Control of Finger Forces during Fast, Slow and Moderate Rotational Hand Movements

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***Abstract*— The goal of this study was to investigate the effect of speed on patterns of grip forces during twisting movement involving forearm supination against a torsional load (combined elastic and inertial load). For slow and moderate speed rotations, the grip force increased linearly with load torque. However, for fast rotations in which the contribution of the inertia to load torque was significantly greater than slower movements, the grip force-load torque relationship could be segmented into two phases: a linear ascending phase corresponding to the acceleration part of the movement followed by a plateau during deceleration. That is, during the acceleration phase, the grip force accurately tracked the combined elastic and inertial load. However, the coupling between grip force and load torque was not consistent during the deceleration phase of the movement.**

In addition, as speed increased, both the position and the force profiles became smoother. No differences in the baseline grip force, safety margin to secure the grasp during hold phase or the overall change in grip force were observed across different speeds.

I. Introduction

Many daily activities require that we reach for objects and interact with them using our hands by applying sufficient grip force to ensure stability. The rate at which we interact with objects could vary depending on the goal of the task (e.g. rapid forearm twisting when playing tennis, slowly bringing a cup of coffee to mouth, etc.). Fast reaching movements have received much attention in the literature as their control is thought not to involve feedback since during rapid movements there is not sufficient time to permit efficient use of sensory information [1]. Most of these studies analyzed the kinematics of the movement or the muscle activity (see [1] for a review).

Some studies have examined the effect of speed on movement smoothness. For example, analysis of the EMG of finger muscles and finger kinematics, has shown that slow finger movements are not smooth; rather they are comprised of discontinuities and velocity fluctuations with a dominant frequency content of 8-10 Hz [2]. The kinematics of rapid aimed movements have also been analyzed in terms of submovements or discrete building blocks of movements, particularly in the context of accuracy [3-6].

This study focused on the kinetic aspects of movement and investigated the effect of speed on the patterns of grip force during a twisting action involving forearm supination. Previous hand-held object manipulation studies involving lifting or transporting objects [7] as well as torque production tasks [8, 9], have demonstrated a near linear relationship between grip force and load force/torque. The effect of speed on the coupling between grip force and load torque has not been systematically documented for forearm supination. The goal of this study was to determine how the speed of rotation influences the coordination of grasp and twist.

II. Methods

A. Subjects

Ten subjects (5 male, 5 female, all right handed) between the ages of 55 and 80 (average= 60.8 years) with no history of neurological disorders were tested. All of the subjects gave their informed consent to the procedures which were approved by the Review Ethics Board of the Centre de recherche interdisciplinaire en réadaptation du Montréal metropolitain.

B. Apparatus

Measurements were performed with a two degree-of-freedom (DOF) robotic interface, EnableHand [10, 11], that allows opening and closing of the hand by means of two plates that slide in opposite directions on a linear bearing. It also has a rotational DOF for supination/pronation of the forearm (see Figure 1B). A contoured surface attached to each plate provides a groove for the index, middle and ring fingers on the top plate and a groove on the bottom plate for the thumb located midway between the three opposing digits. The apparatus is equipped with strain gauges to measure the torque in rotation as well as normal force exerted by thumb (TH) and the combined normal force exerted by the other fingers (defined as a virtual finger (VF) by Arbib et al. [12]). Optical encoders mounted on the motor shafts read the angle of the motors with a resolution of 10,000 counts per revolution which is transformed to give the rotational and translational displacements of the plates. Data were sampled at 1 kHz with ADC resolution of 16 bits after anti-alias filtering with four-pole Bessel filters at a cut-off frequency of 100 Hz.

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C. Procedure

The subject was seated comfortably in a chair in front of the apparatus and display monitor. The elbow was supported on a platform and flexed at about 90 degrees. The shoulder was flexed at about 60 degrees. The forearm was slightly pronated and the wrist was in the neutral position. The initial orientation of the robot was set to -45 degrees with 0 defined as the vertical position of the end-effector.

Subjects performed the task using their right hand. They gripped the plates with the index, middle and ring fingers placed in the grooves on the upper plate and the thumb in the groove on the lower plate and twisted the robot by 20 degrees using forearm supination to a target position displayed on the monitor. The robot was programmed to: (1) exert an elastic load torque during rotation; (2) render a very high stiffness for linear movement of the plates thus keeping the grip aperture constant. The subject maintained the final position for about 2-3 seconds and then slowly reduced the grip force to allow the robot to slip back (See Figure 1A).

Subjects performed the grasp and twist task for three speeds (slow, moderate and fast). For the moderate speed condition, subjects were instructed to perform the rotation task at their preferred pace. For the slow condition, they were asked to perform it slower than normal and for fast trials, they were instructed to rotate as fast as possible. The accuracy requirement was relaxed and subjects were asked not to correct for overshoots in the movement.
The same grip size (45 mm) and final target torque (1.2 Nm for three subjects and 0.9 Nm for the other seven) were used across the different speed conditions.

D. Data Analysis

Force, torque and position data were low-pass filtered using a zero-lag, second-order Butterworth filter with a cutoff frequency of 10 Hz. The average of TH and VF normal force was defined as grip force (GF). The task was separated into four phases [8] as illustrated in Figure 1A: (i) grasp establishment during which the subject gripped the device before rotating it; (ii) dynamic or load phase, defined as the period from the onset of load torque to the point of maximum rotation; (iii) hold phase; 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 variables were used as outcome measures:

- Baseline grip force, i.e. the average force prior to the onset of movement
- The maximum cross-correlation coefficient between grip force and load torque
- Lag between grip force and load torque
- Cross-correlation coefficient between thumb force and virtual finger force at lag zero
- Average rate of change of grip force with respect to load torque (i.e. slope of GF-TQ relation)
- Maximum relative safety margin calculated as the difference between the maximum grip force during the hold phase and its corresponding slip force normalized by the maximum grip force of that trial
- Ratio of maximum grip force to maximum load torque

F. Statistical Analysis

Friedman's two-way analysis of variance by ranks for repeated measures was used to study the effect of speed on outcome measures. Post hoc analysis with Wilcoxon signed-rank was performed and the significance level was established as $p<0.05$.

III. Results

A. Qualitative Description

Fig. 2A-C shows the typical position, velocity, thumb and virtual finger force profiles during the rotation for the three different speeds. Position profiles for fast trials were the smoothest and they generally mimicked a critically damped movement while the slow movements were more irregular with several fluctuations. While fast trials had mainly one or occasionally two velocity peaks, as the speed decreased the number of velocity peaks increased. Visual inspection revealed that the TH and VF force profiles were much smoother for fast trials than for rotations at moderate or slow speeds. The force profiles for slow movements were jerky with several irregularities. In general as speed decreased, the force profiles became more irregular and less smooth.

Fig. 2D-F (top panels) shows the contributions of the inertial and elastic components to the overall load torque across different speeds. For slow and moderate speed rotations, the contribution of inertia to overall load was not significant. With regards to coordination of finger forces and load torque, the slow and moderate speed trials showed an approximately linear relationship between grip force and load torque. Grip force monotonically increased with load torque such that both reached their peak almost simultaneously.

However, for fast movements the inertial torque associated with acceleration and deceleration significantly changed the torque profile. Nevertheless, as illustrated in the panel showing normalized GF and TQ profiles, the grip force profile was similar to the overall load torque during the acceleration phase. However, during deceleration, there was no coupling between grip force and load torque as illustrated in the bottom panel of Fig. 2F where the GF-TQ relation for fast movements shows a linear ascending phase for acceleration phase followed by a plateau for deceleration.

B. Correlation between grip force and load torque

Friedman's two-way analysis of variance by ranks failed to find any differences in the cross-correlation coefficient between GF and TQ across different speeds ($\chi^2(2) = 2.1, p = 0.350$). The correlation between GF and TQ was high regardless of speed. The median values (IQR) of the cross-correlation coefficients were 97.7 (93.8 to 98.9), 98.0 (97.0 to 98.3) and 95.3 (94.1 to 96.9) for slow, moderate and fast speeds, respectively.

C. Lag between GF and TQ

Freidman's test indicated that there was no effect of speed on the lag between GF and TQ ($\chi^2(2) = 1.4, p = 0.497$). The median values (IQR) of the lags were 36.5 (18 to 55) *ms*, 27 (17 to 40) *ms* and 28 (22 to 33) *ms* for slow, moderate and fast speeds, respectively with GF was always leading TQ.

D. Coordination between thumb and virtual finger

There was no effect of speed on the cross-correlation coefficient between thumb force and virtual finger force ($\chi^2(2) = 1.4, p = 0.497$). The correlation between TH and VF was high for all speeds.

E. Ratio of maximum GF to maximum TQ

Based on Friedman's test, there was no difference between distributions of the ratio of maximum GF/TQ across different speeds ($\chi^2(2) = 0.6, p = 0.741$). That is, the overall change in GF was the same regardless of the speed. The median values (IQR) of the ratio of maximum GF to maximum TQ values were 14.78 (11.99 to 21.09) *N/Nm*, 13.89 (11.38 to 21.68) *N/Nm* and 14.87 (11.68 to 18.58) *N/Nm* for moderate, fast and slow speeds, respectively.

F. Baseline grip force

Friedman's test indicated that there was no difference between baseline GF across the different speeds $(\chi^2(2) = 2.6, p = 0.273)$. The median values (IQR) of the baseline GF values were 4.91 (3.83 to 7.27) N, 4.94 (3.36 to 6.3) N and 4.97 (4.63 to 13.93) N for moderate, fast and slow speeds, respectively.

G. Safety margin of grip force

Similarly, Friedman's test found no differences between distributions of the safety margin across the different speeds $(\chi^2(2) = 2.6, p = 0.273)$.

H. Slope of the grip force -load torque relation

Speed had no effect on slope of the grip force-load torque relation when comparing slow and moderate speed movements (Z=-0.866, p=0.386). However, the slope of the relation between grip force and load torque during the dynamic phase of the fast movements was significantly greater than for slow or moderate speed movements (Z=-2.61, p<0.01) as shown in Fig. 4. In addition, the slope in the plateau phase was significantly smaller than for slow and moderate speeds (p<0.01).

IV. Discussion

We investigated the effect of speed on the coordination of grasp and twist. The main finding of this study was that there was strong parallel coupling between grip force and load torque across all speeds for the acceleration phase of twisting movements. However, the strong correlation broke down during the deceleration phase of the fastest movements.

The fastest movements in our task consisted of a single primary movement and thus a single acceleration and deceleration phase. The task involved moving the end-effector of a robot against a combined elastic and inertial load. During fast rotations the maximum inertial load was about 30% of the final load torque and thus significantly changed the torque profile compared to slow or moderate speed movements. Nevertheless, during the acceleration phase of the fastest movements, the shape of the grip force profile accurately tracked the combined load torque of the inertial and elastic components. The relationship between grip force and load torque during the acceleration phase was linear with a slope almost twice that during the slow or moderate speed movements. Following this phase during which grip force increased with load torque, the grip force reached a plateau and although the load torque continued to change (generally by 0.6 Nm to 1 Nm), there was little change in grip force. This plateau phase was associated with the deceleration. During the first half of the deceleration phase, the negative inertial torque almost cancelled out the increase in elastic load torque causing the load torque profile to plateau. During the second half (from peak deceleration to zero), the overall load torque increased due to the greater contribution of the elastic component. The grip force and load torque were decoupled during this phase (which lasted about 70 ms). On average, the slope of GF-TQ relation during the plateau phase was close to zero. Normalizing maximum grip force by maximum load torque resulted in a measure that was invariant across speeds. The grip force controller elevated the grip force during the acceleration phase to a level that was sufficient to prevent slip during the deceleration phase even with the higher elastic load. It might be the case that the controller ensures grasp stability throughout the rotation by elevating the grip force early so that during the braking action the controller can focus on other parameters such as the precision of the final position, etc.

During slow or moderate speed movements, the controller increased grip force in parallel with load torque. Although there are no constraints that require this parallel coupling, doing otherwise would be undesirable. Increasing grip force more rapidly than load torque would require consuming more metabolic energy than necessary; and increasing it too slowly would increase a risk that the object would slip from grasp.

Among other parameters used to characterize the coordination of grasp and twist, there were no significant differences across the different speeds for the baseline grip force, safety margin to secure the grasp during the hold phase, the maximum cross-correlation coefficient between grip force and load torque and the corresponding lag, or the ratio of maximum grip force to maximum load torque.

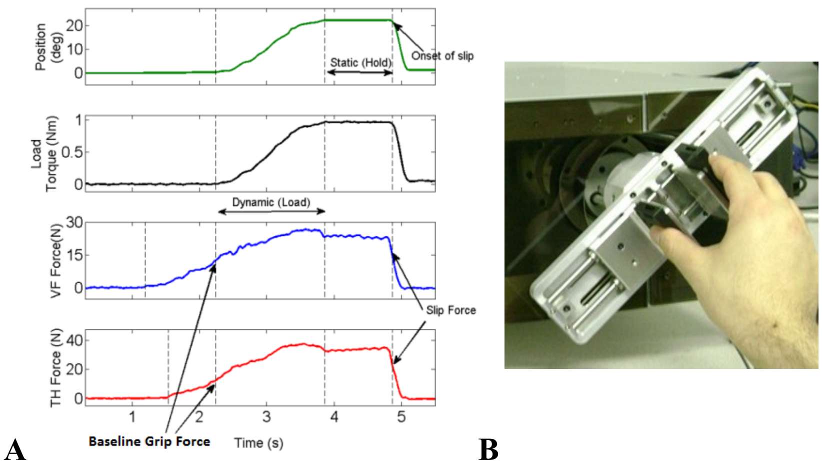

Figure 1. A Profiles of angular position, load torque, and normal force from thumb (TH) and the combined effect of opposing digits (noted as virtual finger (VF)). The four phases of the task are indicated by dashed vertical lines. **B** Measurements were performed with a two degree of freedom robotic interface allowing supination/pronation of the forearm. The device measures normal thumb and virtual finger force, load torque, angle of rotation as well as grip aperture.

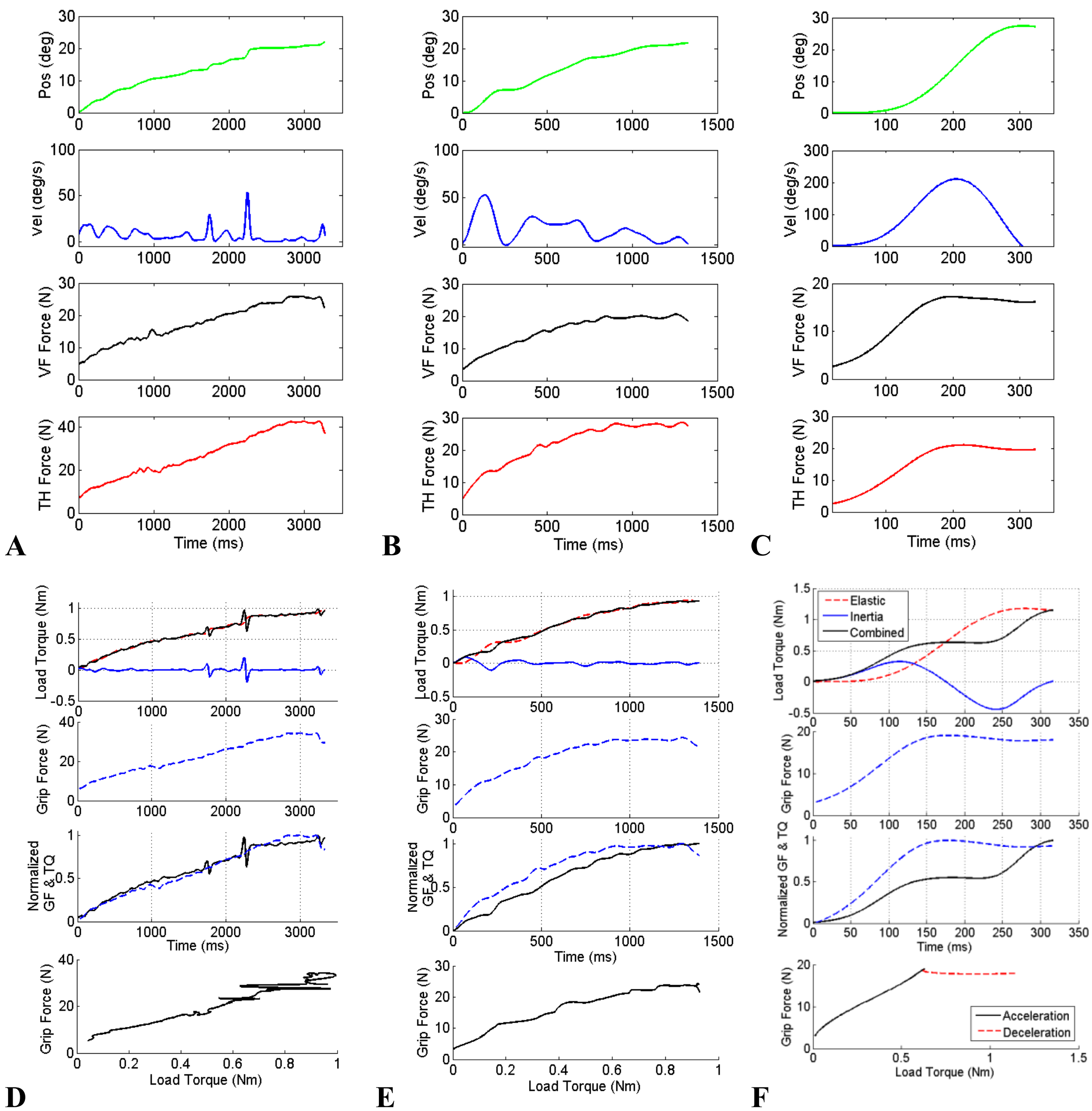

Figure 2. A,B,C position, velocity, thumb and virtual finger force profiles during rotation for three different speeds (**A**) Slow, (**B**) Moderate and (**C**) Fast for a representative subject (#4). Note that the scales are not the same. **D,E,F** Plots of load torque (elastic, inertial and combined load torque(TQ)), grip force (GF), normalized GF and TQ and plots of GF against TQ for (**D**) slow, (**E**) moderate speed and (**F**) fast movements. The inertial load significantly changed the torque profile for fast rotations. Nevertheless, the GF was closely modulated with the combined elastic and inertial load for the acceleration phase and then reached a plateau during the deceleration phase. The parallel coupling of GF and TQ disappeared during the deceleration phase.

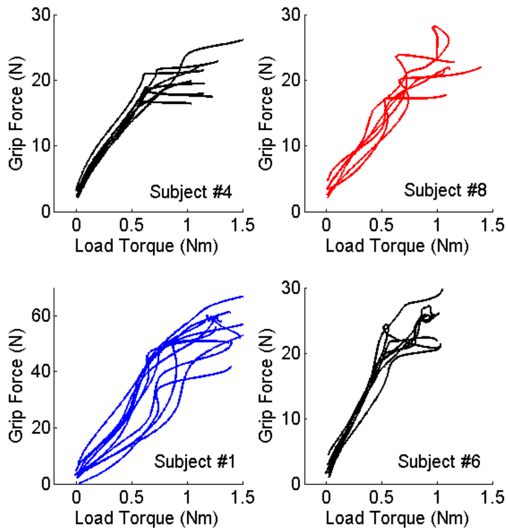

Figure 3. Plots of GF versus TQ superimposed for the dynamic phase of all trials for the fast movements. The GF-TQ relation deviated from a straight line and could be segmented into a sharp ascending phase followed by a plateau. The ascending and plateau phases corresponded to acceleration and deceleration phases of the movements respectively. This was observed for all subjects but is only illustrated for four subjects here.

Hejdukova et al. [13] reported a decoupling between grip force and load force during fast forward and upward movements of a hand-held object. In the study of Flanagan and Wing [14], a small sample of subjects performed vertical, cyclic arm movements with a hand-held object at three different speeds. They reported that the grip force-load force relation was curved (deviated from straight line) for the very fast trials and that increasing frequency resulted in reduced slope but higher intercept of the relation between grip force and load force.

As discussed in [13], Flanagan suggested that there was a cost associated with rapid changes in grip force. Therefore, rather than precisely modulating grip force in parallel with load torque the controller might adopt a strategy of elevating baseline grip force. Despite the differences in the tasks and the loads, we also observed that the grip force–load torque relation deviated from a straight line and that there was decoupling between grip force and load torque during the deceleration phase of the movement. One could interpret the initial increase in grip force with load torque as a strategy to elevate grip force early in the task to ensure grasp stability during the rotation without the need to be concerned about precisely modulating grip force with load during deceleration, as the grip force was sufficient to ensure that there was no risk of the object slipping out of the hand.

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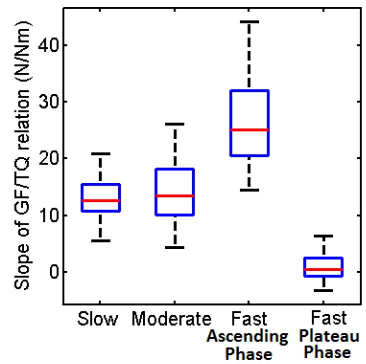

Figure 4. Boxplots of the slope of the GF-TQ relation pooled from all subjects across different speeds. For fast trials, the GF-TQ relation was segmented into phase of parallel modulation associated with acceleration and a plateau associated with deceleration. Data are pooled from all trials.

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