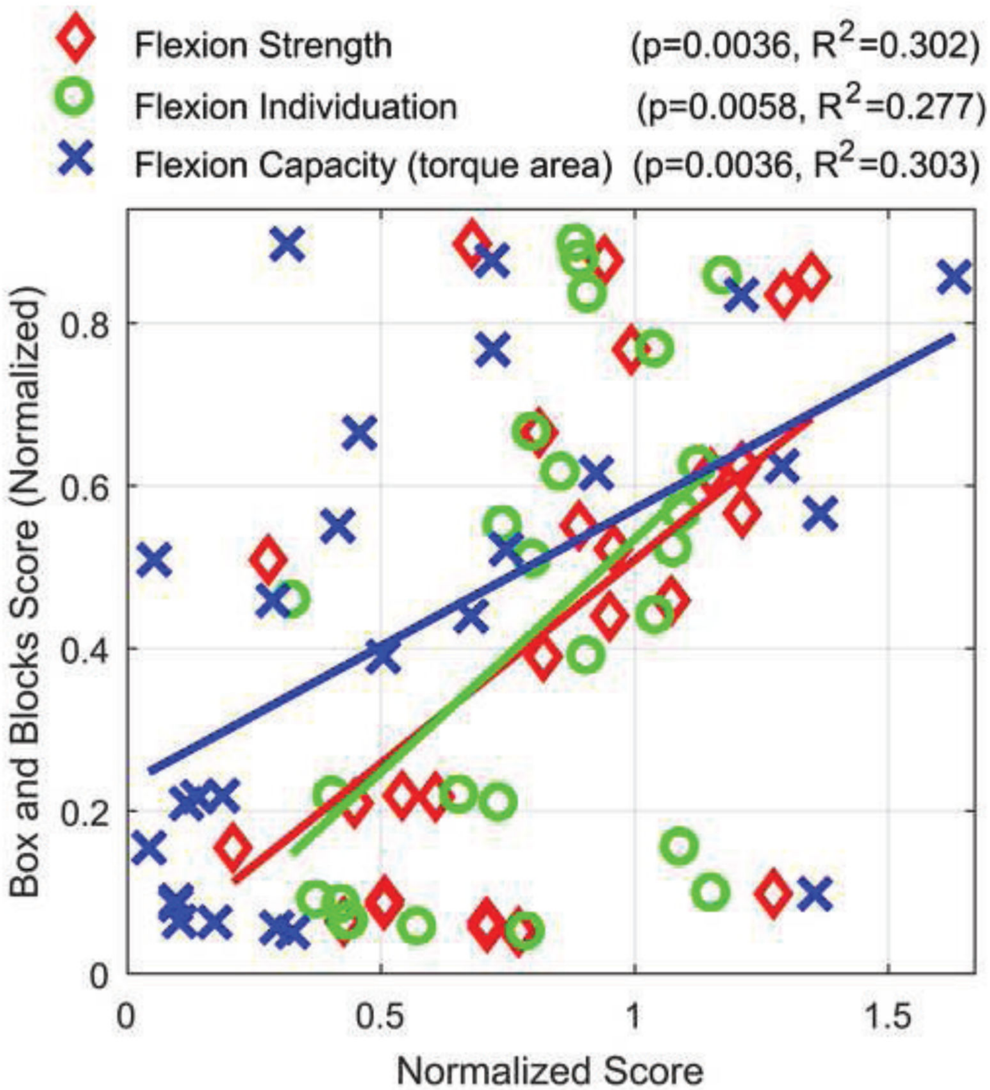


Figure 7.

Flexion strength (normalized to unimpaired hand), individuation, and capacity (normalized to unimpaired hand) vs. Fugl-Meyer score (FM, LEFT) and normalized Box and Blocks (BB, RIGHT). All three flexion metrics of finger performance (strength, individuation, and capacity) correlate strongly with Fugl-Meyer and Box and Blocks scores; they also correlate with Nine-Hole-Peg Test scores (not shown, see Table 3).

Table 1

Predictor and response variables for forward stepwise linear regression. All predictor variables were normalized to the unimpaired hand.

Predictor Variables	Response Variables
FS (Flexion Strength	FM (Fugl-Meyer score)
FI (Flexion Individuation)	BB (Box and Blocks score)
FC (Flexion Capacity)	NHPT (Nine Hole Peg Test score)
ES (Extension Strength)	
EI (Extension Individuation)	
EC (Extension Capacity)	

Table 2

Demographic data and key baseline clinical outcomes. Values before a "±" are means, and values after are standard deviations.

	All (N = 26)
Age (years)	58.3 ± 13.3
Time Since Stroke (months)	31.7 ± 48.2
Gender (Male [M]/ Female [F])	20 M / 6 F
Side of hemiparesis (Right [R]/ Left [L])	11 R / 15 L
Type of Stroke (Ischemic [I]/ Hemorrhagic [H])	17 I / 9 H
Box and Blocks	24.3 ± 17.0
Upper Extremity Fugl-Meyer (max 66)	47.0 ± 11.6

Table 3

Correlations between finger capacity metrics (strength normalized to the unimpaired hand, individuation, and capacity normalized to the unimpaired hand) and the Fugl-Meyer test and two measure of hand function (Box and Blocks and Nine Hole Peg Test), as well as % Corticospinal Tract (CST) injury. For the impairment and hand function assessments, correlations were evaluated via linear regression (Pearson); for % CST injury Spearman's rank correlation (Spearman's ρ) analysis was used because % CST injury was not normally distributed. For the % CST > 0 case, injuries not overlapping the CST, or below the level of the thalamus, were omitted which reduced the number of subjects to N = 17 for these tests. For the % CST ≥ 0 case, all injuries above the level of thalamus were included (N=20). Clear cells indicate correlation significance ($p < 0.05$), darkening shades indicates less correlation significance. All correlations for strength, individuation, and capacity were positive.

		Fugl-Meyer (N=26)	**Box & Blocks (N=26)**	**Nine Hole Peg (N=26)**	**% CST > 0 (N=17)**	**% CST ≥ 0 (N=20)**
Flexion	Strength	p < 0.001 R^2 = 0.432	p = 0.004 R^2 = 0.302	p = 0.013 R^2 = 0.230	p = 0.385 ρ = −0.225	p = 0.021 ρ = −0.513
	Individuation	p = 0.003 R^2 = 0.308	p = 0.006 R^2 = 0.277	p = 0.012 R^2 = 0.237	p = 0.702 ρ = −0.100	p = 0.048 ρ = −0.448
	Capacity (torque area)	p < 0.001 R^2 = 0.436	p = 0.004 R^2 = 0.303	p = 0.004 R^2 = 0.298	p = 0.223 ρ = −0.312	p = 0.008 ρ = −0.577
Extension	Strength	p = 0.021 R^2 = 0.202	p = 0.058 R^2 = 0.141	p = 0.159 R^2 = 0.081	p = 0.660 ρ = −0.115	p = 0.451 ρ = −0.179
	Individuation	p = 0.330 R^2 = 0.040	p = 0.635 R^2 = 0.010	p = 0.527 R^2 = 0.017	p = 0.660 ρ = 0.115	p = 0.361 ρ = −0.216
	Capacity (torque area)	p = 0.003 R^2 = 0.311	p = 0.023 R^2 = 0.198	p = 0.126 R^2 = 0.095	p = 0.636 ρ = −0.124	p = 0.393 ρ = −0.202

Table 4

Predictive model identification using forward stepwise linear regression. The four most common resulting predictive models are shown for each of three response variables (Fugl-Meyer score, Box and Blocks score, and Nine Hole Peg score). In 10 out of 15 of the applications of stepwise linear regression, 1+FC (normalized flexion capacity) was the resulting model.

Linear Regression Model	Fugl-Meyer	Box and Blocks	Nine Hole Peg
1 + FC (normalized flexion capacity)	$p = 0.00024$ $R^2 = 0.436$	$p = 0.0036$ $R^2 = 0.303$	$p = 0.0039$ $R^2 = 0.298$
1 + FC + EC (normalized extension capacity)	$p = 0.0004$ $R^2 = 0.496$	$p = 0.0092$ $R^2 = 0.335$	$p = 0.0171$ $R^2 = 0.298$
1 + FC + $(FC)^2$	$p = 0.0004$ $R^2 = 0.489$	$p = 0.0034$ $R^2 = 0.390$	$p = 0.014$ $R^2 = 0.309$
1 + (FC)(EC)	$p = 0.0001$ $R^2 = 0.603$	$p = 0.0024$ $R^2 = 0.473$	$p = 0.0059$ $R^2 = 0.426$