Characterizing Coordination of Grasp and Twist in Hand Function of Healthy and Post-stroke Subjects

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***Abstract*— The goal of this study was to characterize the coordination of grasp and twist in hand function of normal and post-stroke subjects using a two degree of freedom hand robot. Results of the analysis of data from eight control subjects indicated that normal grip coordination involves the linear modulation of grip force with load torque. Thus, there was a high correlation between grip force and load torque. Also, the force generated by the thumb was highly correlated with the force generated by the index, middle and ring fingers. Finally, the safety margin used to stabilize grasp and avoid slip was consistent across normal subjects. In contrast, results from chronic post-stroke subjects indicated that they generally: (1) exerted excessive grip force to stabilize grasp using their ipsilesional hand; (2) lost the close amplitude coupling between grip force and load torque; and (3) lost the close modulation of the thumb force with finger force. These results suggest that our methods may provide objective, quantitative means of characterizing coordination problems following stroke.**

Keywords—grip coordination; grasp and twist; fingertip forces, stroke; ipsilesional and contralesional hand; assessment of hand function

I. INTRODUCTION

Coordination between the wrist and fingers is critical for controlling hand orientation, for grasping and moving objects and is fundamental for the execution of activities of daily living (ADL) such as drinking from a glass, turning knobs, opening screw lids, turning keys, pouring water from a pitcher, etc. The ability to perform a task in a coordinated manner and to fine tune coordination between muscles is known to be impaired after stroke [2]. Loss of dexterity due to impaired coordination of fingertip forces in precision grip has been the subject of a number of studies [3-8] using the pioneering method of Johansson and Westling [9] to examine grip control. Nowak et al. found that when lifting, holding and performing vertical

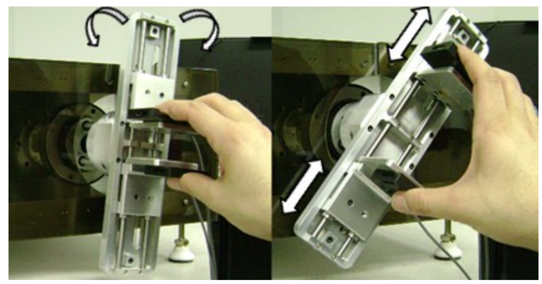

Figure 1. EnableHand, a two DOF robotic interface. Arrows indicate opening/closing and rotational movements of the robot.

point-to point movements with a hand-held object, acute stroke impaired subjects used larger grip forces using their contralesional hand than unimpaired control subjects [3]. Also, the ability of subjects in the acute phase of ischemic stroke to predict inertial load during vertical movements was impaired. Blennerhassett et al. [8] investigated grip force application and timing in a pinch grip task and found that the time needed to grip and lift objects was prolonged and that grip force was excessive prior to starting the lift in stroke impaired subjects compared to unimpaired healthy subjects. Santello and his colleagues have studied the coordination of digit forces and positions in two-digit and multi-digit manipulation in control subjects but also in subjects with Parkinson's disease (for example see [10] and [11]). They found that the anticipatory control of fingertip forces is impaired in subjects with Parkinson's disease.

Johansson et al. [12] studied grip force control when rotating a small object around a horizontal axis using a precision grip between the thumb and index finger. They found that in healthy subjects, grip force increased directly with increased destabilizing torque load. However, changes in the

TABLE 1. DEMOGRAPHICS OF STROKE PARTICIPANTS

Subject code	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Age	48	69	66	59	58	54	54	63	66	54
Gender	M	F	M	M	M	F	M	F	M	F
Time since stroke (months)	35	108	59	12	19	29	24	17	32	18
Affected Hand	R	R	L	L	L	L	R	R	L	R
Hand Dominance	R	R	R	L	R	R	R	R	R	R

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coordination between fingers and wrist following stroke in tasks involving grasp and twist has not been characterized yet.

We have developed a two degree of freedom (DOF) robotic interface, EnableHand, to assist with rehabilitation of three hand impairments following stroke: reduced grip strength, reduced finger extension, and impaired coordination between finger and wrist muscles (Fig. 1). The interface can deliver elastic and viscous loads over a large range for training hand function. It can also serve as an assessment tool since grip force, wrist torque and range of motion can be measured during rotation of a simulated object. The design, construction and performance evaluation of EnableHand is described in [1]. This paper reports on the use of this device to examine the grip force coordination in post-stroke subjects. The first objective was to characterize the coordination of grasp and twist in healthy individuals and develop reliable, repeatable and sensitive measures to quantify grip coordination. The second goal was to characterize the coordination of grasp and twist following stroke and quantify impaired coordination of fingers and wrist.

II. METHODS

A. Subjects

Eight subjects (four male, four female, all right handed) between the ages of 19 and 47 (mean= 24.1) with no history of neurological disorder were examined to characterize the normal coordination of grasp and twist in healthy individuals. To characterize the changes associated with stroke 10 post-stroke subjects were tested., Post-stroke participants must have sustained a single ischemic stroke, leading to upper limb paresis, confined to one side, more than one year prior to participating in the study. Table 1 lists the demographics of the post-stroke subjects.

B. Apparatus

EnableHand operates like a jaw formed by two plates that translate to open and close the jaw for training grasping. It also has a rotational DOF to allow supination/pronation movement of the forearm (Fig. 1). The rotational range of motion (ROM) of the robot is ± 180º and translational ROM (jaw opening) is 15-150 mm. The continuous force capacity for translation is 200 N and the continuous torque capacity for rotation is 5 Nm. Data were sampled at 1 kHz with ADC resolution of 16 bits after anti-alias filtering with a cut-off frequency of 100 Hz with four pole Bessel filters.

C. Procedure

The subject was seated on a chair in front of the robotic device and display screen. The hand gripped the jaw with the index, middle and ring fingers placed in grooves on the upper plate and the thumb in a groove on the lower plate (Fig. 1). The elbow was supported at the subject's side. The shoulder was slightly abducted and the elbow flexed about 120-degrees. This position was chosen to ensure that the elbow and shoulder could not contribute to the movement. Subjects twisted the robot using forearm supination while the robot resisted the movement by exerting a spring-like torque in rotation. The

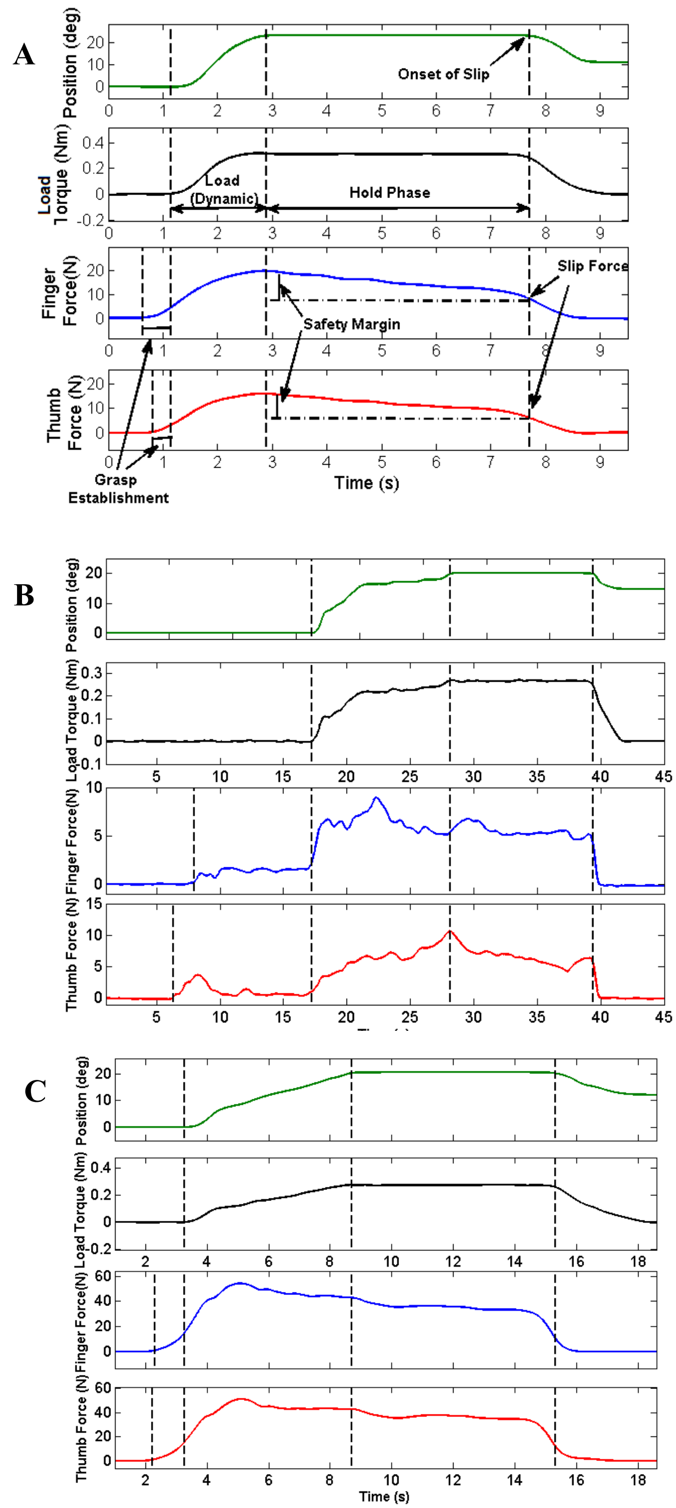

Figure 2. Grasp and twist assessment task. Position, load torque, thumb force and total force exerted by other fingers are shown. The task consists of four phases: grasp-establishment (starting at the onset of grip force), load or dynamic (starting at the onset of load), hold or static and slip. A healthy control subject (A) is compared with stroke subject 1 performing the task with the contralesional hand (B) and the ipsilesional hand of the subject 9 (C).

plates were set at separation of 3 cm (well within a subject's range of hand opening). The EnableHand rendered a very high stiffness that resisted translation, so that that the plates could not move during rotation. Participants twisted the knob 20 degrees clockwise for the right hand or 20 degrees counterclockwise for the left hand, held the final position for 5 s, then slowly reduced the grip force to allow the robot to slip back to the initial position. A low torsional stiffness of 0.015 Nm/deg was used so that the maximum load (0.3 Nm at 20 deg) was within a subject's torque generating capability. Slipping was detected by observation of stalling or backward movement of the robot. This made it possible to compute the minimum grip force required to prevent slip and to measure the safety margin which was defined as the amount of grip force that a subject exerts above that needed to avoid slipping. Subjects performed 10 trials of the grip coordination task in two different sessions. When possible post-stroke subjects performed the task with the contralesional and ipsilesional hands. Five post-stroke subjects had a severe loss of hand function, and so were able to perform the task with the ipsilesional (less affected) hand only .

D. *Experimental Task*

Figure 2A shows the profile of angular position, load torque, force produced by the thumb and other fingers (represented as finger force) during a typical trial performed by a healthy control subject. When the normal forces generated by thumb and fingers were unequal, the smaller of the two forces was considered to be the grip force [13]. Four phases of the task were defined, as illustrated in Fig. 2: (i) grasp establishment phase during which the subject establishes the grip on the device before rotating it, defined as the interval from the onset of grip force to the onset of movement; (ii) dynamic or load phase, defined as the period from the onset of load to the point of maximum rotation; (iii) hold phase, defined as the period during which the angular velocity drops and stays below 2% of the maximum angular velocity; and (iv) onset of slip, defined by the onset of backward movement of the robot. The force at which the device started to move backward was defined as the slip force, i.e. the minimum grip force required to prevent the slip.

E. *Outcome Measures*

The following measures were used to quantify grip coordination:

- The cross-correlation coefficient between the grip force and load torque during the dynamic (load) phase. This parameter determines the degree of correlation between the load torque and grip force. The lag (latency) at which the cross-correlation was maximal defines the latency between the change in grip force and the change in load torque.
- The average safety margin used to prevent slip. Safety margin is the difference between the slip force and the grip force exerted during the static phase in each trial.
- The cross-correlation coefficient between thumb force and total force exerted by the other fingers during the load phase. This parameter determines the degree of correlation between fingertip forces in producing the same normal force when twisting or holding objects.

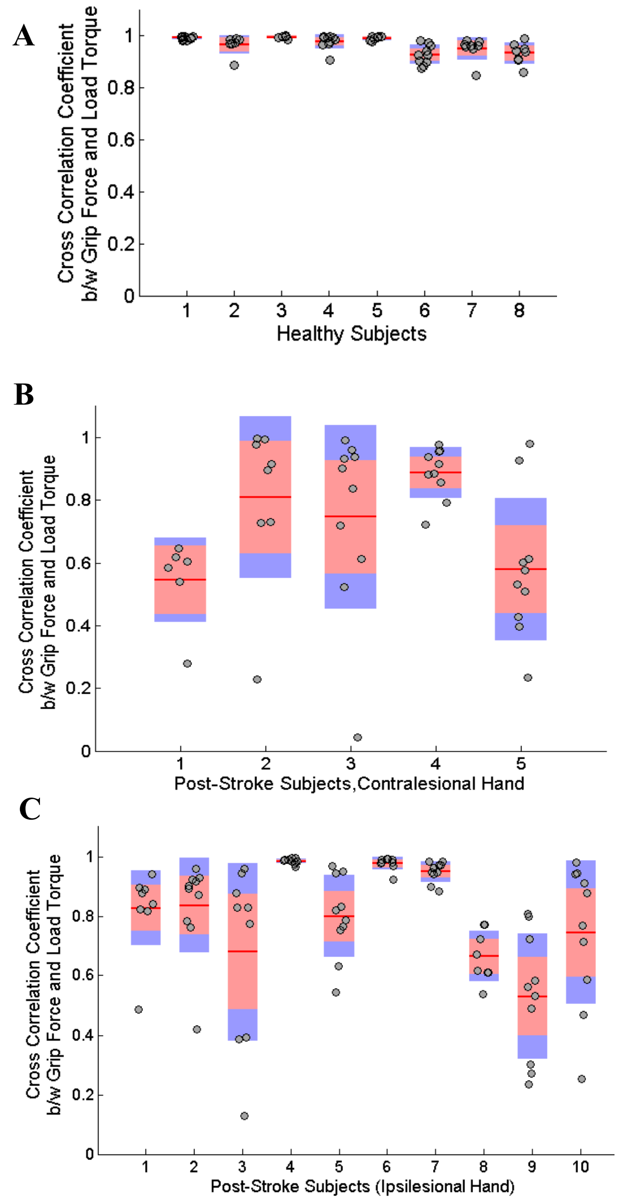

Figure 3. Cross-correlation coefficient between grip force and load torque during dynamic phase of the grasp and twist task. Circles indicate the cross-correlation coefficient value for each trial and the solid red line represents the mean value for those trials. Shaded boxes represent 1.96 SEM (95% confidence interval) in red and a 1 SD in blue. Cross-correlation coefficients for healthy control subjects (A) are compared with those for the contralesional hand (B) and ipsilesional hand of post-stroke subjects (C).

These measures may be used to differentiate between healthy and impaired grip coordination. The hypothesis that is set forward is that the coordination of grasp and twist in individuals with stroke is impaired. This hypothesis leads to three testable predictions:

1. The cross-correlation coefficient between grip force and load torque is smaller in stroke impaired individuals than controls (indicating impaired amplitude modulation of finger force and wrist torque).

2. Stroke impaired individuals exert more grip force than controls to stabilize grasp resulting in a larger maximum safety margin.
3. The cross-correlation coefficient between thumb force and finger force will be lower in stroke impaired individuals than controls (indicating lack of coordination in producing the same force).

F. Statistical Analyses

Significance level was established as $p < 0.05$. Mann–Whitney U-tests were used to compare the measures of grip coordination between post-stroke subjects and control subjects.

III. Results

A. Healthy Subjects

Figure 2A shows a typical grip coordination trial for a healthy subject. It can be seen that the grip force increases smoothly with the load torque and the grip force and load torque simultaneously reach their maximum values. Grip force increases linearly with respect to load torque. Results of cross-correlation analysis indicated that for all subjects the grip force and load torque were highly correlated (Fig. 3A). The ensemble average of the cross-correlation coefficient at lag zero across 76 trials performed by 8 subjects was 0.964 with standard deviation of 0.038. The ensemble average of the cross-correlation coefficient between thumb and finger force was 0.985±0.011.

Figure 4A shows the maximum safety margin employed by healthy subjects. This parameter did not differ significantly among control subjects. The mean of the maximum safety margin was 5.66±1.56 N.

B. Post-Stroke Subjects

Figure 2B illustrates a representative grip coordination trial performed by the contralesional hand of post-stroke subject 1 who was severely impaired. Irregularities in generating grip force using the contralesional hand during twisting the knob are evident. There was no clear relationship between finger force and load torque and the motion was much less smooth than for the subject's ipsilesional hand or controls.

There was also evidence of impaired coordination in the coupling between grip force and load torque in the ipsilesional hand in the post-stroke subjects. Post-stroke subjects reached maximum grip force with their ipsilesional hand early in the task while the load torque was still increasing (Fig. 2C). This is in contrast to control subjects, where the grip force increased smoothly and reached its maximum at the same time as the load torque. Post-stroke subjects used larger grip forces during both dynamic and hold phases of the task when using the ipsilesional hand as indicated by a significantly ($p<0.03$) larger safety margin than controls (Fig. 4B). On average they used 13.6 ± 10.4 N to secure the grasp and avoid rotational slip. The safety margin for the contralesional hand was on average 7.3 ± 4.7 N. Although there was no statistically significant difference in the safety margin between healthy controls and the contralesional hand of the post-stroke subjects, their trial to trial variation was much greater. This was also the case for the ipsilesional hand.

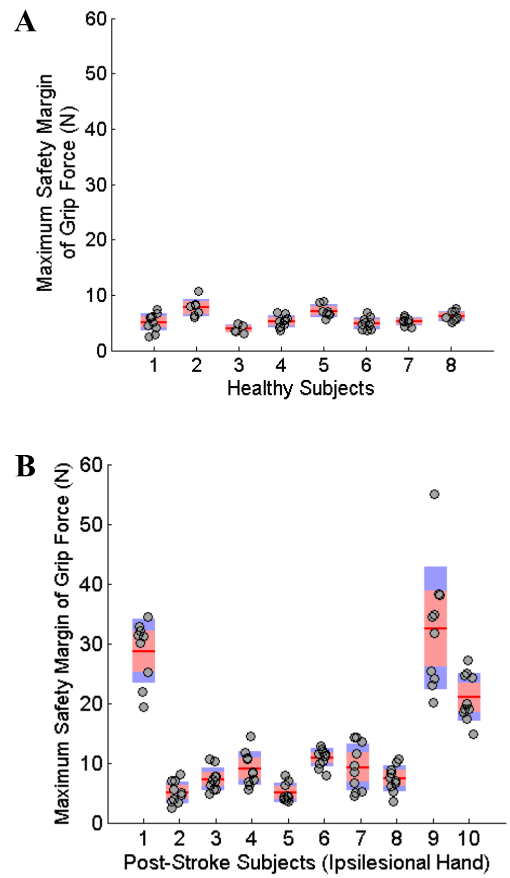

Figure 4. Maximum safety margin of grip force in healthy subjects (A) and ipsilesional hand of post-stroke subjects (B).

Figure 3B compares the cross-correlation coefficient between grip force and load torque at lag zero for the contralesional hand of five post-stroke subjects. Post-stroke subjects (with the exception of subject 4) , using their contralesional hands, had significantly lower cross-correlation coefficients than healthy controls and much greater trial to trial variability. To test the hypothesis that the cross-correlation coefficient between grip force and load torque is smaller in stroke impaired individuals than controls, data from all trials for ipsilesional hand and contralesional hand as well as control subjects were pooled and the Mann–Whitney U-test was performed. The null hypothesis of equal medians between control subjects and contralesional hand of the post-stroke subjects at the 5% significance level was rejected ($p<0.001$). Note that only 5 out of 10 post-stroke subjects were able to complete the assessment task using the contralesional hand. Similarly, Figure 3C shows the cross correlation coefficient between grip force and load torque for the ipsilesional hand of all 10 post-stroke subjects. As can be seen, 7 out of 10 post-stroke subjects, when performing the grip coordination with the ipsilesional hand had significantly lower cross correlation coefficients and higher variability than control subjects. It is interesting to note that the test failed to reject any difference in median of cross correlation coefficient between grip force and load torque in the ipsilesional hand versus contralesional hand of the post-stroke subjects (p=0.19).

Figure 5 shows the thumb and finger forces plotted against load torque during the load phase for healthy control and post-stroke subjects. Several post-stroke subjects showed lack of coordination in regulating thumb and finger forces using either their contralesional (subjects 1 and 5) or ipsilesional hand (subject 9). As can be seen, the two force profiles did not follow the same trajectory. However, forces generated by the thumb and other fingers in normal subjects followed the same trajectory and were highly correlated. The cross-correlation coefficient between thumb and finger force of the contralesional hand for post-stroke subjects 1, 2, and 5 was significantly smaller than for their ipsilesional hand or than compared to control subjects (see Fig. 6). As mentioned earlier, the ensemble average of the cross-correlation coefficient between thumb and finger force in healthy controls was 0.985±0.011.

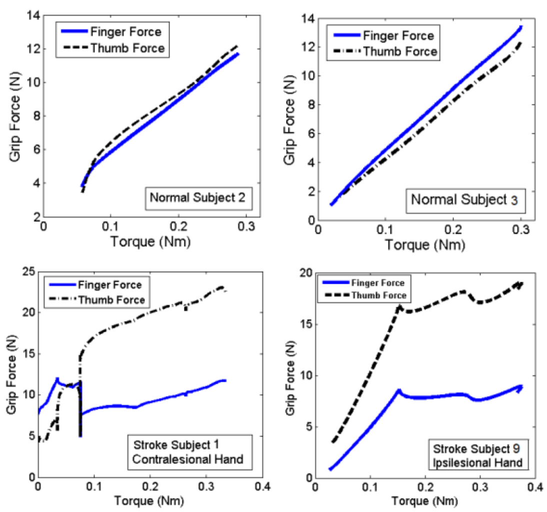

Figure 5. Representative profiles of thumb and finger forces plotted against load torque in normal and post-stroke subjects

IV. Discussion

We developed an experimental protocol to characterize the coordination of grasp with twist in normal and stroke impaired individuals using EnableHand. We recruited 8 healthy and 10 individuals post-stroke and investigated the characteristics of the grip coordination behaviour.

In healthy subjects we found that the coordination of grasp with twist involved modulating the grip force in phase with load torque but that the grip force was always greater than the minimum required to prevent slip. This was in agreement with the findings of Johansson et al. [10]. There was a high correlation between grip force and load torque, indicating that grip force increased linearly with respect to load torque. Also, the normal force exerted by the thumb and that exerted by the other fingers were highly correlated and followed the same trajectory when twisting the end-effector. Finally, the safety margin used to stabilize grasp (amount of grip force that a subject exerts above that needed to avoid slipping) was found to be consistent (did not differ significantly across subjects).

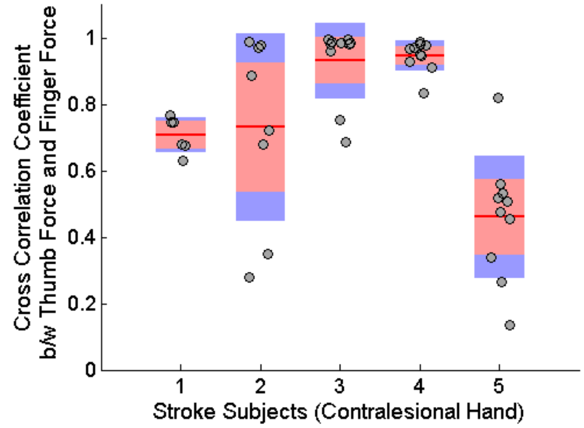

Figure 6. Correlation analysis between thumb force and total force exerted by the index, middle and ring fingers of the contralesional hand of stroke subjects.

In contrast, data from 10 post-stroke subjects show that grip coordination after stroke is impaired in both the contralesional

(affected) and ipsilesional (unaffected) hands. This impairment was evident from three observations. Post-stroke subjects: (1) did not exhibit strong temporal/amplitude coupling of grip force with load torque; (2) exerted unnecessarily large grip forces to stabilize the grasp; (3) did not exhibit parallel amplitude modulation of the force exerted by thumb and fingers.

The hypothesis that the cross-correlation coefficient between grip force and load torque is smaller in stroke impaired individuals than controls was verified by performing Mann-Whitney U test. Also, we demonstrated that the ipsilesional hand of post-stroke subjects exert significantly more grip force than controls to stabilize grasp however the difference between contralesional hand and control subjects was not significant.

Three measures of grip coordination were defined: the cross-correlation coefficient between grip force and load torque while rotating the end-effector, maximum force used to stabilize grasp above that needed to avoid rotational slip (i.e. maximum safety margin) and the cross-correlation coefficient between thumb force and total force exerted by the index, middle and ring fingers. These measures could be used to study the differences between healthy and post-stroke subjects and also track the changes over the course of grip coordination therapy.

Several studies have used the close temporal coupling between grip force and load force as an evidence of proactive control of grip force rather than reactive control [14]. In our study, we also found that latency between grip force and load torque was close to zero in both normal and post-stroke subjects. The ability to apply perturbations to the hand with the EnableHand robot and measure opposing fingertip forces during the grasp and twist task could provide additional insight into differences in force control mechanisms used by post-stroke and healthy subjects when rotating a hand-held object. This will be one of the directions for future work.

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REFERENCES

[1] H.Kazemi, R.E.Kearney, and T.E. Milner, "A robotic interface to train grip strength, grip coordination and finger extension following stroke." Engineering in Medicine and Biology Society (EMBC), 2012 Annual International Conference of the IEEE. IEEE, 2012.

[2] P. Raghavan, “The nature of hand motor impairment after stroke and its treatment,” Curr Treat Options Cardiovasc Med, 2007. 9(3): pp. 221-8.

[3] Nowak, Dennis A., Joachim Hermsdörfer, and Helge Topka. "Deficits of predictive grip force control during object manipulation in acute stroke." Journal of neurology 250.7 (2003): 850-860..

[4] Nowak, D. A., and Hermsdörfer, J. (2005). Grip force behavior during object manipulation in neurological disorders: toward an objective evaluation of manual performance deficits. Movement disorders, 20(1), 11-25.

[5] Rost, K., Nowak, D. A., Timmann, D., and Hermsdörfer, J. (2005). Preserved and impaired aspects of predictive grip force control in cerebellar patients. Clinical neurophysiology, 116(6), 1405-1414.

[6] Nowak, D. A., Grefkes, C., Dafotakis, M., Küst, J., Karbe, H., & Fink, G. R. (2007). Dexterity is impaired at both hands following unilateral subcortical middle cerebral artery stroke. European Journal of Neuroscience, 25(10), 3173-3184.

[7] Hermsdörfer J, H.E., Nowak DA, Marquardt C, Grip force control during object manipulation in cerebral stroke. Clin Neurophysiol, 2003. 114(5): p. 915-29.

[8] Blennerhassett JM, C.L., Matyas TA, Grip Force Regulation During Pinch Grip Lifts Under Somatosensory Guidance: Comparison Between People With Stroke and Healthy Controls. Archives of Physical Medicine and Rehabilitation, 2006. 87(3): p. 418-429.

[9] R. S. Johansson and G. Westling, Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. Experimental Brain Research, 1984. 56(3): p. 550-564.

[10] Muratori, L. M., McIsaac, T. L., Gordon, A. M., & Santello, M. (2008). Impaired anticipatory control of force sharing patterns during whole-hand grasping in Parkinson’s disease. Experimental Brain Research, 185(1), 41-52.

[11] Fu, Q., Zhang, W., & Santello, M. (2010). Anticipatory planning and control of grasp positions and forces for dexterous two-digit manipulation. The Journal of Neuroscience, 30(27), 9117-9126.

[12] Johansson, R. S., Backlin, J. L., and Burstedt, M. K. (1999). Control of grasp stability during pronation and supination movements. Experimental Brain Research, 128(1), 20-30.

[13] Latash, M.L. and V.M. Zatsiorsky, Multi-finger prehension: control of a redundant mechanical system. Adv Exp Med Biol, 2009. 629: p. 597-618.

[14] Flanagan, J. R., Bowman, M. C., and Johansson, R. S. (2006). Control strategies in object manipulation tasks. Current opinion in neurobiology, 16(6), 650-659.