THESIS

THE IMPACT OF GRIP STRENGTH RECOVERY ON GRIP FORCE ACCURACY IN CHRONIC STROKE

Submitted by

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ABSTRACT

THE IMPACT OF GRIP STRENGTH RECOVERY ON GRIP FORCE ACCURACY IN CHRONIC STROKE

Decreased grip force accuracy and grip strength are two well-documented grip impairments that impede upper extremity function after stroke. Grip force accuracy is essential to perform precise motor actions in everyday life. Further, grip strength represents the ability to produce maximal grip force in a short duration of time and constitutes as a hallmark of upper extremity recovery in chronic stroke. Adequate grip strength and grip force accuracy are both important for regaining motor function after stroke. Despite this, no study has investigated whether the recovery of grip strength influences improvements in force accuracy. **Purpose:** Therefore, the purpose of the study was to investigate the impact of grip strength recovery on grip force accuracy in chronic stroke patients. **Methods:** We recruited two distinct stroke groups with low (less than 60%) and high (60% or more) grip strength recovery. The grip strength recovery was computed as the percent of paretic grip strength relative to nonparetic grip. A total of thirty-three participants, eleven in low strength recovery group (age 64 $\pm$14.8 years; 6 females and 5 males), eleven in high strength recovery group (age 65.9 $\pm$ 9.9 years, 7 females and 4 males) and eleven age matched controls (age 69.6 ± 9.8 years, 4 females and 7 males) participated in the study. To examine the impact of grip strength recovery on grip force accuracy, all participants performed two tasks; 1) maximum voluntary contraction (MVC) and 2) dynamic force tracking task, using each hand. We quantified grip strength as the maximum force produced in the MVC task. Further, we assessed force accuracy by measuring root mean square error relative to the absolute target force. **Result:** The grip strength recovery in low strength recovery stroke group (27.1 ± 17.7)% was lower compared to the high strength recovery group (92.4 ± 24.9)% and controls (94.9 ±18.9)%. A significant main effect of Group [F (2, 30) = 34.53, $p < 0.05$, partial $\eta^2 = 0.69$] revealed the grip strength recovery in low strength recovery group was significantly less than the high strength recovery stroke group ($p < 0.05$) and control ($p < 0.05$) whereas, the high strength recovery group was not significantly different than the control group ($p > 0.05$). A significant interaction between Group×Hand, [F (2, 30) = 7.21, $p < 0.05$, partial η2 = 0.33] demonstrated that the relative RMSE of paretic hand was significantly increased in low strength recovery stroke group compared to the high strength recovery ($p < 0.05$). Importantly, the relative RMSE of paretic hand in high strength recovery group was significantly greater than the control group's non-dominant hand ($p < 0.05$). Overall, a significant negative relationship between grip strength recovery and paretic relative RMSE (r = -0.598, p = 0.003) was found when investigating correlations in both groups together. In low strength recovery group, we found a negative association between the grip strength recovery and paretic relative RMSE, ($r = -0.552$, $p = 0.078$). However, in high strength recovery group, we found no association between the grip strength recovery ($r = 0.308$, $p = 0.357$). **Conclusion:** Grip strength recovery and force accuracy follow differential patterns of improvement for low and high strength recovery stroke groups. In chronic stroke survivors with strength recovery less than 60%, grip strength recovery is associated with grip force accuracy. However, in chronic stroke survivors with strength recovery more than 60%, the grip force accuracy may still be impaired despite near-normal grip strength recovery. After substantial gain in grip strength recovery, interventions that enhance grip force accuracy may be needed to improve upper-extremity function. Our study results suggest, after improvement in strength, patients need additional interventions such as exergaming that will train force accuracy, to help them use this regained strength more meaningfully.

ACKNOWLEDGMENTS

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DEDICATION

I would like to dedicate this thesis to my extraordinarily awesome husband, Rashed and my wonderful families in both countries.

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CHAPTER 1 - INTRODUCTION

Decreased grip force accuracy and grip strength are two well-documented grip impairments in chronic stroke.[1-4] Grip force accuracy is necessary for the precise application of grip forces to prevent slipping caused by application of too little force or crushing of an object caused by application of too much force. Decreased grip force accuracy is detrimental to our ability to perform movements with precision such as, meet the physical requirements of a grasping, lifting and moving an object.[5-7] Grip strength represents the ability to produce maximal amount of grip force in a short duration of time and constitutes as a hallmark of upper extremity recovery in chronic stroke.[1,8-12] Empirical evidence suggests that the notable deficits in strength often coexist with decreased force accuracy, unpredictable and slower force development, and other residual motor impairments in chronic stroke individuals.[13-16] Thus, one may expect that improvements in grip strength lead to concomitant improvements in grip force accuracy. Although extensive research suggests grip strength as an important indicator of upper extremity recovery after stroke, until now, no study has examined the impact of grip strength recovery on grip force accuracy.

Typical assessment of grip strength in the clinic relies on measurement of the absolute performance of the paretic limb alone. This approach may be insufficient to determine the proportion of recovery already achieved and that which remains to be attained. The limitations of absolute paretic grip strength measure can be addressed by assessing the grip strength recovery.[17] Grip strength recovery assesses percent recovery of paretic grip strength relative to the nonparetic grip. Empirical evidence suggests that 60% of strength recovery may be a critical milestone in progress toward stroke recovery. Beyond this point the strength and motor control likely follow separate trajectories of improvement.[16,18] For example, in mild to moderate stroke individuals, Schaefer et al. (2012) observed that the paretic grip type and task goal requirements influence the reaching and grasping performance strategy with 70% of grip strength recovery.[19] In addition, participants with a 58% grip strength recovery have shown reduced hand functions due to decreased movement control in all segment of upper extremity.[20] In a relative force target of 20% MVC during dynamic bimanual finger force tracking task, the chronic stroke participants showed decreased force accuracy with 60% finger strength recovery.[21] Similarly, in an absolute target level tracking task, Kim et al. (2016) observed a decreased multifinger force accuracy in chronic stroke participants with 62% grip strength recovery.[15] No study to date has directly investigated how grip force accuracy is altered in low and high grip strength recovery chronic stroke groups.

In the current study, we used a cutoff score of 60% grip strength recovery to recruit and categorize individuals into low and high strength recovery stroke groups. Participants with less than 60% grip strength recovery formed the low strength recovery stroke group, whereas the high strength stroke recovery group consisted of participants with 60% or more grip strength recovery. A grip strength recovery close to 100% implied full recovery.[1,18] Recent work from our lab suggests that in mild-moderately impaired stroke individuals, the paretic lower limb showed decreased accuracy despite substantial ankle strength recovery.[16] However, the evidence is lacking regarding the relation between upper extremities force accuracy and strength recovery in stroke survivors. Therefore, the current study compares low and high strength recovery groups to determine the impact of grip strength recovery on force accuracy.

Typically, everyday activities such as eating, grooming, drinking coffee from a cup, interacting with touch screen devices, etc. demand accurately control of grip forces.[22,23] The magnitude of force required to do these tasks ranges between 16% to 20% of the individual's maximum grip strength.[5-7,24,25] Our dynamic force tracking task employs up to 20% of individuals' maximum grip strength, thus is appropriate to assess the impact of grip strength recovery on grip force accuracy. Further, visuomotor feedback during the tracking task ensures dynamic modulation by systemically increasing and decreasing the forces.[22,26] Consequently, our study will enhance the understanding of the grip force accuracy at force levels required for everyday activities in low and high grip strength recovery chronic stroke groups.

Since the everyday activities demand both grip strength and precise application of grip forces according to the task requirements, understanding the impact of grip strength recovery on force accuracy is of significant importance in upper extremity rehabilitation. Although strength training interventions target to improve functional capacity, the impact of the degree of strength improvement on grip force accuracy has not been studied yet in chronic stroke.[27-30] Furthermore, in the chronic stage of recovery studying only grip strength may be inefficient to ameliorate the performance in functional activities.[31] Therefore, assessing the impact of low and high grip strength recovery on force accuracy may provide the appropriate milestone to implement further focused interventions to optimize function.

Therefore, in the current study, we investigate the impact of grip strength recovery on grip force accuracy in low and high strength recovery stroke groups. We assess the force accuracy using the dynamic force tracking task at a 20% MVC level.[4,21,32] First, we hypothesize, in the low grip strength recovery stroke group, the paretic and nonparetic maximum voluntary contraction (MVC) of grip values will be reduced compared to the high strength recovery stroke group and control group.[4,33,34] Further, the grip MVC in the high strength recovery stroke group will be comparable to the control group.[16] Our second hypothesis is that the grip strength recovery in the low strength recovery stroke group will be reduced compared to the high strength recovery stroke group and the control group. Further, the grip strength recovery of the high strength recovery stroke group will be comparable to the control group. Finally, our third hypothesis is that the paretic grip force accuracy will be different in low and high strength recovery stroke groups than the non-dominant hand in control group. Low strength recovery group will exhibit reduced paretic grip force accuracy compared to the high strength recovery stroke group. Given that the mild to moderately impaired individuals have shown motor impairment even after substantial strength recovery in paretic lower limb, we hypothesize that the high strength recovery group will demonstrate decreased force accuracy with the paretic hand compared with the non-dominant hand in control. Moreover, there will be an overall positive relationship between the grip strength recovery and force accuracy such that the force accuracy will be increased with the improvement in grip strength recovery.[16,18]

CHAPTER 2 - METHODS

2.1 Participants:

A total of 22 chronic stroke participants were recruited. Eleven participants (six females, five males, mean age = 60.18 ±14.20 years) with less than 60% grip strength recovery qualified to participate in low strength recovery stroke group. Eleven participants (four females, seven males, mean age = 65.95± 9.86 years) with 60% or more grip strength recovery qualified to participate in the high strength recovery stroke group. The additional eligibility criteria to be recruited in either of the two stroke groups included; 1) diagnosis of a cerebrovascular event at least six months prior to participation, 2) the ability to maintain a neutral position of the wrist joint with or without custom made styrofoam support tool, 3) the ability to voluntarily grasp a cylindrical object, and 4) the ability to understand and follow a three-step command. In addition, eleven healthy age-matched older adults (four females, seven males, mean age = 69.54 ± 9.80 years) participated in the control group. The participants characteristics for all three groups are presented in **Table1**.

The exclusion criteria for all the participants included the presence of any other neurological or musculoskeletal condition, severe visual neglect, uncorrected vision or hearing impairments and pain. We performed the visual acuity test to ensure that the participants do not persist any visual impairment. To assess the spasticity of upper extremity we used the modified Ashworth Scale (MAS).[35] Prior to participation, every participant read and provided written informed consent to participate in the study. The study procedures and informed consent form were approved by the Institutional Review Board of Colorado State University.

Table 1. Participant characteristics.

	Low strength recovery stroke group (N =11)	**High strength recovery stroke group (N =11)**	**Control (*N=11*)**
Age (years)	60.18±14.20	65.95 ± 9.86	69.54 ± 9.80
Sex (Male/Female), *N*	5/6	4/7	7/4
Height (cm)	164.25±15.43	169.80 ± 14.42	170.19 ± 7.13
Premorbid hand dominance (right), *N*	8	11	9
Hemiparetic side (left/right), *N*	7/4	3/8	N/A
Time since stroke (years)	6.77 ± 4.14	4.91 ± 2.85	N/A
FMA-UE	34.91 ± 18.82	57.73 ± 4.88	N/A
MOCA	24.18 ± 6.35	27.73 ± 1.95	27.73 ± 2.20
Visual acuity test (both)	20/20	20/20	20/20
Modified Ashworth Scale (MAS)	0	0	–

FMA-UE – Fugl-Meyer assessment of upper extremity (maximum score 66); MoCA- Montreal cognitive assessment (maximum score 30); N/A – not applicable. All scores are mean ± standard deviation.

2.2 Clinical evaluations:

For both stroke groups, we used the upper extremity subsection of Fugl-Meyer Assessment (FMA) to assess the severity of upper extremity motor impairments.[36] Chronic stroke participants were instructed over the phone to bring the clinical documentation of the cerebrovascular event while visiting the lab. We recorded the time since stroke from the documents. To determine the hand dominance in controls, we used the Edinburgh Handedness Inventory. [37] The stroke participants self-reported the hand dominance prior to stroke. We performed the visual acuity test to determine the visual impairment.[38] In the test, the participants were asked to wear glasses or contact lenses if they use one and stand or sit 20 feet (6 meters) from the eye chart with both eyes open. Then we asked them to cover one eye with the palm of hand while the examiner read out loud the smallest line of letters the participant can see on the chart. Visual acuity 20/20 is a normal score and means that the participants visual acuity at 20 feet away from an object is normal. The MAS testing was conducted with each stroke patient positioned supine on a padded mat table. We examined the spasticity of all of the upper extremity muscles using MAS.[35] Further, we determined the cognitive status of the participants by Montreal Cognitive Assessment (MoCA).[39]

2.3. Experimental procedures:

Each experimental session consisted of a single session of ~3 hours. In each experimental session, participants were clinically evaluated and performed two tasks that included: 1) maximum voluntary contraction (MVC) using both paretic and nonparetic hands and, 2) visually guided dynamic force tracking task using for paretic and nonparetic hands.

Experimental set-up: **Figure 1** shows the experimental set-up for the maximal voluntary contraction (MVC) and dynamic force tracking task. The participants sat comfortably in an upright chair. A 32-inch LCD monitor placed in front, approximately 45 inches away from the chair. Participants seated with their forearms and elbows resting on an adjustable height table. The arms rested on the table with shoulders positioned in ~20˚ abduction and 30˚ flexion, elbows in 80-90˚flexion, and the wrist in a neutral position. In this position, participants held a custom-designed gripping device with an embedded force transducer. The LCD monitor displayed the visual prompts, the target force, and visual feedback of the force exerted by the participant.

2.3.1 Maximum voluntary contraction (MVC):

Task: The participants were instructed to exert maximum force using the grip unimanually for 3s in response to a visual prompt "GO" on the screen. The MVC was assessed unimanually for each hand, i.e., paretic and nonparetic hands in both stroke groups and non-dominant and dominant hands in the control group. The order of the hand conditions was randomized for each participant. All participants performed three to five MVC trials until two trial values were within 5% of each other. Between trials, a rest period of 60s was provided to avoid fatigue. Participants were instructed to avoid any other extraneous movements during the task.

2.3.2 Dynamic force tracking task:

Task: The dynamic force task involved tracking a trapezoid trajectory for a total of 17s. The task required a controlled linear increase in force (3% MVC/s) for 6.5s followed by a constant 20% MVC force for 2s, and then, a linear decrease of force (3% MVC/s) for 6.5s. We selected 20% grip MVC as a target force to make the force production level comparable to the everyday manual tasks force requirement level.[24,25]

The participants were instructed to track the target trajectory as accurately as possible. Each trial started with a visual prompt "GET READY," and participants received real-time visual feedback of their force output relative to the target force trajectory on the computer monitor. Before the experimental sessions, each participant performed 2-3 familiarization trials with each hand condition. Following familiarization trials, participants completed a block of five experimental trials with each hand condition. We provided a 20s rest period interspersed between successive trials to avoid fatigue. Participants performed the force tracking task unimanually with each hand. The order of hand conditions was randomized across participants.

Data acquisition: We performed the data acquisition using a custom-written program in Matlab, 2017b (MathWorks, Natick, MA, USA). A force transducer (Model- MLP, capacity-150 LBS, and Model Transducer Techniques Inc., CA, USA) was embedded in each of the customized gripping devices to measure the grip force. The force signal from each transducer was sampled at the rate of 1000 Hz on a 16-bit analog-to-digital converter (A/D; NI DAQ, National Instruments) and amplified by a gain factor of 100 by using Bridge-8 Transducer Amplifier Module (World precision instrument Inc., FL, USA). The raw force signal data were filtered using a fourth-order Butterworth low pass filter with a cut-off frequency of 10 Hz. All data were saved for offline analysis.

Data analysis: The grip strength outcome was the maximum force produced in Newton (N). Within each MVC trial, the maximum force was computed as the average of 10 samples (0.01s) around the peak force produced.

Form the dynamic force tracking task, we quantified the deviation of the participant's force output from the target force using root mean square error (RMSE) to measure the force accuracy (Equation 1).

$$RMSE = \sqrt{\frac{\sum_i^n \left(X_{participant,i} - X_{target,i}\right)^2}{n}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

We normalized the absolute RMSE by the mean force to allow comparison between participants with varying levels of grip strength. Higher values for relative RMSE indicate less accuracy of force output.[21]

2.3.3 Grip strength recovery:

We measured the grip strength recovery following the completion of MVC task for all participants. **Equation 2.** demonstrates the formula used to calculate the grip strength recovery in both stroke groups.

$$\text{Grip strength recovery} = \frac{\text{MVC of paretic grip}}{\text{MVC of nonparetic grip}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

For the control group, we used **Equation 3.** to assess the grip strength recovery.

$$\text{Grip strength recovery} = \frac{\text{MVC of non} - \text{dominant grip}}{\text{MVC of dominant grip}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Grip strength recovery was used to categorize chronic stroke participants into low and high strength recovery groups. We used a cut off 60% grip strength recovery to distinguish individuals in the low and high strength recovery stroke group. Specifically, participants with less than 60% grip strength recovery qualified to be in the low strength recovery stroke group and participants with 60% or more grip strength recovery qualified to be high strength recovery stroke group.[18]

1. Experimental setup for the grip strength and grip force tracking task

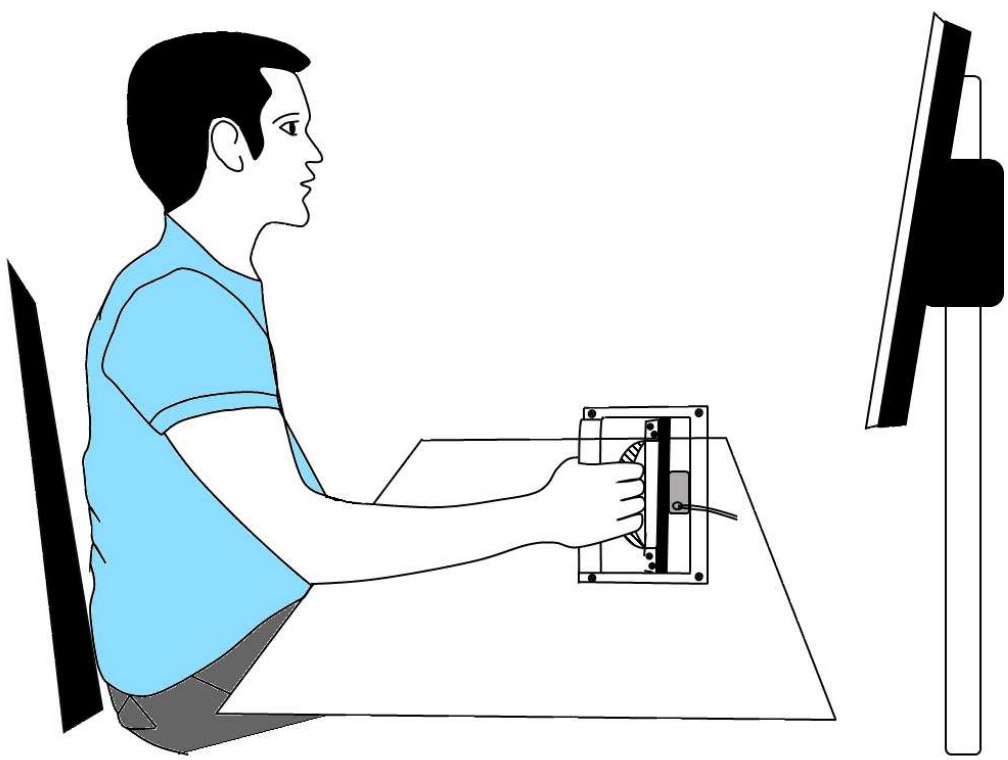

Figure 1: Experimental setup for the grip strength (MVC: maximum voluntary contraction) and grip force tracking task. Participants were seated in an upright chair in front of a computer screen and performed the grip MVC and the dynamic grip force tracking tasks holding the customized grip device in one hand at a time. In the MVC task, participants exerted maximum grip force. In the force tracking task, participants tracked a trapezoid trajectory as accurately as possible.

CHAPTER 3 - STATISTICAL ANALYSIS

We examined the distribution of the data with the Shapiro-Wilk test, where $p > 0.05$ indicated the normal distribution of the data. We compared the three groups using 2 x 2 (Group: low and high strength recovery stroke groups and control group; Hand: paretic/nonparetic for low and high strength recovery stroke groups and non-dominant/dominant for the control group) mixed model analysis of variance (ANOVA) on the following measures: i) grip strength, ii) force accuracy. Further, to compare the grip strength recovery of three groups, we performed one-way ANOVA. Significant main effect and interactions were followed up with Bonferroni post-hoc comparisons.

We performed Pearson's bivariate correlations to examine the relationship between grip strength recovery, paretic and nonparetic grip strength, and relative RMSE for both groups together. To examine whether the premorbid hand dominance and side-affected impact the grip strength, grip strength recovery and force accuracy, we performed a secondary analysis. Here, for each stroke group separately, an independent *t* test compared individuals with paretic dominant hand and nonparetic dominant hand. Also, to test the effect of sex grip strength, grip strength recovery and force accuracy, an independent *t* test compared females and males in each stroke group separately. Additionally, partial eta squared (η^2) was calculated to provide an estimate of the amount of variance accounted for by each factor in the ANOVAs. All statistical analyses were performed with an alpha level set at $p < 0.05$ using SPSS 25.

CHAPTER 4 – RESULTS

4.1 Demographics:

Table 1 presents demographics of all three groups and performance on clinical tests of both stroke groups. In the control group, the grip strength of non-dominant hand expressed as the percentage of dominant hand was 94.93 ± 18.89 % (range 72 - 131%). The mean grip strength recovery of low strength recovery stroke group was 31.86 ± 17.58 % (range 6 - 57%). In high strength recovery stroke group, the mean grip strength recovery was 92.40 ± 24.94% (range 63−132%). There was no significant difference between the three groups for age [F (2, 30) = 0.625; $p = 0.543$, $\eta^2 = 0.040$] and MoCA [F (2, 30) = 2.82; $p > 0.05$, $\eta^2 = 0.158$). In addition, no significant difference was found between the two chronic stroke groups for time the time since stroke ($t_{|20|} = 1.23$; $p > 0.05$). The FMA-UE scores were significantly higher in high strength recovery stroke group than the low strength recovery group ($t_{|20|} = -3.89$; $p < 0.05$).

4.2 Grip Strength:

Figure 2 demonstrates the paretic and nonparetic grip strength in the low and high strength recovery stroke group, and the non-dominant and dominant grip strength in the control group. A two-way mixed-design ANOVA revealed a significant main effect of Group, [F (2, 30) = 5.94, $p < 0.05$, partial $\eta^2 = 0.29$]. Further, the grip strength in the high strength recovery stroke group was significantly reduced than the control group ($p < 0.05$). We found a significant main effect of Hand on grip strength, [F (2, 30) = 35.43, $p < 0.05$, partial $\eta^2 = 0.54$]. We found a significant Group ×

Hand interaction, [F (2, 30) = 21.510, $p < 0.05$, partial $\eta^2 = 0.59$]. The Bonferroni post-hoc pairwise comparison showed paretic grip strength in the low strength recovery stroke group, was significantly reduced than high strength recovery ($p < 0.05$) and non-dominant hand in the control group ($p < 0.05$). In low strength recovery stroke group, the paretic grip strength was significantly reduced than the nonparetic grip strength ($p < 0.05$). Further, the paretic grip strength in the high strength recovery stroke group was significantly reduced than the non-dominant hand in the control group ($p < 0.05$). We found no significant difference between nonparetic grip strength in low and high strength recovery stroke groups ($p > 0.05$), low strength recovery stroke group and control ($p > 0.05$), and high strength recovery stroke group and control ($p > 0.05$).

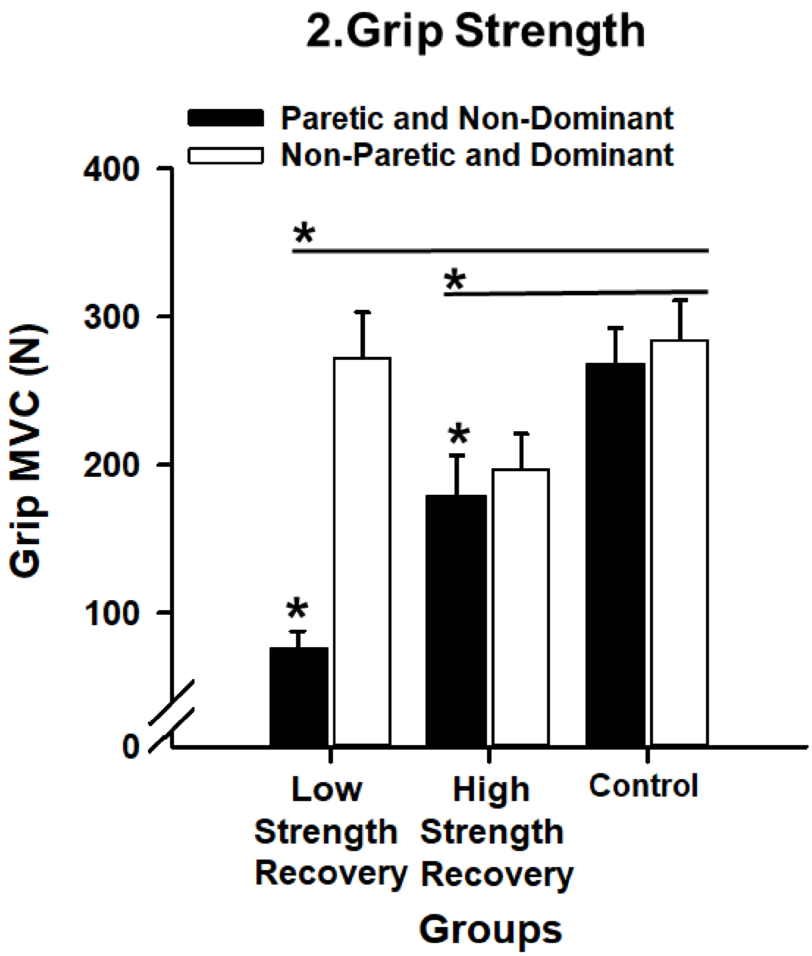

Figure 2: Grip strength in low, high strength recovery stroke group and control. Strength was quantified by maximum voluntary grip force (MVC) for each hand across all three groups. The paretic grip strength in the low strength recovery stroke group was significantly lower than the high strength recovery stroke group and the non-dominant hand in the control group. The nonparetic (stroke groups) and the dominant grip (control groups) strength was not significantly different. The error bars represent the standard error of the mean. Significant difference between three groups are shown by $*p < 0.05$.

4.3 Grip Strength Recovery:

Figure 3 demonstrates the grip strength recovery in the low and high strength recovery stroke groups, and control group. The one-way ANOVA showed a significant difference between the three groups, [$F\ (2, 30) = 34.53$, $p < 0.05$, partial $\eta^2 = 0.69$]. The Bonferroni post-hoc pairwise comparison demonstrated that the grip strength recovery in the low strength recovery stroke group was significantly less than both the high strength recovery stroke group ($p < 0.001$) and the control group ($p < 0.001$). The grip strength recovery of the high strength recovery group was not significantly different than the control group ($p > 0.05$).

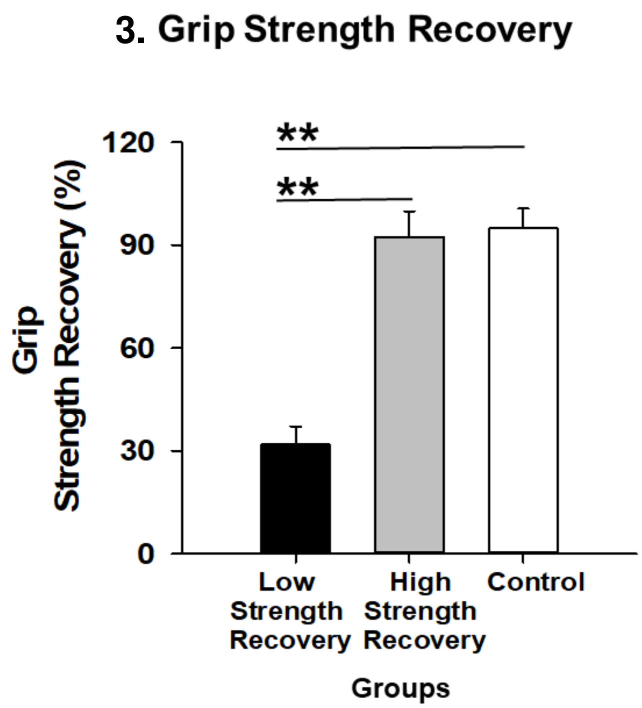

Figure 3: Grip strength recovery in low and high strength recovery stroke groups, and control group. The grip strength recovery was quantified by using the percentage of paretic grip MVC relative to nonparetic grip MVC in low and high strength recovery stroke groups and non-

dominant grip MVC relative to dominant grip MVC in the control group. The grip strength recovery in the low strength recovery stroke group was significantly different than the high strength recovery stroke group and the control group. The error bars represent the standard error of the mean. Significant difference between three groups are shown by $*p < 0.05$; $**p < 0.01$.

4.4 Force accuracy:

Figure 4A shows the force accuracy of the paretic hand in low and high strength recovery stroke groups, and the non-dominant hand grip strength in the control group. We found a significant main effect of Group, [$F\ (2, 30) = 11.95$, $p < 0.001$, partial $\eta 2 = 0.44$]. In addition, we found a significant main effect of Hand, [$F\ (2, 30) = 8.15$, $p < 0.05$, partial $\eta 2 = 0.22$]. Further, we found a significant Group × Hand interaction, [$F\ (2, 30) = 7.21$, $p < 0.05$, partial $\eta 2 = 0.33$]. Post-hoc analysis confirmed that the relative RMSE of paretic hand in the low strength recovery stroke group was significantly greater than the high strength recovery stroke group ($p < 0.05$) and non-dominant hand in the control group ($p < 0.001$). Further, the relative RMSE of paretic hand in the high strength recovery stroke group was significantly higher than the non-dominant hand in the control group ($p < 0.05$).

Figure 4B shows the force accuracy of the nonparetic hand in low and high strength recovery stroke groups, and the dominant hand grip strength in the control group. We found a significance difference between nonparetic hand relative RMSE in low strength recovery group and dominant hand in the control ($p < 0.05$). The nonparetic hand's relative RMSE between low and high strength recovery stroke groups showed no significant difference ($p > 0.05$). Further, the nonparetic hand's relative RMSE in high strength recovery stroke group and dominant hand in control group showed no significant difference ($p > 0.05$).

4. Grip Force Accuracy

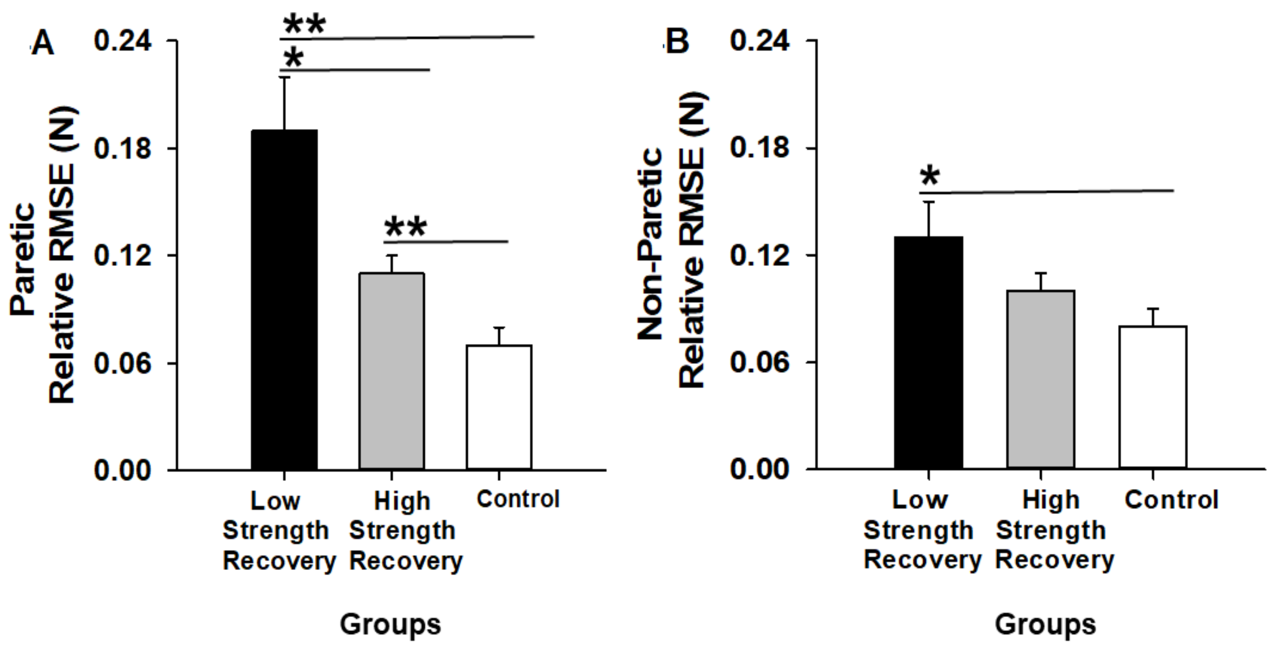

Figure 4A: Paretic and non-dominant grip force accuracy and Figure 4B: Nonparetic and dominant grip force accuracy, in low and high strength recovery stroke groups and control group. The force accuracy was quantified by relative RMSE of the force tracking task for both hands across all three groups. The relative RMSE of paretic hand in the low strength recovery stroke group was significantly higher than the high strength recovery stroke group and the non-dominant hand in the control group. Further, the relative RMSE of the paretic hand of the high strength recovery stroke group was significantly higher than the non-dominant hand in the control group. In the nonparetic hand, the relative RMSE of the low strength recovery stroke group was significantly higher than the dominant hand in the control group. The error bars represent the standard error of the mean. Significant difference between three groups are shown by $*p < 0.05$; $**p < 0.01$.

4.5 Relation between grip strength recovery and force accuracy

Figure 5 shows the relationship between grip strength recovery and force accuracy for both stroke groups together. **Table 2** shows the correlation between grip strength recovery, paretic and nonparetic grip strength, and relative RMSE in low and high strength recovery stroke groups. We found a significant negative relationship between grip strength recovery and relative RMSE of paretic hand ($r = -0.598$, $p = 0.003$). Overall, he greater strength recovery was correlated to the reduced relative RMSE in the paretic hand when investigating correlations in both groups together. We also investigated if the correlation between strength recovery and relative RMSE was also found in each group separately. A trend suggesting a moderate negative correlation between grip strength recovery and RMSE emerged in the low strength recovery group ($r = -0.552$, $p = 0.078$). However, in high strength recovery group, we found no association between paretic relative RMSE and the grip strength recovery ($r = 0.308$, $p = 0.357$).

Table2: Pearson's Bivariate correlations (r) of strength recovery, the strength of paretic and nonparetic hand with force accuracy.

		Strength recovery		**Paretic MVC**		**Nonparetic MVC**	
		r	*p*	*r*	*p*	*r*	*p*
Low strength recovery group	Paretic relative RMSE	-0.55	0.08	-0.42	0.05	–	–
	Nonparetic relative RMSE	- 0.15	0.66	–	–	0.08	0.81
High strength recovery group	Paretic relative RMSE	- 0.21	0.55	- 0.15	0.65	–	–
	Nonparetic relative RMSE	- 0.22	0.52	–	–	- 0.35	0.29
Low and high strength recovery stroke groups	Paretic relative RMSE	- 0.59**	0.00	-0.42	0.50	–	–
	Nonparetic relative RMSE	- 0.32	0.15	–	–	0.06	0.79

*MVC – Maximum Voluntary Contraction, RMSE – Root Mean Squared Error; **p < 0.01*

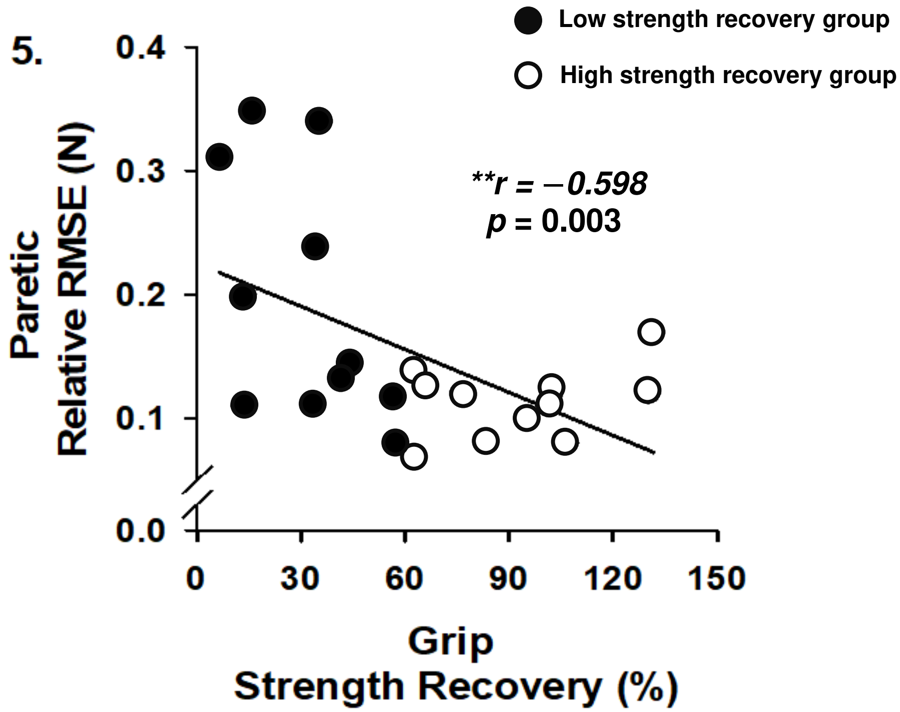

Figure 5: A correlation analysis showed a significant negative association between the grip strength recovery and relative RMSE of the paretic hand in low and high strength recovery stroke groups taken together. **$p < 0.01$.

4.6 Secondary analysis:

4.6.1 Effect of hand dominance:

Figure 6 shows the effect of hand dominance on **(A)** grip strength, **(B)** grip strength recovery and **(C)** force accuracy in low strength recovery stroke group. To examine whether the premorbid hand dominance and side-affected impact grip strength, grip strength recovery and force accuracy, we performed an independent *t* test for each stroke group separately. Here, the independent *t* test compared the individuals with paretic dominant hand and nonparetic dominant hand. In low strength recovery stroke group, we had 4 participants with paretic dominant hand and 7 participants with paretic non-dominant hand. In the high strength recovery stroke group, we had 8 participants with paretic dominant hand and 3 participants with paretic non-dominant hand.

In low strength recovery stroke group, there was no significant difference between the paretic dominant and non-dominant hand for the paretic grip strength ($t_{|9|}$ = 0.553, $p > 0.05$) and nonparetic grip strength ($t_{|9|}$ = -0.775, $p > 0.05$), grip strength recovery ($t_{|9|}$ = 1.29, $p > 0.05$), the paretic relative RMSE ($t_{|9|}$ = -0.775, $p > 0.05$) and nonparetic relative RMSE ($t_{|9|}$ = -0.038, $p > 0.05$).

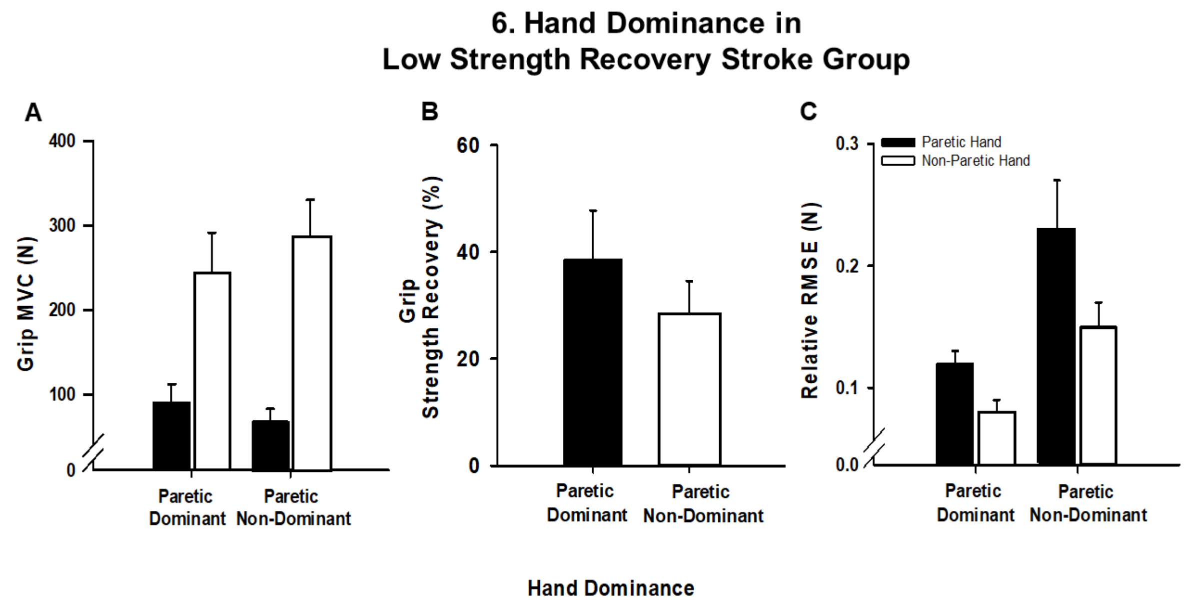

Figure 6: The effect of hand dominance on (A) grip strength, (B) grip strength recovery and (C) relative RMSE in low strength recovery group. No significant difference was found between the paretic dominant hand and the paretic non-dominant hand on grip strength, grip strength recovery and relative RMSE. The error bars represent the standard error of the mean.

Figure 7 shows the effect of hand dominance on **(A)** grip strength, **(B)** grip strength recovery and **(C)** force accuracy in high strength recovery stroke group. In high strength recovery stroke group, there was no significant difference between the paretic dominant and non-dominant hand for the paretic grip strength ($t_{|9|}$ = -0.801, $p > 0.05$) and nonparetic grip strength ($t_{|9|}$ = -1.74, $p > 0.05$), grip strength recovery ($t_{|9|}$ = 1.175, $p > 0.05$), the paretic relative RMSE ($t_{|9|}$ = 1.38, $p > 0.05$) and nonparetic relative RMSE ($t_{|9|}$ =0.396, $p > 0.05$).

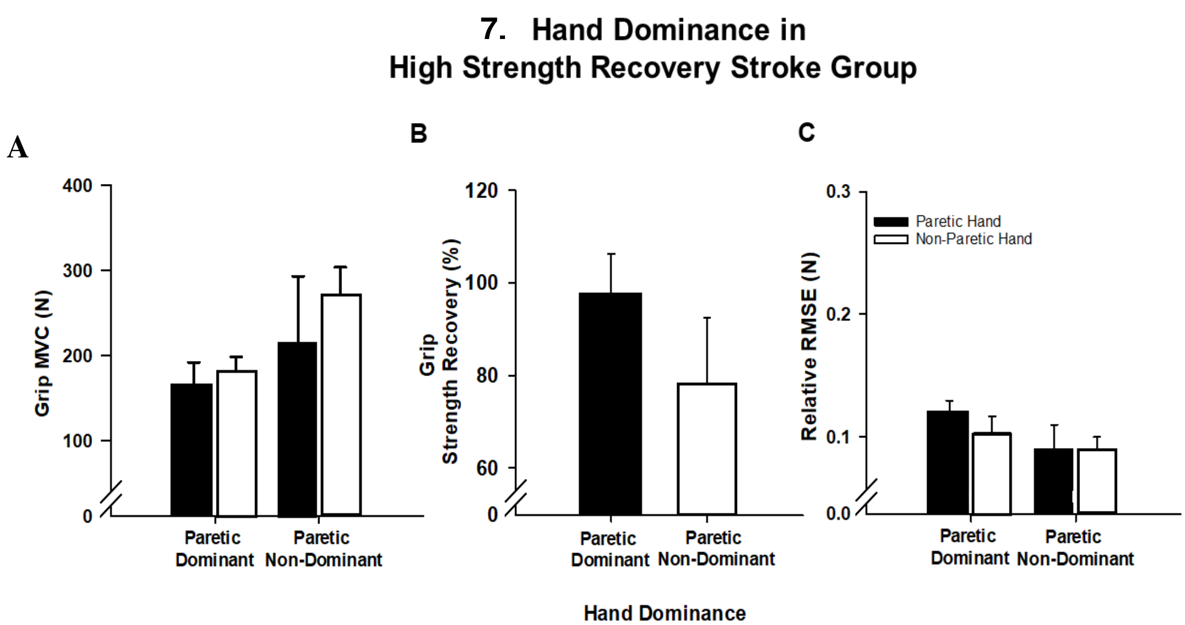

Figure 7: The effect of hand dominance on (A) grip strength, (B) grip strength recovery and (C) relative RMSE in high strength recovery stroke group. No significant difference was found between the paretic dominant hand and the paretic non-dominant hand on grip strength, grip strength recovery and relative RMSE. The error bars represent the standard error of the mean.

4.6.2 Effect of sex:

Figure 8 illustrates the effect of sex on (A) grip strength, (B) grip strength recovery, and (C) force accuracy in low strength recovery group. To investigate whether the sex impacts the grip strength, grip strength recovery and force accuracy, we performed an independent *t* test for each stroke group separately. In low strength recovery stroke group, we had 6 females and 5 males. In high strength recovery stroke group, we had 7 females and 4 males.

In low strength recovery stroke group, we found the nonparetic grip strength in the females are significantly reduced compared with the nonparetic grip strength of male ($t_{|9|} = -4.46$, $p < 0.05$). However, we found no significant difference between females and males for the paretic grip strength ($t_{|9|} = -6.74$, $p > 0.05$), grip strength recovery ($t_{|9|} = 1.28$, $p > 0.05$), paretic relative RMSE ($t_{|9|} = 0.763$, p= 0.465) and nonparetic relative RMSE ($t_{|9|} = 0.565$, $p > 0.05$).

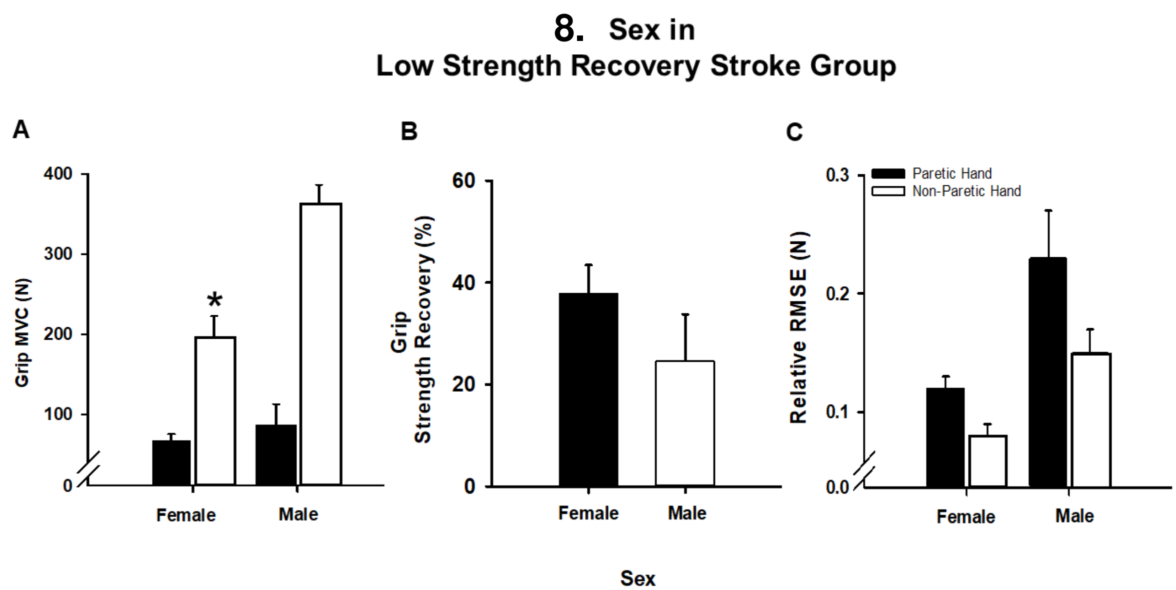

Figure 8: The effect of sex on (A) grip strength, (B) grip strength recovery and (C) relative RMSE in low strength recovery group. The nonparetic grip strength in females was significantly lower than the male nonparetic hand.

Figure 9 demonstrates the effect of sex on (A) grip strength, (B) grip strength recovery and (C) force accuracy in high strength recovery group. In high strength recovery stroke group, we found the nonparetic grip strength in the females are significantly reduced compared with the nonparetic grip strength of male ($t_{|9|} = -2.46$, $p < 0.05$). We found no significant difference between females and males on paretic grip strength ($t_{|9|}$ = -1.59, $p > 0.05$), nonparetic grip strength ($t_{|9|} = 0.45$, $p > 0.05$) grip strength recovery ($t_{|9|} = 0.65$, $p > 0.05$), paretic relative RMSE ($t_{|9|} = 0.452$, $p > 0.05$) and nonparetic relative RMSE ($t_{|9|} = 0.715$, $p > 0.05$).

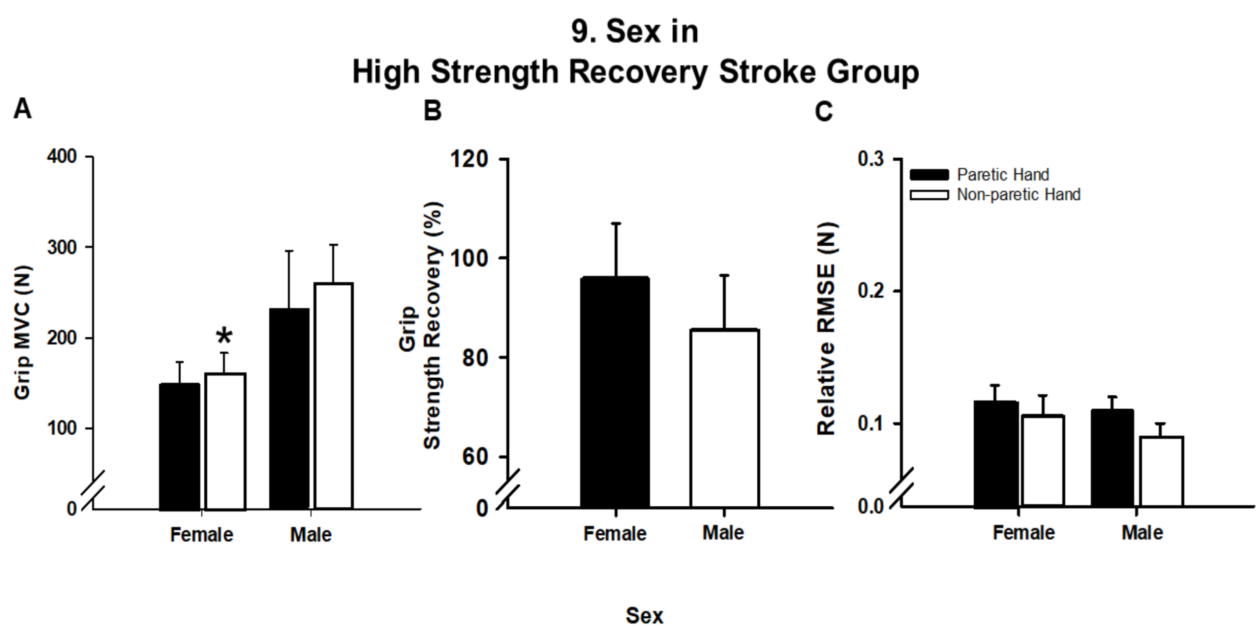

Figure 9: The effect of sex on (A) grip strength, (B) grip strength recovery and (C) relative RMSE in high strength recovery group. The nonparetic grip strength in females was significantly lower than the male nonparetic hand.

CHAPTER 5 - DISCUSSION

The purpose of the study was to investigate the impact of grip strength recovery on grip force accuracy in chronic stroke patients. The current study applied stringent criteria to recruit individuals in low and high strength recovery stroke groups. The low strength recovery stroke group manifests decreased grip strength recovery and decreased force accuracy compared to the high strength recovery group. Further, the high strength recovery stroke group exhibits grip strength recovery comparable to the control group, yet decreased force accuracy compared with the control group. Therefore, our study provides novel evidence that despite near-normal grip strength recovery, the grip force accuracy may still be impaired in chronic stroke individuals.

5.1 Grip Strength recovery in low and high strength recovery chronic stroke groups

The grip strength recovery expresses the paretic grip strength as a percentage of the nonparetic grip strength.[1,10,12,15,18,40] In our study, by design, the grip strength recovery is significantly different between the low and high strength recovery group. Thus, the low strength recovery stroke group demonstrated a significantly reduced strength recovery (27.1 ± 17.7) than the high strength recovery stroke group (92.4 ± 24.9). On the contrary, the high strength recovery stroke group exhibited near-normal grip strength recovery, which was comparable to the control group (94.9 ± 18.9). These results confirm that our experimental manipulation of distinguishing the low and high-strength recovery groups was successful.

Grip strength recovery provides insights into the extent of recovery by including both paretic and nonparetic grip strength measurements, that cannot be obtained by measuring the absolute paretic grip strength alone.[17] For example, two stroke individuals may have the same absolute strength in paretic grip (for example, 90 N), but their strength recovery can be very different. Suppose, the first individual shows a 90% recovery (given, the nonparetic strength was 100 N) while the second individual shows 30% recovery (given, nonparetic strength was 300 N). Presuming that before the stroke, the nonparetic strength was comparable to the paretic hand strength, measuring strength recovery allows clinicians to know what percent of strength recovery has been already achieved by the stroke survivors and what might be the available room for additional recovery. In the above example, the first individual has 10% additional room for recovery while the second person has 70% additional room for recovery. Therefore, assessing the grip strength recovery, instead of only absolute paretic grip strength, enables the detection of treatment effects and scope for recovery, despite inter-individual variability in absolute paretic grip strength.[17]

5.2 Grip strength in low and high strength recovery stroke groups

Low strength recovery stroke group exhibited a significant decline in paretic grip strength compared with the high strength recovery group and the non-dominant hand in the control group. Decline in paretic grip strength aligns with the previous findings of chronic stroke-related weakness in grip muscles.[3-5,11,34,41] Interestingly, the nonparetic grip strength in the low strength recovery stroke group was greater than the high strength recovery stroke group. The finding partially contradicts our first hypothesis, that both the paretic and nonparetic grip strength of low strength recovery stroke group will be reduced compared to the high strength recovery group. Compared with the high strength recovery stroke group, the low strength recovery stroke group had significantly reduced paretic grip strength, whereas the nonparetic grip strength was not impaired when compared to the high strength recovery or control groups. One possible explanation for the increased nonparetic grip strength in low strength recovery compared to high strength recovery group may be related to the magnitude of hand use. In chronic stroke, a regular and repeated overuse of the nonparetic hand may be related to the degree of impairment.[42] Since the low strength recovery individuals have a severe degree of impairment, they are unable to use their paretic limb effectively due to the existing deficits. Perhaps, in everyday life, low strength recovery individuals start overusing nonparetic hand regularly and repeatedly than the high strength recovery stroke group with a mild-moderate degree of impairment. Thus, repeated overuse can positively impact the grip strength in the nonparetic hand. In contrast, the high strength group may be using both hands in everyday life and, therefore, have comparable grip strengths in paretic and nonparetic hands.

Another possible explanation comes from the previous reports on the impaired sense of effort in stroke.[34,43-45] Even though stroke individuals produce less force with the paretic limb, they may overestimate the amount of force produced by the paretic grip. Therefore, stroke individuals may overcompensate by producing more force in the nonparetic grip.[45,46] Perhaps, the severity of stroke motor impairments influences the sense of effort differentially such that individuals with low strength recovery show greater nonparetic overcompensation than those with high strength recovery. However, the evidence regarding the role of the sense of effort in severe to moderate-mildly impaired chronic stroke individuals is sparse and needs further investigation.

Our study results suggest that low grip strength recovery group produced less force with their paretic grip (67.4 $\pm$ 37.2. N) compared to the nonparetic grip (294.8$\pm$ 109.1 N). On the contrary, the high strength recovery group produced comparable forces with their paretic grip (179.6 $\pm$ 89.0 N) compare to the nonparetic grip (196.9 $\pm$79.5 N). Further, we found the high strength recovery group manifested a decline in paretic strength compared with the non-dominant hand in the control group. We found no significant decline in nonparetic and dominant grip strength across the three groups. The findings are in line with the previous results of nonparetic grip strength in stroke group compared to the dominant grip in control.[4,27,41,47] In summary, our findings suggest that the paretic and nonparetic grip strength may show differential profiles of decline between low and high strength recovery stroke groups relative to controls.

5.3 Grip force accuracy in low and high strength recovery stroke group

A noteworthy finding is that the paretic grip force accuracy in both low and high strength recovery stroke group showed a significant reduction compared with the control group. This finding is especially notable given the high strength recovery group showed near-normal grip strength recovery but a persistent decline in grip force accuracy of the paretic hand. The result supports our hypothesis that the paretic force accuracy in the high strength recovery stroke individuals will be reduced compared to the control group. Further, our results might appear to contradict a previous report, where regardless of strength recovery, severe to moderate-mildly impaired individuals showed a similar level of force accuracy while tracking at similar absolute force levels.[40] However, the key difference between the Lindberg et al. (2012) study and our study is that we had relative force target with a 3% MVC/s ramp up and fall rate while the previous study used an absolute force target of 10%, 20% and 30% of MVC.[40] Another point to note is that at lower target force levels, the force accuracy is expected to be amplified in stroke participants compared with control.[40,48] However, we eliminated the impact of the %MVC force level by normalizing the RMSE to the mean force (relative RMSE). Thus, comparing the relative RMSE in low and high strength recovery stroke groups and non-dominant grip in control provides better insight into the impact of strength recovery on force accuracy.[21] Further, our finding aligns with the previous results where force accuracy was decreased in stroke compared to healthy adults when the force target is set relative to the participant's MVC.[49,50] The result from our study confirm reduced grip force accuracy in the paretic hand in both low and high strength recovery stroke groups compared with the control group.

Paretic grip force accuracy is important for ensuring the precise application of grip forces to prevent slipping or crushing while grasping an object.[5-7] The high strength recovery individuals belong to the mild to moderate motor impairment trajectory and are often categorized as the high functioning stroke individuals with greater functional autonomy in everyday life.[16,51-53] Nevertheless, the recovery of force accuracy determines the skillful use of paretic hand in everyday life functions. So, a crucial but unaddressed question is that unlike strength recovery, why does force accuracy not improve in the high strength recovery group. One possible interpretation of our finding is that two separable recovery systems for grip strength recovery and the improvement of force accuracy may exist. Previously, Xu et. al. postulated that two different recovery systems might be responsible for improvement in strength and force control. Below 60% of strength recovery, both these recovery systems follow similar trajectory. Therefore, the low strength recovery stroke group showed a parallel decrease in both grip strength and force accuracy than the high strength recovery stroke group. However, once 60% strength recovery is achieved in the high strength recovery group, strength and force control follow disparate trajectories of improvement, such that further increase in strength are seen but no accompanying improvements in force accuracy are noted.[16,18] In line with this, our findings suggest that despite comparable grip strength recovery, the paretic grip force accuracy was significantly lower in high strength recovery group than the control non-dominant grip. The current study extends the previous work that showed that high-functioning stroke survivors demonstrated a decline in lower-limb motor control tasks despite strength gains.[16] Taken together, our work illustrates that stroke survivors may show deficiency in force accuracy, even after the substantial grip strength recovery.

5.4 The association between grip strength recovery and force accuracy

Another interesting finding of the study is that we observed a negative correlative between the grip strength recovery and paretic relative RMSE, implying paretic grip force accuracy increased with grip strength recovery. The direction of the association between the grip strength recovery and grip force accuracy may depend on the low and high strength recovery group. The correlation, separately done in the low grip strength recovery showed negative correlation between grip strength recovery and relative RMSE, implying the positive relationship between grip strength recovery and force accuracy. Similar analysis in the high strength recovery group revealed no relationship between grip strength recovery and relative RMSE. The latter correlation analysis is analogous to the Xu et al. (2017) findings that the strength recovery and control follow separate trajectory of improvement in chronic stroke.[18] Our finding reveals the independence of grip strength recovery and force accuracy in high strength recovery group. Even after substantial strength recovery, deficits in force accuracy can impact functional capacity.[16,53] Given the strength training interventions have been implemented to improve functional capacity, assessing grip strength recovery may provide the appropriate milestone beyond which focused interventions may be needed to improve grip force accuracy for improving function.[27,29,31,54,55] In the study we did not include the RMSE of force increment and decrement phases separately; rather, we focused on the RMSE of the whole task. In chronic stroke, force decrement showed decreased accuracy while performing a bimanual task compared to the force increment.[21,56] Therefore, a logical extension of the study would be to look at the impact of grip strength recovery on force accuracy in force increment vs force decrement.

CHAPTER 6 - LIMITATIONS AND CONSIDERATIONS

We investigated the impact of strength recovery on grip force accuracy in low and high strength recovery stroke groups. Although grip strength has received considerable attention as an important indicator of upper extremity recovery after stroke, no study has investigated stroke survivors based on the grip strength recovery. Clinical assessments that measure the absolute performance of the paretic limb may be insufficient to determine the proportion of recovery already achieved and that which remains to be attained. In the current study, we had a very small sample size. To provide reliable conclusions on the association between grip strength recovery and force accuracy, larger sample of high and low strength recovery individuals needs to be recruited.[57,58] Also, we had unequal number of dominant side effect and non-dominant side affected individuals. Therefore, reliable conclusion on the effect of the hand dominance could not be drawn. Future study is required to determine the impact of grip strength recovery on force accuracy by recruiting a large sample size and controlling the hand dominance.[59,60] In addition, we did not investigate functional hand dexterity and the association between grip strength recovery and functional motor tasks. Future research is required to determine the contribution of grip strength recovery and functional hand dexterity to functional motor task in stroke individuals with low and high grip strength recovery.

6.1 Clinical relevance:

Grip strength and precise application of grip forces according to the task requirement are crucial to perform activities of daily life. Our study provides evidence that the impact of grip strength recovery on grip force accuracy varies between the low and high strength recovery group. Thus, the interventions and rehabilitation strategies targeting strength recovery alone might not be sufficient.[4,16,53] Notably, our study results suggest, after treatments that improve strength, , patients need additional interventions such as exergaming that will train force accuracy, to help them use this regained strength more meaningfully

CHAPTER 7 - CONCLUSION

In summary, our study provides novel evidence that the impact of grip strength on grip force accuracy varies in the low and high strength recovery group. We demonstrated that the low strength recovery group showed reduced strength recovery and decline in force accuracy relative to the high strength recovery stroke group and the control group. However, the high strength recovery group demonstrated near-normal strength recovery but persistent decline in force accuracy compared to the control group. Therefore, grip strength recovery assessment can provide a reliable measure to detect appropriate milestone beyond which rehabilitation goals should be focused on improving grip force accuracy to ensure functional recovery.

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APPENDIX

Participant Information

Participant ID: _______________

Date: ______________________

Date of Birth: _______________________

Sex: _______________________

Weight (Kg): _______________________

Height (cm): ________________

1. Condition

☐ Healthy (Young)

☐ Healthy (Elderly)

☐ TIA   Date of TIA: __________   Motor Symptom? _______________

☐ Stroke   Date of Stroke: __________Type/Location: _______________

2. Affected Side

☐ Right Arm   ☐ Left Arm

☐ Right Leg   ☐ Left Leg

3. Dominant Hand (Self report)

☐ Right Hand   ☐ Left Hand

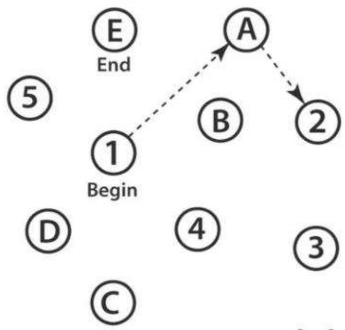
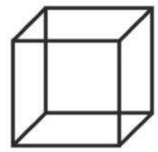
4. Vision screen

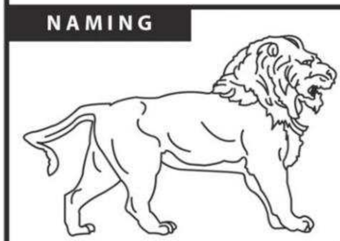
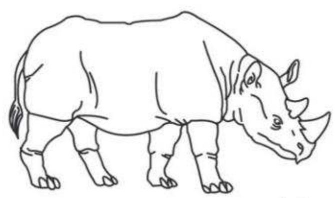
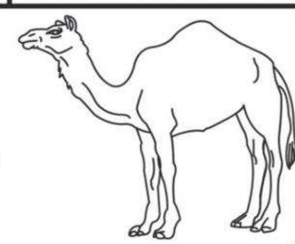
Rt   Lt   Both

Montreal Cognitive Assessment (MOCA)

MONTREAL COGNITIVE ASSESSMENT (MOCA)
Version 7.1 Original Version

NAME :
Education :
Sex :
Date of birth :
DATE :

			POINTS
VISUOSPATIAL / EXECUTIVE	Copy cube	Draw CLOCK (Ten past eleven) (3 points)	
 [ ]	 [ ]	[ ] Contour [ ] Numbers [ ] Hands	___/5

			POINTS
NAMING			
 [ ]	 [ ]	 [ ]	___/3

MEMORY Read list of words, subject must repeat them. Do 2 trials, even if 1st trial is successful. Do a recall after 5 minutes.		FACE	VELVET	CHURCH	DAISY	RED	No points
	1st trial						
	2nd trial						

		POINTS
ATTENTION Read list of digits (1 digit/ sec.).	Subject has to repeat them in the forward order [ ] 2 1 8 5 4 Subject has to repeat them in the backward order [ ] 7 4 2	___/2
Read list of letters. The subject must tap with his hand at each letter A. No points if ≥ 2 errors	[ ] F B A C M N A A J K L B A F A K D E A A A J A M O F A A B	___/1
Serial 7 subtraction starting at 100	[ ] 93 [ ] 86 [ ] 79 [ ] 72 [ ] 65 4 or 5 correct subtractions: **3 pts**, 2 or 3 correct: **2 pts**, 1 correct: **1 pt**, 0 correct: **0 pt**	___/3
LANGUAGE	Repeat : I only know that John is the one to help today. [ ] The cat always hid under the couch when dogs were in the room. [ ]	___/2
	Fluency / Name maximum number of words in one minute that begin with the letter F [ ] ___ (N ≥ 11 words)	___/1
ABSTRACTION	Similarity between e.g. banana - orange = fruit [ ] train – bicycle [ ] watch - ruler	___/2

DELAYED RECALL	Has to recall words WITH NO CUE	FACE [ ]	VELVET [ ]	CHURCH [ ]	DAISY [ ]	RED [ ]	Points for UNCUED recall only	___/5
Optional	Category cue							
	Multiple choice cue							

ORIENTATION	[ ] Date	[ ] Month	[ ] Year	[ ] Day	[ ] Place	[ ] City	___/6

© Z.Nasreddine MD **www.mocatest.org** Normal ≥26 / 30 TOTAL ___/30
Add 1 point if ≤ 12 yr edu

Administered by: ______________________

Edinburgh Questionnaire

Instructions

For each of the activities below,

Which hand you prefer for that activity?

Do you ever use the other hand for the activity?

Activities	**Left**	**Right**	**Do you use the other hand**
Writing			
Drawing			
Throwing			
Using Scissors			
Using Toothbrush			
Using a Knife (without fork)			
Using a Spoon			
Using a broom (upper hand)			
Striking a match			
Opening a box (holding the lid)			
Items below are not from the standard inventory			
Holding a computer mouse			
Using a key to unlock a door			
Holding a hammer			
Holding a brush or a comb			
Holding a cup while drinking			

Maximal Voluntary Contraction – Gripping

Trial	Gripping (N)	Notes
Left 1		
L2		
L3		
Extra		
Right1		
R2		
R3		
Extra		
Both 1		
B2		
B3		
Extra		

Force Tracking Practice – Gripping & finger flexion

Trajectory -
Ramp up -
Duration –
Target Force (% MVC) -
EMG - Yes / No Which Muscles -

Left – Gripping				
		RMSE up	RMSE down	Notes
Practice				
Extra				

Right – Gripping				
		RMSE up	RMSE down	Notes
Practice				
Extra				

Both – Gripping				
		RMSE up	RMSE down	Notes
Practice				
Extra				

Force Tracking – Gripping

Trajectory -
Ramp up -
Duration –
Target Force (% MVC) -
EMG - Yes / No Which Muscles -

Left				
		RMSE up	RMSE down	Notes
Trial 1				
Trial 2				
Trial 3				
Trial 4				
Trial 5				
Extra				

Right				
		RMSE up	RMSE down	Notes
Trial 1				
Trial 2				
Trial 3				
Trial 4				
Trial 5				
Extra				

Both				
		RMSE up	RMSE down	Notes
Trial 1				
Trial 2				
Trial 3				
Trial 4				
Trial 5				
Extra				

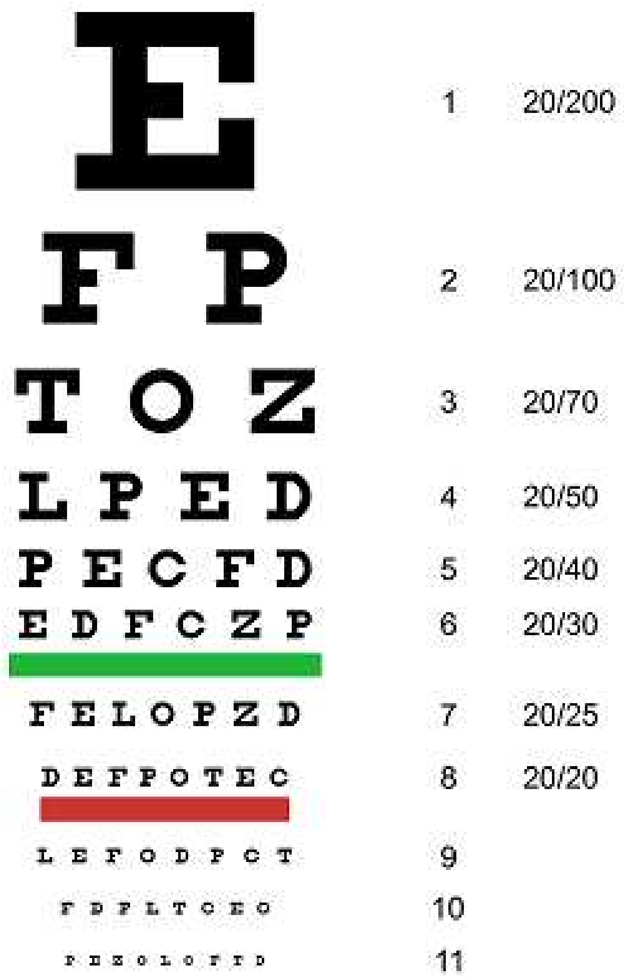
Participant distance from monitor: _____ inches

Modified Ashworth Scale (MAS)

Upper extremity item	**Score (/4)**
Shoulder extensors	
Shoulder flexors	
Shoulder adductors	
Shoulder abductors	
Shoulder internal rotators	
Shoulder external rotators	
Elbow flexors	
Elbow extensors	
Forearm pronators	
Forearm supinators	
Wrist flexors	
Wrist extensors	
Finger flexors	
Finger extensors	

Median score: _______ (/4)

Visual Acuity Test Chart



FMA-UE – Fugl-Meyer assessment of upper extremity

A. UPPER EXTREMITY, sitting position			
I. Reflex activity		**none**	**can be elicited**
Flexors: biceps and finger flexors (at least one) **Extensors**: triceps		0 0	2 2
Subtotal I (max 4)			

II. Volitional movement within synergies, without gravitational help		**none**	**partial**	**full**
Flexor synergy: Hand from contralateral knee to ipsilateral ear. From extensor synergy (shoulder adduction/ internal rotation, elbow extension, forearm pronation) to flexor synergy (shoulder abduction/ external rotation, elbow flexion, forearm supination).	Shoulder retraction elevation abduction (90°) external rotation Elbow flexion Forearm	0 0 0 0 0 0	1 1 1 1 1 1	2 2 2 2 2 2
Extensor synergy: Hand from ipsilateral ear to the contralateral knee	Shoulder adduction/internal rotation Elbow extension Forearm pronation	0 0 0	1 1 1	2 2 2
Subtotal II (max 18)				

III. Volitional movement mixing synergies, without compensation		**none**	**partial**	**full**
Hand to lumbar spine hand on lap	cannot perform or hand in front of ant-sup iliac spine hand behind ant-sup iliac spine (without compensation) hand to lumbar spine (without compensation)	0	1	2
Shoulder flexion 0°- 90° elbow at 0° pronation-supination 0°	immediate abduction or elbow flexion abduction or elbow flexion during movement flexion 90°, no shoulder abduction or elbow flexion	0	1	2
Pronation-supination elbow at 90° shoulder at 0°	no pronation/supination, starting position impossible limited pronation/supination, maintains starting position full pronation/supination, maintains starting position	0	1	2
Subtotal III (max 6)				

IV. Volitional movement with little or no synergy		**none**	**partial**	**full**
Shoulder abduction 0 - 90° elbow at 0° forearm	immediate supination or elbow flexion supination or elbow flexion during movement abduction 90°, maintains extension and pronation	0	1	2
Shoulder flexion 90° - 180° elbow at 0° pronation-supination 0°	immediate abduction or elbow flexion abduction or elbow flexion during movement flexion 180°, no shoulder abduction or elbow flexion	0	1	2
Pronation/supination elbow at 0° shoulder at 30°- 90° flexion	no pronation/supination, starting position impossible limited pronation/supination, maintains start position full pronation/supination, maintains starting position	0	1	2
Subtotal IV (max 6)				

V. Normal reflex activity assessed only if full score of 6 points is achieved in part IV; compare with the unaffected side		**0 (IV), hyper**	**lively**	**normal**
biceps, triceps, finger flexors	2 of 3 reflexes markedly hyperactive or 0 points in part IV 1 reflex markedly hyperactive or at least 2 reflexes lively maximum of 1 reflex lively, none hyperactive	0	1	2
Subtotal V (max 2)				
Total A (max 36)				

B. WRIST support may be provided at the elbow to take or hold the starting position, no support at wrist, check the passive range of motion prior testing		**none**	**partial**	**full**
Stability at 15° dorsiflexion elbow at 90°, forearm pronated shoulder at 0°	less than 15° active dorsiflexion dorsiflexion 15°, no resistance tolerated maintains dorsiflexion against resistance	0	1	2
Repeated dorsiflexion / volar flexion elbow at 90°, forearm pronated shoulder at 0°, slight finger flexion	cannot perform volitionally limited active range of motion full active range of motion, smoothly	0	1	2
Stability at 15° dorsiflexion elbow at 0°, forearm pronated slight shoulder flexion/abduction	less than 15° active dorsiflexion dorsiflexion 15°, no resistance tolerated maintains dorsiflexion against resistance	0	1	2
Repeated dorsiflexion / volar flexion elbow at 0°, forearm pronated slight shoulder flexion/abduction	cannot perform volitionally limited active range of motion full active range of motion, smoothly	0	1	2
Circumduction elbow at 90°, forearm pronated shoulder at 0°	cannot perform volitionally jerky movement or incomplete complete and smooth circumduction	0	1	2
	Total B (max 10)			

C. HAND support may be provided at the elbow to keep 90° flexion, no support at the wrist, compare with unaffected hand, the objects are interposed, active grasp		**none**	**partial**	**full**
Mass flexion from full active or passive extension		0	1	2
Mass extension from full active or passive flexion		0	1	2
GRASP				
a. Hook grasp flexion in PIP and DIP (digits II-V), extension in MCP II-V	cannot be performed can hold position but weak maintains position against resistance	0	1	2
b. Thumb adduction 1-st CMC, MCP, IP at 0°, scrap of paper between thumb and 2-nd MCP joint	cannot be performed can hold paper but not against tug can hold paper against a tug	0	1	2
c. Pincer grasp, opposition pulpa of the thumb against the pulpa of 2-nd finger, pencil, tug upward	cannot be performed can hold pencil but not against tug can hold pencil against a tug	0	1	2
d. Cylinder grasp cylinder shaped object (small can) tug upward, opposition of thumb and fingers	cannot be performed can hold cylinder but not against tug can hold cylinder against a tug	0	1	2
e. Spherical grasp fingers in abduction/flexion, thumb opposed, tennis ball, tug away	cannot be performed can hold ball but not against tug can hold ball against a tug	0	1	2
	Total C (max 14)			

D. COORDINATION/SPEED, sitting, after one trial with both arms, eyes closed, tip of the index finger from knee to nose, 5 times as fast as possible		**marked**	**slight**	**none**
Tremor	at least 1 completed movement	0	1	2
Dysmetria at least 1 completed	pronounced or unsystematic slight and systematic	0	1	2
		≥ 6s	**2 - 5s**	**< 2s**
Time start and end with the hand on the	at least 6 seconds slower than unaffected side 2-5 seconds slower than unaffected side less than 2 seconds difference	0	1	2
	Total D (max 6)			
	Total A-D (max 66)			

H. SENSATION, upper extremity eyes closed, compared with the unaffected side		**anesthesia**	**hypoesthesia or dysesthesia**	**normal**
Light touch	upper arm, forearm palmary surface of the hand	0 0	1 1	2 2
		less than 3/4 correct or absence	**3/4 correct or considerable difference**	**correct 100%, little or no**
Position small alterations in the position	shoulder elbow wrist thumb (IP-joint)	0 0 0 0	1 1 1 1	2 2 2 2
			Total H (max12)	

H. SENSATION, upper extremity eyes closed, compared with the unaffected side		**anesthesia**	**hypoesthesia or**	**normal**
Light touch	upper arm, forearm palmary surface of the hand	0 0	1 1	2 2
		less than 3/4 correct or absence	**3/4 correct or considerabl**	**correct 100%, little or no difference**
Position small alterations in the position	shou lder elbo w	0 0 0 0	1 1 1 1	2 2 2 2
			Total H (max12)	

A. UPPER EXTREMITY	**/36**
B. WRIST	**/10**
C. HAND	**/14**
D. COORDINATION / SPEED	**/ 6**
TOTAL A-D (motor function)	**/66**
H. SENSATION	**/12**