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Motor control goes beyond physics: differential effects of gravity and inertia on finger forces during manipulation of hand-held objects

Vladimir M. Zatsiorsky, Fan Gao, and Mark L. Latash

Biomechanics Laboratory, Department of Kinesiology, The Pennsylvania State University, University Park, PA, 16802, USA, Tel.: +1-814-865-3445, Fax: +1-814-865-2440

Vladimir M. Zatsiorsky: vxz1@psu.edu

Abstract

According to basic physics, the local effects induced by gravity and acceleration are identical and cannot be separated by any physical experiment. In contrast—as this study shows—people adjust the grip forces associated with gravitational and inertial forces differently. In the experiment, subjects oscillated a vertically-oriented handle loaded with five different weights (from 3.8 N to 13.8 N) at three different frequencies in the vertical plane: 1 Hz, 1.5 Hz and 2.0 Hz. Three contributions to the grip force—static, dynamic, and stato-dynamic fractions—were quantified. The static fraction reflects grip force related to holding a load statically. The stato-dynamic fraction reflects a steady change in the grip force when the same load is moved cyclically. The dynamic fraction is due to acceleration-related adjustments of the grip force during oscillation cycles. The slope of the relation between the grip force and the load force was steeper for the static fraction than for the dynamic fraction. The stato-dynamic fraction increased with the frequency and load. The slope of the dynamic grip force–load force relation decreased with frequency, and as a rule, increased with the load. Hence, when adjusting grip force to task requirements, the central controller takes into account not only the expected magnitude of the load force but also such factors as whether the force is gravitational or inertial and the contributions of the object mass and acceleration to the inertial force. As an auxiliary finding, a complex finger coordination pattern aimed at preserving the rotational equilibrium of the object during shaking movements was reported.

Keywords

Prehension; Grasping; Stato-dynamic relation; Grip force; Load force

Introduction

When people hold a vertically-oriented object statically with a prismatic grip (a grip in which the thumb opposes other fingers), they exert a grip force (G , normal force) that increases in a linear fashion with object weight (Kinoshita et al. 1995; Monzee et al. 2003). The grip force is larger than the minimal force necessary to prevent slip; the difference between the actual grip force and the minimal one has been called the *safety margin* (Johansson and Westling 1984). When a person moves a hand-held object up or down, in addition to the gravitational force an inertial force acts in the vertical direction. The load force (L , tangential force) in this

case equals $L=W+ma$, where W is the weight, m is mass of the object and a is its acceleration. When the load force increases, the grip force also increases (Johansson and Westling 1984), apparently to prevent slip.

A relation between the normal and tangential digit forces applied when lifting an object—a grasping synergy (Zatsiorsky and Latash 2004)—develops at an early age (Forssberg et al. 1991; Blank et al. 2001) and is a sign of skilled hand function (see Gordon 2001 for review). The grip force is modulated by the weight of the object (Johansson and Westling 1984; Winstein et al. 1991), abrupt load perturbations (Cole and Abbs 1988; Eliasson et al. 1995; Serrien et al. 1999), friction conditions (Cole and Johansson 1993; Cadoret and Smith 1996; Burstedt et al. 1999), tangential torques (Kinoshita et al. 1997), gravitational changes during parabolic flights (McIntyre et al. 1998; Hermsdorfer et al. 1999a; Augurelle et al. 2003), and inertial forces that act during shaking and point-to-point arm movements (Flanagan and Wing 1993, 1995; Flanagan et al. 1993; Flanagan and Tresilian 1994; Kinoshita et al. 1996) as well as during locomotion (Gysin et al. 2003). During similar manipulations, the grip forces are larger in senior adults (Vandervoort et al. 1986; Kinoshita and Francis 1996a; Cole and Rotella 2002) and patients with neurological disorders (Gordon and Duff 1999; Babin-Ratté et al. 1999; Hermsdorfer et al. 1999b; Serrien and Wiesendanger 1999; Fellows et al. 1998, 2001). Local skin anesthesia and digit cooling make the coordination of the load and grip force less precise but does not change the general pattern of coordination (Nowak et al. 2001; Monzee et al. 2003; Nowak and Hermsdörfer 2003). Based on these observations it has been concluded that the grip force-load force coupling is mainly controlled by a feed-forward mechanism: a central controller regulates the grip force according to the expected load force (Johansson and Westling 1984; Flanagan and Wing 1995) while a feedback mechanism triggered by cutaneous sensation acts if an assessment of an expected load force happens to be erroneous.

Despite the great deal of attention paid to the G - L coupling, the differential contributions of gravitational and inertial forces to the production of grip force has not been addressed systematically in the literature. According to basic physics, the local effects induced by gravity and acceleration are identical and cannot be separated by any physical experiment; for example, physics in a gravitational field is equivalent to physics in an accelerating spacecraft (the so-called “equivalence principle”, Einstein 1907). Does this then mean that people adjust the grip force to gravity (weight) and inertial forces identically?

If gravity and inertial contributors to the load force—where gravitational load changes result when objects with different mass are alternately grasped, and inertial load changes result from object transport—induce equal effects on central assessments of necessary grip force, similar variations in the gravitational and inertial forces should induce identical changes in the grip force. For instance, if the grip force (normal force) is $G=kF_t$, where F_t is a tangential force (when a grasped handle is oriented vertically the tangential force equals the load force L) and k is a coefficient of proportionality, then the coefficient k should be the same whether L is changed due to a change in the weight of the object or to its acceleration (Fig. 1a). In experiments, we obtained evidence that this is not the case: Manipulations of object weight and acceleration are associated with different modulations of grip force, as illustrated in Fig. 1b. In Fig. 1b, three grip force-load force relations can be traced:

- A *static* relation between the grip force and the weight of the object.
- *Dynamic* relations between the grip force and the inertial force change; the dynamic relations are represented by the ellipse-like force-force curves.
- A *stato-dynamic relation* (dotted line) that relates the average grip force during the movement to the weight of the object.

The goals of the present experiment were: (1) to quantify the static, dynamic, and stato-dynamic relations and their contributions to the grip force, and (2) to determine the effects of the gravitational and inertial forces on grip force production. To this end, two task variables were manipulated: object mass and oscillation frequency (acceleration).

Methods

Six healthy right-handed male subjects (27 ± 6 years, 75 ± 9 kg) participated voluntarily in this study. Subjects had no previous history of neuropathies or trauma to the upper extremities. All subjects gave informed consent according to the procedures approved by the Office for Regulatory Compliance of The Pennsylvania State University.

Experimental set-up

The subjects manipulated an aluminum handle composed of two horizontal bars and two vertical pillars. Five six-component force/moment transducers (Nano-17, ATI Industrial Automation, Garner, NC, USA) were mounted on the pillars. The center points of the index and middle finger sensors were located 37.5 mm and 12.5 mm, respectively, above the midpoint of the handle (Fig. 2). The center points of the ring and little finger sensors were located 12.5 mm and 37.5 mm, respectively, below the midpoint. The grip width (the distance between the surfaces of the thumb contact and the finger contacts) was 60 mm. The surfaces of the transducers were covered with 100-grit sandpaper. The friction coefficient between the skin and sandpaper in different subjects ranged between 1.4 and 1.5 (Gao 2002). A tri-axial accelerometer (EGA 3, Entran, USA, range ± 5 g, weight 0.5 g) was mounted on the horizontal bar at the lower left corner to record the acceleration of the handle.

The output cables of the sensors were tied together and hung 20 cm above the top of the handle to avoid interference during the cyclic movement. The cables were connected to a customized box that split the cables into separate channels corresponding to individual signals and input the signals to two 32-channel 12-bit AD converters (PCI-6033E, National Instruments, Austin, TX, USA). The digital signals were processed using a computer (Dell Dimension 8200, USA). The sampling frequency was set at 200 Hz. Data were recorded by a customized program written in LabView 6.1 (National Instruments, Austin, TX, USA).

Test procedure

Before the experiment, subjects cleaned the tips of the digits with alcohol to normalize skin condition. The subjects were instructed to hold the handle statically with the forearm unsupported while placing the tips of the digits at the centers of the sensors before each trial. Before each of the task conditions the subjects were trained to ensure proper performance. In particular, for different movement frequencies, a rhythmic audio signal was provided, and the subjects tried to follow the tempo of the signal. The recording did not start until the subjects could match the rhythm well.

Subjects were instructed to make vertical cyclic arm movements while timing the movements with beeps generated by the metronome. Two horizontal ropes, 10 cm apart in the vertical direction, were used to mark the target amplitude of the movements. The subjects were instructed to move the handle along a straight line and to keep its orientation constant throughout the test. The movements of the handle were visually monitored by the experimenter. Handle rotation was not recorded but, based on visual observation, it was assumed negligible. Three movement frequencies, 1 Hz, 1.5 Hz and 2 Hz, and five different loads—3.8 N, 6.3 N, 8.8 N, 11.3 N and 13.8 N—were used. Since maximal acceleration during a harmonic motion equals $\omega^2 x_0$ where ω is the circular frequency (rad/s) and x_0 is the amplitude of the motion, the doubling of frequency from 1 Hz to 2 Hz induced a four-fold increase in the inertial force.

Combined with the load force increase due to the changes in the mass of the object, the experimental tasks secured almost a 15-fold difference in the load forces between the light weight, low frequency and the heavy weight, high frequency tasks. Each test lasted 15 s; 20-second breaks were given between consecutive trials. At the beginning of the test for each load condition, subjects were asked to hold the handle in equilibrium with minimum effort, and the static finger forces were recorded for 15 s. The order of the tests was randomized.

Data analysis

Raw data were low-pass filtered at 5 Hz with a fourth-order Butterworth filter. In the transducer-fixed reference system the grip forces were normal to the transducer surface (in the z -direction). The load force was tangential to the surface (along the y -axis), aligned with the vertical pillars.

The contributions of static, dynamic, and stato-dynamic fractions to the grip force were calculated as follows: (a) the static fraction is equivalent to the grip force during a static task; (b) the dynamic fraction is the projection of the L - G vector from an ellipse center along the major axis of the ellipse on the grip force axis; and (c) the stato-dynamic fraction is the difference between the center of the ellipse and the static fraction for a given weight of object (Fig. 3).

To divide the entire force-time history into individual cycles, the instances where the vertical acceleration equaled zero (or was closest to zero) were selected. These instances were labeled and used to identify individual cycles for further analysis. In some trials, low-frequency changes in the normal force were observed. Therefore, a high-pass filter at a cutoff frequency of 0.3 Hz was applied to the normal force and an offset was added such that the filtered force had the same means as the unfiltered grip force.

Statistical analysis

To compute the static L - G relation, the grip force measured during static tasks was linearly regressed on the load force (the object weight); see Fig 1 and Fig 3. Note that this relation represents inter-task changes.

The dynamic component was determined in two complementary ways: (a) the changes in the grip force during a trial were linearly regressed on the changes of the load force, and (b) the major axis of the force-force ellipse was determined by principal component analysis. The major axis corresponds to the eigenvector of the force-force relation with the maximal eigenvalue. Error ellipse fitting was applied to the relation between grip force and load force, and the confidence level was chosen at 85%. The dynamic relations represent the intra-task dependencies between the grip and load forces.

One of the goals of this study was to determine whether people react to the gravity and inertia force variations in a similar manner. To do this, we compared the slopes of the L - G ellipses of the dynamic relations with the slopes of the static relations. Because sequences of instant L - G observations during a trial were not independent, usual statistical methods of comparing slopes of regression equations could not be applied. For that reason, the differences between the slopes of the static and dynamic relations were determined for each subject and task. A non-parametric analog of repeated-measures ANOVA, the Friedman test, was applied; in addition Wilcoxon's signed-rank test was used.

The stato-dynamic fraction of the grip force was determined—for a given subject, oscillation frequency, and object weight—as the difference between the projection of the geometric center of the dynamic force-force ellipse recorded during an oscillation test on the grip force axis and the grip force in static conditions (Fig. 3). For each oscillation cycle, a value of the grip force

at the instant when the vertical acceleration was zero was determined. The values of the grip force at these instances were averaged over all cycles. Then the data for different object weights were combined and the parabolic regression of the second order of the stato-dynamic constituent of the grip force on the object weight was computed. This regression signifies an inter-task relation between the average grip force recorded during object oscillation and in the static tests.

In the time domain, cross-correlation analysis was performed to examine the phase relation between the grip force and load force.

Statistical analysis was performed in the Statistics toolbox of Matlab 6.1 (The MathWorks, Inc., Natick, MA, USA).

Results

Force changes in an oscillation cycle

This section includes experimental data that—although auxiliary to the main goal of the study—substantiate the employed method of data analysis, in particular using the sum of normal force magnitudes of the five digits as a measure of the grip force.

The normal force exerted by the thumb equaled the total normal force exerted by the four fingers, referred to later as the virtual finger (VF) force (see Arbib et al. 1985; Baud-Bovy and Soechting 2001, MacKenzie and Iberall 1994), at any instant during the oscillation cycles (Fig. 4). This relation was expected from the conditions of equilibrium: a force inequality would result in object acceleration in the horizontal direction. Hence, analysis of the VF normal force provides the same results as analysis of the thumb force.

In contrast, the tangential forces of the thumb and VF were not equal; the difference changed in a systematic way during a movement cycle (Fig. 5). Two unequal parallel forces exert a torque on the object. To prevent handle rotation, the torque due to the tangential forces was opposed by the torque of the normal forces; during the cycle, the sharing pattern of finger forces changed in a rhythmic manner (Fig. 6) such that the rotational equilibrium was preserved.

While the mechanisms of preserving rotational equilibrium of hand-held objects during manipulation deserve attention, we mention the above facts solely to explain why we used the sum of the absolute values of the normal forces exerted by all five digits as a measure of grip force. An alternative choice would be using only the thumb or the VF forces. However, because tangential forces of the thumb and VF are not equal while the normal forces are similar, such an approach would result in an unnecessarily complex analysis.

Grip force-load force relations

An example of the grip force–load force relation is presented in Fig. 7. In this particular subject the slopes of all dynamic relations are below 1.0 (an increase of the load force by 1 N induces an increase of the grip force <1 N) while the slope of the static relation equals 1.22 and the stato-dynamic relation is a quadratic parabola with positive coefficients.

Expanding the grip forces into the contributing fractions

The magnitudes of the contributing fractions—static, stato-dynamic and dynamic—to the grip force for various tasks are presented in Fig. 8.

The static grip force-load force relations satisfy a linear regression equation $G_{\text{stat}} = a + bW$, where G_{stat} is the static fraction of the grip force, Table 1. Note that the intercepts of the regression

are small and, hence, the static relation can be approximated by a product $G_{\text{stat}}=kW$, where k is a coefficient.

The stato-dynamic fraction increases with the frequency and load with only one exception, the relation between load 4 and load 5 at frequency 2 Hz (Fig. 9). The stato-dynamic fraction (G_{stodyn}) was significantly influenced by frequency and load conditions (Friedman's test, $p<0.001$). The parabolic regression equations for the entire group are:

$$\text{Frequency 1Hz; } G_{\text{stodyn}} = 0.027W^2 - 0.274W + 0.66; R^2 = 0.94$$

$$\text{Frequency 1.5Hz; } G_{\text{stodyn}} = 0.045W^2 - 0.42W + 1.44; R^2 = 0.91$$

$$\text{Frequency 2Hz; } G_{\text{stodyn}} = 0.02W^2 + 0.85W - 1.55; R^2 = 0.92$$

Dynamic grip force-load force relations

From Fig. 7 above, one can clearly see that the dynamic relations between grip force and load force are different from the static relation. Within a single oscillation cycle, the changes in grip force depend on (a) the range of the variation in load force—completely defined by the task mechanics (the amplitude and frequency of oscillation and the object weight); (b) the slope of the grip force–load force relation, which can be controlled by the performer.

As already mentioned (see Fig. 8), the magnitude of the dynamic part increased with increasing object mass. This effect was expected: the grip force scales with the load force, which—at the same frequency—changes linearly with the mass. However—and this was not expected—the slopes of the dynamic grip force–load force relations (the major axes of the force-force ellipses) decreased with movement frequency for all masses of the objects (Fig. 10); in other words, equal increments of the load force induced smaller increments of the grip force at high frequencies. In contrast, the slopes increased with increasing load (with only two exceptions: the loads of 3.8 N and 6.3 N for 1-Hz and 2-Hz frequencies—not shown in the figures).

The differing effects of frequency and mass increments on the L - G relations suggest that the central controller takes into account—when determining the grip force magnitude—not only the expected load force but also its origin and whether the force is increased due to the an increase in mass or acceleration.

To determine the differences between the slopes of the static and dynamic relations, the differences were computed individually for each subject, frequency and task and then the non-parametric Wilcoxon signed-rank test was applied. In 11 of the 15 cases the difference was statistically significant at $p<0.05$, and in the other four cases—6.3 N and 13.8 N at frequency 1.5 Hz, 8.8 N and 11.3 N at frequency 2 Hz—the p values were 0.06, 0.06, 0.16 and 0.09 respectively. Furthermore, the slopes of the dynamic relations were significantly affected by the frequency and load conditions for all subjects ($p<0.001$, Friedman's test).

Cross-correlation between grip force and load force

As already mentioned, the dynamic relation between grip force and load force has an ellipse-like shape (see Fig. 7). The existence of the ellipse-like—rather than perfectly linear—relation is due to the phase lag between the grip force and the load force time histories. To test this, cross-correlation between the grip force and load force was computed. Positive lags were observed in 400 out of 630 cases (15 tasks×6 subjects×7 digit combinations—each of the digits, VF and the total force of five digits), which means that the peak of grip force preceded that of the load force in most of the cases. Figure 11 gives an example of the time delay between the grip force and load force. The magnitude of the time lag varied from zero to 50 ms. Despite the fact that the positive lags dominated in most of the trials, the mean time lag for the entire set of 630 trials was about zero to 5 ms. Thus, on average, the grip force and load force were

modulated in phase. In this sense, the parallel modulation of grip force with load force (Flanagan and Wing 1995) has been confirmed. The existence of (small) negative lags in certain cases deserves future research.

Discussion

The main result of this study is straightforward: When manipulating hand-held objects, people adjust grip force to the expected gravitational and inertial forces differently. Three contributions to grip force—static, dynamic and stato-dynamic—have been quantified and they will be discussed in this section. As an auxiliary finding we would like also to mention the complex finger coordination pattern aimed at preserving the rotational equilibrium of the object during oscillatory movement (Figs. 4 and 5).

On the whole the paper points at, and quantitatively separates, control mechanisms of prehension that act in parallel. In this regard, the present data agree with the principle of superposition (Arimoto et al. 2001; Zatsiorsky et al. 2004) according to which a dexterous grasp is realized by a linear superposition of two commands, one command for the stable grasping and the second one for regulating the orientation of the object.

When subjects hold an object statically, the vertical force exerted by the performer on the object balances the object weight. With an increase in the static load force the grip force also increases, evidently to prevent slip (Johansson and Westling 1984; Cole and Abbs 1988; Flanagan and Tresilian 1994). The relation between the grip force and load force is linear over the entire range of the object weights explored in this study (Fig. 1). Similar findings have been reported by other authors (see Kinoshita et al. 1995).

When subjects move the object in the vertical plane, the extra force in the vertical direction is needed to accelerate or decelerate the object. According to Newton's Second Law of motion, the net load (tangential) force is directly related to the mass and acceleration of the object a ,

$$L = \sum_{i=1}^5 L_i = W + ma$$

where L_i represents the load forces exerted by individual digits. Accordingly, an increase in the mass of the object and/or acceleration will result in an increase in the load force. The grip force changes with the load force. When the object is oscillated, the dynamic relation between the grip force and load force show ellipse-like patterns and, on a coarse scale, the forces change in phase with only small time lags. However, the gains/slopes of the load force–grip force relations are not constant. An increase in the acceleration/frequency leads to a drop in the slopes while an increase in the mass makes the relations steeper. Hence, the central controller adjusts the grip force not only to the magnitude of the load force but also to the differential contributions of the mass and acceleration to the ma product. When the object is stationary, the relation between the load force (which is defined only by gravity) and grip force is the steepest. Hence, we conclude that the controller regulates the grip force in static and dynamic tasks differently.

The stato-dynamic part (the difference between the average grip force during a dynamic task and the static task performed with the same object) characterizes a background force level on which the rhythmic dynamic oscillations of the grip force in individual cycles are superimposed. This level, albeit not completely stable, is maintained throughout the entire trial. The stato-dynamic part signifies a general reaction of the performer to the task, possibly to a perceived risk of dropping the object during the movement. When the load and/or acceleration increase, the stato-dynamic part also builds up. In other words, when the task becomes more

challenging, the controller adjusts the grip force to a higher level. If the task is easy, for instance when the object mass and frequency of oscillation are low, the controller may even decrease the general level of the grip force as compared with the corresponding static task (note the standard error bars in Fig. 8).

The origins of the different grip adjustments to gravity and inertial forces are as yet unknown. They may include:

1. Effects related to more proximal joints: *mechanical* (for example the central controller may act not only with respect to the forces exerted at the finger tips but to the self-induced acceleration at the proximal joints).
2. Effects related to different reactions of sensory receptors: *sensory*. For instance, safety margin—the difference between the actual grip force and the minimal grip force necessary to prevent slip (Johansson and Westling 1984)—may be viewed as being defined by a desire of the system to have a certain level of sensory signals from the receptors at the finger tips (see Cole 1991; Cole et al. 1999). If motion is associated with elevated excitability of the receptors, they require less grip force to produce similar levels of activity.
3. Effects related to assuring stable performance of the task: *motor control*. For instance, the safety margin may be kept lower if the system relies on corrective responses to partial slip (Mori et al. 2003). Partial slip is expected to be higher during motion than during static holding. Maybe the average grip force drops because of the higher efficacy of the corrective responses.

Special experiments are needed to explore the above-mentioned hypotheses. In particular, it might be useful to perform an experiment where both effective gravitational load changes and inertial changes are achieved simultaneously. A hand-held object's effective weight could be altered by servomotor-controlled bands attached to opposite ends of the handle.

A general conclusion from this study is that when adjusting the grip force to the requirements of a task, the central controller takes into account not only the magnitude of the load force but also whether the force is exerted statically or dynamically.

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Fig. 1.

a,b Effects of object weight and inertial force on the grip force. The inertial forces are due to an up-and-down oscillation of the vertically oriented handle. **a** An expected relation between the grip and load forces in the event that the grip force adjustments to the weight and inertial forces are identical. The expected dynamic grip force adjustments (*open ellipses*) are oriented along the same line as the static grip force-load force relation. **b** If the effects on the grip force of moving the handle differ from the static relation, the ellipses may be expected to shift with respect to the static line and to be oriented differently. Three fractions of the grip force—static (*solid straight line*), stato-dynamic (*dotted line*), and dynamic (*ellipses*)—are explained further in the text (see Fig. 3)

Fig. 2.
Schematic drawing of the experimental set-up (the drawing is not to scale)

Fig. 3. Expanding the grip force into three fractions: static, stato-dynamic and dynamic. W is the object weight. The static relation is represented by a *straight line*. The dynamic relation is represented by an *ellipse*. The L - G vector (not shown in the picture) goes from the ellipse center to the star representing an L - G pair selected for the analysis

Fig. 4.

The normal force of the thumb versus the normal force of the virtual finger (VF). The virtual finger is an imaginary finger that generates the same mechanical effect as the four fingers combined. Data for a representative subject are illustrated

Fig. 5.

The time history of the difference between the tangential forces of the thumb and virtual finger (VF) in a typical trial. The frequency was 2 Hz, the weight was 13.8 N. Data for a representative subject are shown. To obtain the torque generated by this difference it should be multiplied by the moment arm (the width of the grasp: 60 mm)

Fig. 6.

Changes in the sharing pattern of the normal finger forces during a trial as a percentage of the total force. To avoid a messy figure only the sharing percentages of the index and little fingers are shown. Normal forces of these fingers produce opposite moments of force about the thumb as a pivot. Hence, an increase in the sharing percentage of one finger with a simultaneous decrease of the other finger alters the moment of the normal forces exerted on the object. Frequency 2 Hz, weight 13.8 N. Data for a representative subject are shown

Fig. 7.

Static, dynamic and stato-dynamic relations between the grip and load forces. The inertial forces are due to an oscillation of the vertically-oriented handle at 1.5 Hz over about 10 cm in the vertical plane. The weights are 3.8, 6.3, 8.8, 11.3, and 13.8 N. The total force of five digits is shown for a representative subject, Subject 1. W is the object weight, the load force $L=W+ma$

Fig. 8.

a–c Static, stato-dynamic and dynamic contributions to the grip force at various loads and oscillation frequencies. The dynamic contribution was computed by projecting the major axes of the force ellipses onto the grip force axis. Group averages and standard errors of the mean are shown. Frequency: **a** 1 Hz; **b** 1.5 Hz; **c** 2 Hz. LD1–LD5 correspond to the weight values 3.8, 6.3, 8.8, 11.3 and 13.8 N, respectively

Fig. 9. Stato-dynamic fractions at various frequencies and loads. The data are group averages. The vertical bars are standard errors of the mean

Fig. 10. Slopes of the dynamic and static grip force-load force relations. Equal increments of the load force may induce unequal increments of the grip force

Fig. 11. Grip force and load force (N) time histories. Subject 6, frequency 1 Hz. The lower panel shows a close-up of the upper panel, the peak values of the curves are labeled with *circles*

Table 1

Static grip force–object weight relations for individual subjects

Subject	Equation	Coefficient of correlation
1	$G_{\text{stat}} = -0.38 + 1.226W$	0.984
2	$G_{\text{stat}} = -1.226 + 1.111W$	0.966
3	$G_{\text{stat}} = -0.841 + 1.551W$	0.993
4	$G_{\text{stat}} = 0.653 + 1.03W$	0.999
5	$G_{\text{stat}} = 0.748 + 1.537W$	0.975
6	$G_{\text{stat}} = -1.035 + 1.482W$	0.934