Fine finger control and strength recover after stroke along a time-invariant impairment function

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The ability to produce a power grip and the proficiency in finely control one's digits are the two complementary aspects of hand function. The most common observation after stroke is that both are impaired (Kamper and Rymer, 2001; Kamper et al., 2006; Lang and Schieber, 2003). While strength often recovers remarkably after stroke, fine finger control is often persistently impaired, causing lasting disability (Heller et al., 1987; Sunderland et al., 1989). It is, however, not clear what the relationship is between these two aspects of recovery. Using data from a one-year longitudinal study of stroke, we attempted to determine the relationship between finger strength and individuation using an ergonomic device and a novel paradigm.

Fifty-four first-time ischemic stroke patients with hemiparesis, and 14 age- and education- matched healthy control participants were recruited from three centers: Johns Hopkins Hospital, Columbia University, and University of Zurich. Patients were tested five times during the first year following stroke onset: within first 2 weeks (W1), 4-6 weeks (W4), 12-14 weeks (W12), 24-26 weeks (W24), and 52-54 weeks (W52). Healthy controls were tested following the same schedule and procedure as patients. During each visit, hand function was tested using an ergonomic device that measures isometric forces produced by each finger (Fig. 1A). Two functional aspects for each finger were tested: maximal voluntary contraction (MVC) and finger individuation. In the MVC task, participants were asked to depress a single finger with maximum strength and hold it for 2s; in the Individuation task, patients had to depress each individual finger at a sub-MVC level of force, while at the same time keeping their other fingers immobile on the keys, producing minimum force (Fig. 1B). Both the paretic and the non-paretic hand were tested at 20%, 40%, 60%, and 80% of MVC. We derived a sensitive Individuation Index (Fig 1 C-E) to track the recovery of fine finger control.

Strength and individuation in the paretic hand showed a time-invariant impairment function (Fig. 2A). Hierarchical piecewise linear regression and a Chi-square test ($\chi^2 = 58.99$, $p = 4.838\text{e-}12$) indicated that the relationship between strength and individuation is best characterized with two piecewise linear functions with a breaking point when strength reaches to 58% of the non-paretic level. This relationship is also highlighted by a strong correlation between strength and individuation when the hand is more impaired and a dramatic decrease of correlation between the two variables are at mild levels of impairment; consistently the association between the two variables was not present in the non-paretic or a healthy hand (Fig. 2B). When patients were stratified by their final levels of recovery, the correlation between strength and individuation remained high over time in patients with poor recovery, but dropped rapidly after W4 for those with good recovery (Fig. 2C).

Recovery after stroke can be characterized as a fast migration along the impairment function for good recoverers during the acute-subacute period, indicating a high level of plasticity, but a relatively slow movement and lingering in the lower half of the function for poor recoverers (Fig. 2C). That there is a period of early heightened plasticity in which most recovery from impairment occurs is supported by lower across time-point correlations in this period (Fig. 2D). Consistently, regression analysis showed relatively weak predictability from both W1 and W4, but relatively more accurate prediction by W4 for final recovery of strength (best cross-validated R^2=0.32 for W1, and 0.48 for W4) and individuation (best cross-validated R^2=0.17 for W1, and 0.48 for W4). We conclude that there is an underlying function that relates strength and control at any time after stroke. What changes is where a patient lies in this space. Most traversal across this space occurs early after stroke.

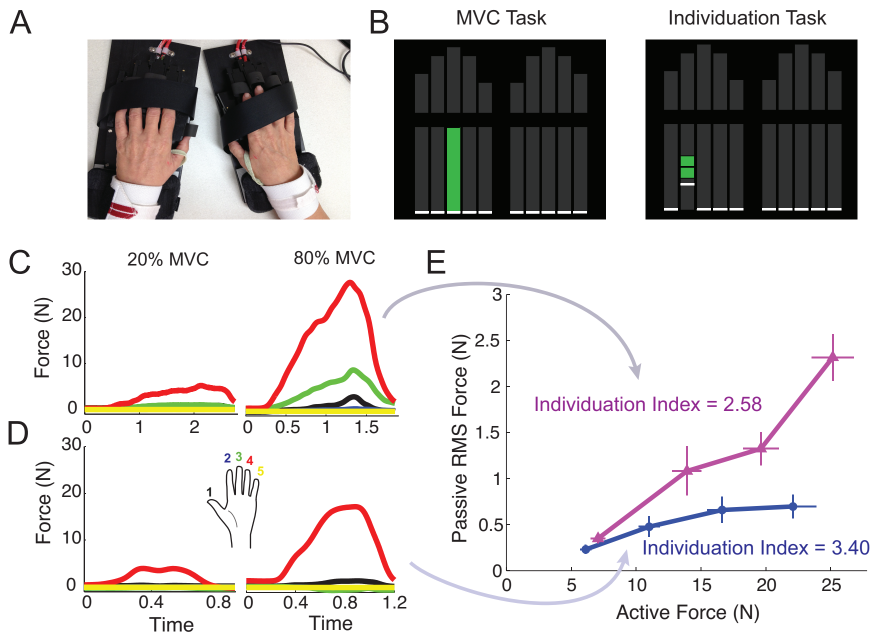

Figure 1. *Strength and Individuation task. (**A**) Ergonomic hand devices. The patient's fingers are securely placed on the keys using Velcro straps. (**B**) Visual stimuli showing instructional stimulus that indicated both which finger to press (left middle finger) and how much force to produce (height of the green bar). (**C**, **D**) Example trials from one individual during the Individuation tasks at two different time points. Four trials are shown, one at 20% and one at 80% of MVC for each time point. In this case the forth finger (red) was the active finger. Note the higher level of forces in the passive fingers especially during the high active force level. (**E**) The mean deviation from baseline in the passive fingers plotted against the force generated by the active finger for the two scenarios. Increased enslaving with increasing active force levels is clearly visible. Individuation Index is the negative log of the slope of the regression line between active force and passive mean deviation.*

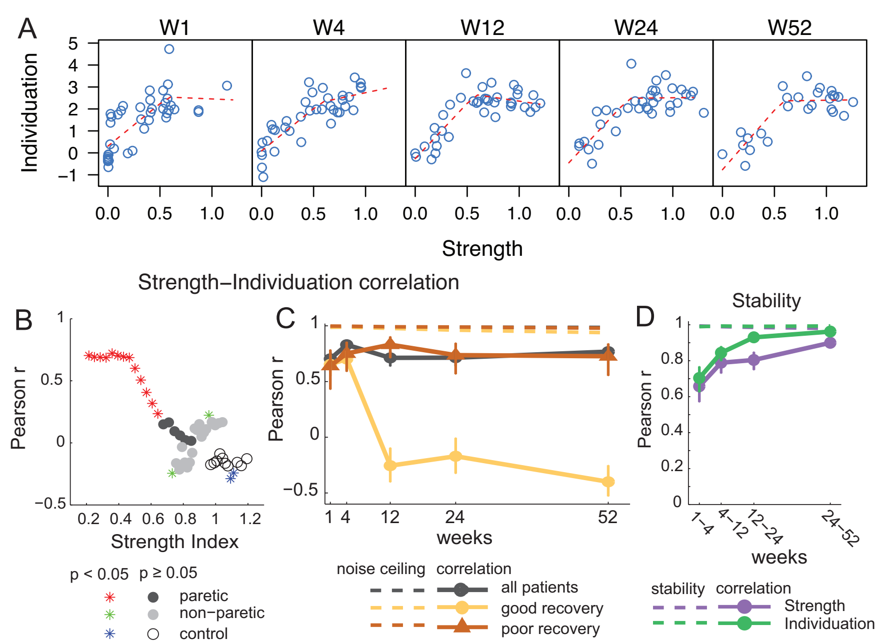

Figure 2. *Correlation between Strength and Individuation Indices. (**A**) Scatter plots between strength and individuation for each time point and the best-fitting piece wise function. (**B**) Correlations between Strength and Individuation Indices across entire data sets on the paretic side (red stars and dark gray dots), non-paretic side (green stars and light gray dots), and controls (blue stars and black circles), sorted by level of Strength Index, with a sliding window of 80 data points. (**C**) Correlations between Strength and Individuation Indices within each time point. Dashed lines are noise ceilings for the correlations. (**D**) Week-to-week correlations between adjacent time points for Strength and Individuation Indices. Dashed lines are reliabilities for the correlations.*

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