Experimental Investigation of the Human Grip Force System

Alejandro Villaseñor-Herrera[1], Sophie J. De Serres[2], Ross Wagner[1], Robert E. Kearney[1]

[1]Department of Biomedical Engineering, McGill University, Montreal, Canada.
[2]School of Physical and Occupational Therapy, McGill University, Montreal, Canada

INTRODUCTION

The control of human grip force plays an important role in interfacing the hand with the environment. It allows the handling of a variety of objects between the pads, tips or sides of the fingers, even in the presence of unpredictable disturbances. Many precise manipulative tasks in the activities of daily living (e.g. eating, dressing) depend on the precision control of grip force. Previous studies have shown that cutaneo-receptors in the glabrous skin of the digits play an important role in the control of manipulatory functions of the hand ([1],[2]).

However, few studies have examined the involvement of the peripheral neuro-muscular system in the control of grip force. Emphasis on latencies between loading and grip phases has been done, nevertheless quantification of the reflex components and voluntary mechanisms have not been reported.

In particular the human grip force system (HGFS) has not been completely identified. This is the dynamic relationship between the vertical force (i.e. input) and the resulting grip force (i.e. output) as illustrated in Figure 1.

Therefore, studying the relative contributions of passive, reflex and voluntary mechanisms in the human grip force response should contribute to future applications in the development of more objective evaluations of sensorimotor deficits resulting from acute or chronic conditions such as stroke and normal aging.

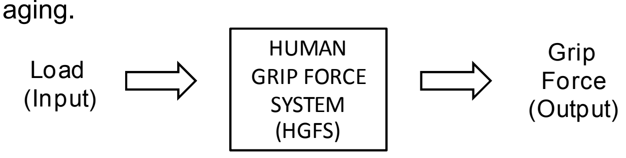

Figure 1: Illustration of the paradigm of the Human Grip Force System (HGFS).

In this study we will describe the experimental apparatus, and analysis procedures we have developed to investigate the HGFS. Results from some pilot experiments will also be presented.

METHODS

<u>Subjects</u>

Three male and one female subjects, between the ages of 23 and 41, with no history of neuromuscular disorders participated in this study. All subjects gave informed consent to the experimental procedure.

<u>Apparatus</u>

A schematic diagram of the experimental apparatus is shown in Figure 2. It is comprised of a six degree-of-freedom force transducer (Mini40 ATI-Industrial Automation) for measuring the grip forces. It is attached by a pulley-system to a servo-controlled rotatory motor (motor SA01ACN-8, 100 w, max.Torque 0.95 N-m; digital servo-driver HAR-5/60, Elmo-Motion Control) that applies perturbations of load or position in the vertical direction. Two load cells (Model 11, tension-compression, Sensotec) located on the pulley-system measured the resultant vertical loads at all time. A potentiometer (P2201 A502, Novotechnik) placed on the shaft of the motor measured the vertical displacement of the force transducer.

Surface EMG signals were recorded (Delsys Bagnoli-4 EMG System, BW 20-2,000 Hz, gain: 1,000.) from the primary long flexor of the index: Flexor Digitorum Superficialis (FDS); and the primary intrinsic thumb muscles: Flexor Pollicis Brevis (FPB) and Adductor Pollicis (AdP). Bipolar surface electrodes (Delsys DE-2.1) were placed over the muscle belly, aligned with the muscle fiber direction and in agreement with Klein et al. ([6]). The reference electrode (Dermatrode, American Imex) was attached over the elbow (i.e. olecranon). Grip force, position of the transducer, vertical loads and EMG signals were sampled at 1 kHz using a NI-4472 data acquisition card in the Host PC1(AMD Athlon™,2.20 GHz, 2 GB RAM). Anti-aliasing filtering was performed by the card with a cutoff frequency of 486.3 Hz.

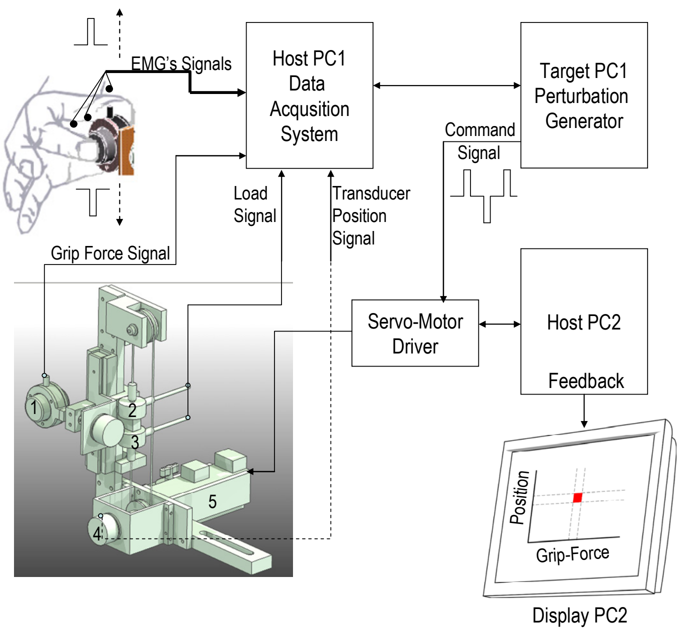

Figure 2: Schematic representation of the experimental apparatus. The main components include: 1) Force Transducer (F.T), 2) Load Cell1, 3) Load Cell2, 4) F.T. Position potentiometer and 5) Servo-motor.

Procedures

Subjects sat comfortably in a chair with the right arm flexed and the forearm resting on a wooden support. The hand was immobilized with a custom-made cast of thermoplastic material, with the wrist resting and in a midposition towards pronation. Subjects gripped the force transducer with the tips of the thumb and the index finger. The orientation of the force transducer was adjusted to allow the most comfortable grip. Figure 3 shows subject grasping the force transducer and the location of the 3 surface EMG electrodes.

Visual Feedback

A video screen (Display-Host PC2 AMD Athlon™, 1.33 MHz, 1 GB RAM) placed in front of the subjects, at a distance of about 46 cm, displayed a cursor providing instantaneous visual feedback of the grip force and vertical position of the force transducer. This feedback signal was generated using a custom display built Simulink (The Mathworks Inc.). Grip force and transducer position signals where sent to the Display-PC using a UDP network protocol (every 0.02 s). The cursor displacement across the horizontal direction (i.e. x-axis) indicated the level of grip force applied, whereas the cursor displacement in the vertical direction (i.e. y-axis) indicated the vertical position of the force transducer.

Servo-motor

The servo-controlled motor was operated as a torque control servo (current loop BW up to 2.5 KHz) driving and used to apply load perturbations in the vertical direction. Communication with the digital servo-driver (HAR-5/60, Elmo-Motion Control) was carried out through the RS-232 serial port of the Host PC2 (AMD Athlon™, 1.33 MHz, 1 GB RAM).

Pulse Perturbation Trials

Pulse perturbation trials (i.e. command input) were applied to the force transducer in a random fashion. The command input signal generated in real-time was carried out using xPC Target (The Mathworks inc.) on the Target PC1 (AMD Athlon ™, 1.6 GHz, 256 MB RAM). Each pulse trial lasted 180 s and comprised alternating positive and negative pulses with fixed amplitude, pulse-width of 50 ms and random switching intervals between 5 and 10 s.

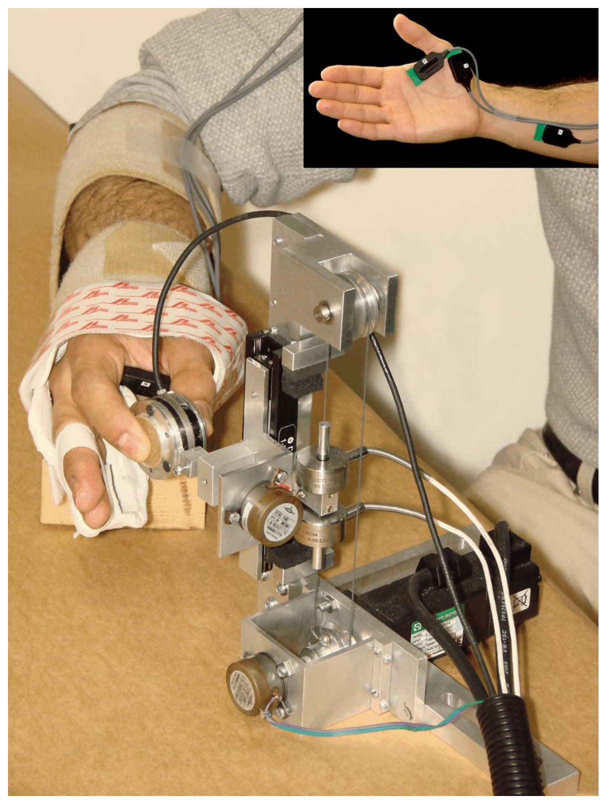

Figure 3: Subject's hand for grip force task, and location of the surface EMG electrodes.

Conditions

The experiments were carried out under two conditions: counterbalance and preload. For the first condition the force transducer held by the subject was free of gravity (i.e. the weight of the transducer – approx. 100 g – was counterbalanced). For the second condition, a pre-load was present, equivalent to the weight of the transducer. In both conditions, the surfaces of the force transducer (diameter of 2.6 cm) were covered with sandpaper.

Four pulse trials were performed for condition 1, with load magnitudes of 0.62, 1.80, 2.95 & 4.11 N. Whereas for condition 2, three pulse trials were performed with the same load magnitudes except for the last one (i.e. 4.11 N). Resting periods of 2 min between trials and 5 min between the two conditions occurred, in order to prevent fatigue.

Task

Prior to the pulse perturbation trials, subjects were asked to perform a maximal voluntary contraction (MVC) by squeezing the force transducer between the thumb and index finger. Throughout the pulse perturbation trials, each participant was instructed to maintain an initial grip force (normal to the surfaces of the transducer) corresponding to 15% of this MVC. Taking into account the comfort and morphology of the subject's hand, the initial vertical position was also fixed to a middle point within the range of motion (i.e. 5 cm) of the force transducer. A squared window shown on the visual feedback screen was thus set with these two parameters (grip force at 15% MVC and vertical position middle point). For each perturbation trial the subject was instructed to keep the cursor within the limits of this window, in order to maintain the appropriate initial force and vertical position of the transducer

Analysis Procedures

System Identification techniques (SID) provide the means for characterization of dynamic systems, generally on the basis of experimental input-output data. These techniques have been used to characterize human joint dynamics ([4],[5],[7]). In this study, preliminary experiments have been performed, where a variety of load signals (i.e. input) were applied to the system (i.e. hand + force transducer) in order to observe the resulting changes in grip force (i.e. output).

Reflex responses when grasping an object between the fingers have been shown to have latencies between 70 and 100 ms after the onset of the load perturbation ([1],[2],[5]). On this basis, the signals acquired for the load force, grip force and transducer position were each ensemble averaged over a period of 300 ms starting at the time of onset of the load perturbation. EMG signals were rectified; ensemble averaged and digitally low pass filtered (IIR Chebyshev Type 2, 8^{th} order, cut-off frequency of 10 Hz). These procedures were carried out by using Matlab (Version 7.5, R2007b, The Mathworks Inc.).

RESULTS

Data from all subjects were qualitatively similar. As an example, Figures 4 and 5 show the ensemble average data collected for one subject under the counterbalance condition (i.e. no initial pre-load). The responses to the four different load magnitudes applied are shown. In the case of upwards perturbations as the load magnitude increased (Fig. 4b) and moved the force transducer upwards (Fig. 4a) a biphasic grip force response (Fig. 4c) was observed. Both phases were clearly divided by the peak latency (2^{nd} dotted line) of the EMG2-FPB signal (i.e. Flexor Pollicis Brevis, Fig. 4d) occurring 83 ms after the onset of the load perturbation.

Phase 1 of the grip force response (between the two vertical dotted lines) showed the magnitude of the grip force decreased as a proportion of the magnitude of the applied unloading. However there was no clear EMG activity preceding this change in force suggesting that passive mechanisms must be involved in the system.

Phase 2, in contrast, showed the grip force increased as a proportion of the re-applied load, reaching a maximum value 136 ms after the re-load onset. As the peak of the EMG burst of the FPB muscle was preceding the peak grip force by 53 ms, this behavior is likely to indicate a reflex mechanism involved in the grip force response.

The grip force response evoked by downwards perturbations (Fig. 5) also presented a biphasic behavior. In phase 1 the magnitude of the grip force increased as a proportion of the load applied. However, no EMG burst was observed preceding this increase in force.

Similarly to upwards perturbations, in phase 2, the grip force increased (Fig. 5c) as a proportion of the load applied (Fig. 5b). The peak of the force occurred 156 ms after the load onset. When increasing the load, two peaks of EMG2-FPB activity (Fig. 5d) with latencies of 88 and 134 ms, were preceding the peak grip force. Again, this behavior suggests the presence of reflex mechanisms in the grip force response.

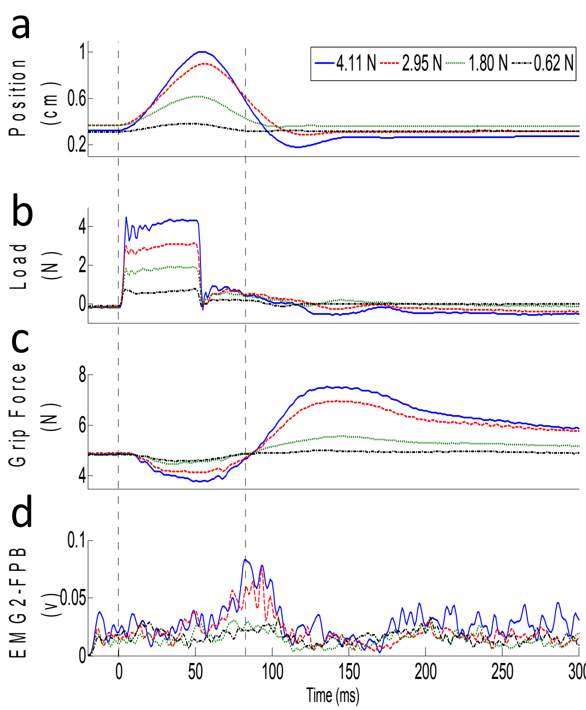

Figure 4: Ensemble average of a typical trial for upwards perturbations: a) Force transducer position, b) Load perturbation, c) Grip force response and d) Rectified EMG2 of Flexor Pollicis Brevis (FPB). Color lines indicate different magnitudes of the applied loads.

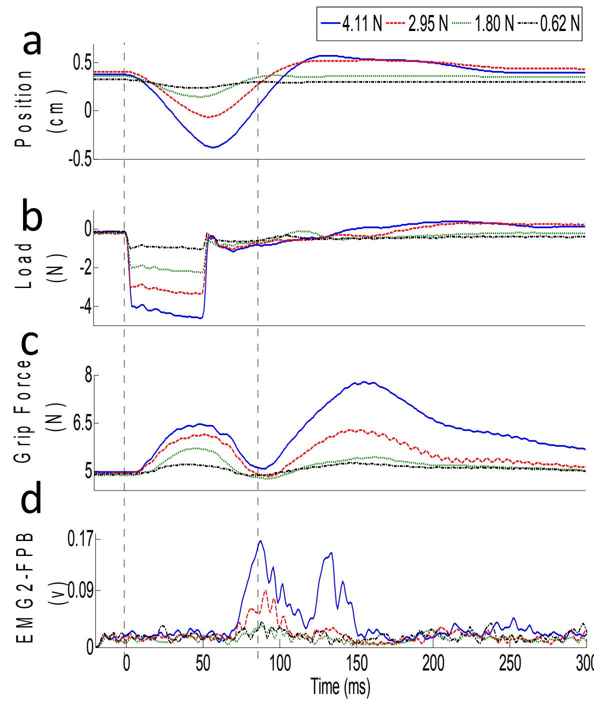

Figure 5: Ensemble average of a typical trial for downwards perturbations: a) Force transducer position, b) Load perturbation, c) Grip force response and d) Rectified EMG2 of Flexor Pollicis Brevis (FPB). Color lines indicate different magnitudes of the applied loads.

CONCLUSIONS

The EMG peak latencies presented here are consistent with previous findings ([1],[2],[5]). The preliminary results presented have established the paradigm for the HGFS and will allow us to better define appropriate experimental conditions to characterize the relative contributions of passive, reflex and voluntary mechanisms using System Identification techniques.

ACKNOWLEDGEMENTS

The first author would like to thank the Mexican National Council of Science and Technology (CONACYT) for financial support, and also thanks the team of the REKLAB. Thanks to the Natural Sciences and Engineering Research Council of Canada (NSERC).

REFERENCES

[1] V. G. Macefield and R.S. Johansson, “Control of grip force during restraint of an object held between finger and thumb: responses of muscle and joint afferents from the digits,” *Exp. Brain Res.,* vol. 108, pp. 172-184, 1996.

[2] R.S. Johansson , C. Häger, and R. Riso, “Somatosensory control of precision grip during unpredictable pulling loads. III. Impairments during digital anesthesia. *Exp. Brain Res.,* vol. 89, pp. 204-213, 1992.

[3] R.E. Kearney and D.T. Westwick, “Nonlinear identification methods for modeling biomedical systems”. *2nd International Biomedical Engineering Days,* IEEE Press Series on Biomedical Engineering, 1998.

[4] F. Lacquaniti , “Neural control of limb mechanics for visuomanual coordination”, *Hand and Brain: The Neurophysiology and Psychology of hand movements,* Edited by A.M. Wing, P. Haggard and J.R. Flanagan, Chapter 11,pp. 213-237,1996.

[5] A.Fagergren, Ö. Ekeberg, and H. Forssberg, “Precision grip force dynamics: A system identification approach”, *IEEE Transactions on Biomedical Engineering,* vol. 47, No. 10, pp. 1366-1375, 2000.

[6] M.D. Klein B., K.J. Simura and M. Flanders, “Timing of muscle activation in a hand movement sequence”, *Cerebral Cortex,* vol. 17, pp. 803-815, 2006.

[7] R.E. Kearney and I.W. Hunter, “System Identification of human joint dynamics”. *Critical Reviews in Biomedical Engineering,* vol. 18, No. 1, pp. 55-87, 1990.