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Grip-force modulation in multi-finger prehension during wrist flexion and extension

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Abstract

Extrinsic digit muscles contribute to both fingertip forces and wrist movements (FDP and FPL – flexion, EDC – extension). Hence it is expected that finger forces depend on the wrist movement and position. We investigated the relation between grip force and wrist kinematics to examine whether and how the force: (1) scales with wrist flexion-extension (FE) *angle*; (2) can be predicted from accelerations induced during FE *movement*. In one experiment subjects naturally held an instrumented handle using a prismatic grasp and performed very slow FE movements. In another experiment, the same movement was performed cyclically at three prescribed frequencies. In quasistatic conditions, the grip force remained constant over the majority of the wrist range of motion. During the cyclic movements, the grip force changed. The changes were described with a linear regression model that represents the thumb and virtual finger (VF = four fingers combined) normal forces as the sum of the effects of the object's tangential and radial accelerations and an object-weight-dependent constant term. The model explained 99% of the variability in the data. The independence of the grip force from wrist *position* agrees with the theory that the thumb and VF forces are controlled with two neural variables that encode referent coordinates for each digit while accounting for changes in the position dependence of muscle forces, rather than a single neural variable like referent aperture. The results of the cyclical *movement* study extend the *principle of superposition* (some complex actions can be decomposed into independently controlled elemental actions) for a motor task involving simultaneous grip force exertion and wrist motion with significant length changes of the grip-force producing muscles.

Keywords

multi-finger prehension; wrist flexion extension; principle of superposition; referent configuration hypothesis

Introduction

This paper investigates the effects of wrist flexion and extension on the grip force exerted by the five fingertips on a hand-held object. To hold an object vertical and without motion in a prismatic grasp – thumb and four fingers in opposition like in holding a glass of water – the forces of the thumb (TH) and the virtual finger (VF: an imagined digit with the same mechanical effect as that of the four fingers combined (Arbib et al., 1985)) normal to the contact surfaces must be balanced. These two balanced normal forces are collectively called *grip force*.

During object manipulation, however, the TH and VF normal forces may be unbalanced, for example, while moving the object parallel to these forces. During manipulation, the set of finger forces acting on the object can be partitioned into (a) internal force: the set of digit forces that do not disturb object equilibrium, i.e. the forces that cancel each other, and (b) manipulation force: the resultant unbalanced digit force responsible for object acceleration (Kerr & Roth, 1986; Yoshikawa & Nagai, 1991). In the present work, the internal force, in particular, the portions of the TH and VF normal forces that cancel each other, is understood as the grip force (a more detailed discussion is available in Gao et al., 2005). The grip force magnitude equals the minimum of the TH and VF normal forces.

Task mechanics can only specify a lower bound for the grip force necessary to avoid object slip. The object can be gripped harder without affecting the state of the hand-object system. The manipulation and internal forces are mathematically independent (Murray et al., 1994), and they are controlled separately in robots (Zuo & Qian, 2000). Humans, however, do not use this option. Several researchers have shown that internal forces, in particular the grip force, are influenced by the movement mechanics (Zatsiorsky & Latash, 2008).

When a vertically held handle is moved in the vertical direction, the grip force increases with the load force (handle weight + mass $\times$ acceleration) (Johansson & Westling, 1984; Zatsiorsky et al., 2010). This tendency is evident even when the grip force is greater than the minimum grip force required to avoid object slip (Flanagan & Wing, 1995). While lifting a vertically held object, the maximum grip force is at the point of maximum acceleration, whereas during horizontal transport of the same object, the maximum grip force occurs at the point of maximum velocity and hence zero acceleration (Gao et al., 2005; Smith & Soechting, 2005). While moving a handle in planar, circular trajectories, which are a combination of translations parallel and orthogonal to the normal forces, grip force can be described as a summed effect of two basic central commands associated with the parallel and orthogonal translations (Slota et al., 2011).

In this paper, we analyze the effect of the wrist angle about a vertical flexion-extension (FE) axis on grip force. The research was inspired by the following considerations. (a) The task mechanics are different from previous studies. The wrist FE task requires translation of the object (as in the movements studied by Slota et al., 2011) and additionally involves object rotation. (b) The involved muscles simultaneously influence the wrist movement and grip force production. The extrinsic hand muscles producing fingertip grip force (FDP: Flexor Digitorum Profundus and FPL: Flexor Policis Longus) pass through the wrist joint and are also involved in wrist flexion. Similarly, the extrinsic hand muscles producing finger extension (EDC: Extensor Digitorum Communis) are involved in wrist extension (Platzer, 2004). Therefore, tasks involving simultaneous action of the fingertips and the wrist may be expected to show interdependence, and grip force is expected to depend on wrist FE angle. (c) It is a common everyday movement. We studied the effect of wrist FE *position* and then the effect of wrist FE *movement* on grip force.

Grip strength, defined as the maximum voluntary grip force, is a function of wrist angle for a variety of grasp types (Li, 2002; O'Driscoll et al., 1992; Pryce, 1980). It is also well known that the sub-maximal grip force exerted on objects is greater than that required to prevent object slip, and its magnitude depends on cutaneous afferent input, i.e. local friction and the estimated object weight (Burstedt et al., 1999; Flanagan & Wing, 1995). We investigated whether the sub-maximal, voluntary grip force with a five-digit prismatic grasp also varies with wrist angle.

Werremeyer & Cole, 1997 studied the effect of discrete wrist FE movements on grip force with a pinch grasp. The grip force increased with object total load (inertial load + weight),

and the increase in grip force was more than what could be expected due to the increase in inertial load. We focus on the effects of cyclic wrist FE movement on the grip force produced for five-digit prismatic grasp.

To summarize, the objectives of the study are as follows:

1. To study grip force variation with wrist angle. Since the maximal grip force is expected to vary across wrist FE angles, and due to the considerations of the relevant muscle architecture, we hypothesize (H1) that given the object weight, the sub-maximal grip force will depend on the wrist angle for static holding.
2. To quantify the grip force patterns while performing wrist FE movements and to develop a mathematical model to predict the finger normal forces, in particular the grip force, from the movement kinematics. Note that the grip force does not immediately affect the handle movement and hence cannot be computed by solving the inverse problem of dynamics. The dependence between the grip force and the movement kinematics—if it exists—is due to motor control mechanisms, not the task mechanics. We are interested in whether the model developed by Slota et al., 2011 for handle movement along circular paths can be extended to wrist FE movement. We hypothesize (H2) that the model can be generalized to a different kind of movement, as explained above.

Finally, we interpret the findings within two competing views on the neural control of movement, the referent-configuration hypothesis, which is an extension of the equilibrium-point hypothesis (Feldman 1986, 2011), and the idea of internal models (Kawato 1999; Shadmehr and Wise 2005). The latter approach is based on notions from control theory; it assumes computational operations performed by neural structures. The former approach does not assume neural computations; it considers voluntary movements as consequences of shifts in *referent body configurations* defined as configurations at which all muscles are at their thresholds of activation via the tonic stretch reflex. For recent comparisons of the two approaches see (Ostry and Feldman 2003; Hilder and Milner 2003; Feldman and Latash 2005).

Methods

Two sets of experiments were performed. The first set included static (quasistatic) tasks, and the second included cyclic movement tasks.

Subjects

Three female and six male right-handed subjects (age 30.6 ± 6.3 years, weight 77.12 ± 10.8 kg, height 1.73 ± 0.1 m, hand length 0.08 ± 0.01 m, and hand width 0.08 ± 0.006 m) voluntarily participated in the first set of experiments. Two female and six male right-handed subjects (age 32.8 ± 5.2 years, weight 69.6 ± 13.9 kg, height 1.71 ± 0.01 m, hand length 0.18 ± 0.01 m, and hand width 0.087 ± 0.01 m) performed the second set of experiments on a different day. Four male subjects performed both tests. The subjects had no history of neuropathy or upper-limb trauma. All subjects gave informed consent according to the procedures approved by the Office of Research Protections of The Pennsylvania State University.

Equipment

Five 6-component (3 force and 3 moment components) transducers (4 Nano-17s for the fingers and one Nano-25 for the thumb; ATI Industrial Automation, Garner, NC) were attached to an aluminum handle (Fig. 1). The distance between the finger sensors in the vertical (X') direction was 30 mm, and the thumb sensor was placed midway between the

middle and ring fingers along the X' axis. The grip width, which is the shortest distance between the contact surfaces of thumb and finger sensors in Z' -direction, was 86 mm. Sandpaper (100-grit) was placed on the contact surface of each transducer to increase the friction between the digits and transducers. The finger pad-sandpaper static friction coefficient was about 1.4–1.5 (previously measured by Savescu et al., 2008). The sensors were aligned in the $X'-Y'$ plane. A frame was constructed to support the subject's forearm. A lever, attached to the frame via a hinge joint, supported the subject's hand so as to prevent ulnar abduction. A potentiometer that measured the wrist flexion-extension angle was housed along the axis of the hinge.

Thirty analog signals from the sensors (5 sensors $\times$ 6 components) were routed to a 12-bit analog–digital converter (PCI-6031, National Instruments, Austin, TX). The signal from the potentiometer was sent to a serial port at the same time. A customized LabVIEW program was used for data acquisition and subject feedback. MATLAB programs were written for data analysis.

Experimental procedure

For both studies, subjects were seated comfortably in a chair. They rested their right forearm on the frame such that the shoulder was abducted at 45° and flexed at 0° , the elbow was flexed at 90° , and the palm faced medially. The forearm was strapped to the frame to restrict pronation and supination. The bottom of the hand rested on the lever, and was strapped to it to further prevent pronation-supination movement. The hand was positioned so that the wrist FE axis was aligned with the hinge axis when the forearm and the hand were aligned (zero wrist flexion angle). The subjects gripped the instrumented handle with the fingertips and maintained its vertical orientation.

Quasistatic test—A spirit level placed on top of the handle enabled subjects to maintain the vertical orientation of the handle during this experiment. The experiment consisted of three tests. In Test 1, the range of wrist flexion-extension motion (ROM) of the subject was measured. The subject maximally flexed the wrist while holding the handle vertical and maintained this pose for 5 s. The mean value of wrist angle was considered the maximum flexion angle. The procedure was repeated with the wrist in the maximally extended position.

In Test 2, (static maximum voluntary contraction (MVC) test) subjects maximally squeezed the handle for 5 s while holding it vertical at seven discrete, equally-spaced wrist locations over the subject's ROM. Visual feedback of the desired and the actual wrist angle was provided on the computer screen (Fig. 1 (b)) as a radial line. The angle of the line corresponded to wrist angle, and the length of the line was proportional to grip force magnitude. Two trials were conducted at each location. The intervals between the trials were 30 s, and the locations were presented in a quasirandom order.

In Test 3 (quasistatic test), subjects performed slow flexion and extension movements that covered their entire ROM. Visual feedback to the subject consisted of two fixed radial lines indicating the extreme wrist positions, a rotating radial line indicating the current wrist position, and a clock indicating elapsed time (Fig. 1 (b)). Each trial consisted of starting at one extreme position and moving the wrist steadily to reach the other extreme position while holding the handle vertical using 'natural' grip force. All valid trials took between 20 and 25 s. Each subject performed 18 trials with 30-s intervals between consecutive trials: three repetitions each of flexion and extension motions with three handle weights (300 g, 500 g, and 700 g). The trials were block randomized for weight, and the block order was randomized across subjects.

Cyclic movement test—For the cyclic movement test, the spirit level was replaced with a thin metal rod (mass 120 g) that extended vertically upwards from the handle. Another vertical metal rod was attached to the lever. The two rods were parallel when the handle was vertical. The subject held the handle using the finger tips and performed wrist flexion-extension motions to the beat of a metronome while keeping the metal rods parallel, i.e. keeping the handle vertical. Each subject performed eighteen trials: two repetitions at each frequency (0.75 Hz, 1 Hz and 1.25 Hz) with three handle weights (300 g, 500 g and 700 g, reported excluding the metal rod's weight). The lowest frequency, selected based on pilot tests, allowed subjects to produce smooth cyclical wrist movements. The highest frequency and handle weight were selected such that the subjects could move the handle without slip and without significantly reducing their range of motion. Each trial lasted 15 s, and any trial where excessive deviation from the vertical was visually observed was repeated ($\sim 30^\circ$, as indicated by subsequent data analysis). The trials were block randomized for weight, and the blocks were randomized across subjects.

Data analysis

All data were collected at 1000 Hz. They were low-pass filtered at a cutoff frequency of 5 Hz using a fourth-order, zero-lag Butterworth filter.

Data analysis for the quasistatic test—The maximum grip force recorded during the two trials at each of the seven discrete wrist locations (static MVC test, Test 2) were used to describe the grip strength vs. wrist angle relation using a quadratic fit. The grip force during the quasistatic task (Test 3), the minimum of the TH and VF normal forces, was computed for each task and sampled at five locations: (1) location of maximum grip strength, (2) midway between position (1) and maximum flexion, (3) midway between position (1) and maximum extension, (4) maximum flexion, and (5) maximum extension. These values were subjected to 3-way repeated measures ANOVA with factors POSITION (5 levels), DIRECTION (flexion-extension) and WEIGHT (300 g, 500 g, 700 g). Data were pooled across subjects.

Data analysis for the cyclic movement test—The cyclic movement data analysis was conducted in two steps. First, we used Newton's second law of motion to estimate some of the handle's kinematic variables. Then, we computed the grip force (minimum of the TH and VF normal forces) and studied its variation with wrist kinematics via a linear regression model.

Three kinematic parameters, namely, the magnitude of vector $\mathbf{r}$ locating the handle CG relative to the wrist center, the angle β measuring the tilt of the handle from the vertical and the angle θ between the TH/VF normal force line of action and the vector $\mathbf{r}$ (Fig. 2) were not measured in this experiment. These parameters were assumed to be constant during individual flexion and extension *half-cycles*, based on visual inspection of the subjects' movements. Appendix 1 provides details of an algorithm used to estimate these variables, and its main features are as follows. Fig. 2 shows three coordinate frames located at the handle CG. Of primary interest is the frame defined by unit vectors $\hat{\mathbf{e}}_{x'} - \hat{\mathbf{e}}_{y'} - \hat{\mathbf{e}}_{z'}$ attached to the subject's palm. For computational purposes, the palm is assumed to always remain vertical, so that $\hat{\mathbf{e}}_{x'}$ is always vertical. The analysis is focused along $\hat{\mathbf{e}}_{z'}$, since grip force is exerted in this direction. The kinematic parameters were estimated by minimizing the squared error in the time series of the left- and right-hand-sides of the equation

$$\sum F_{z'} = mass \times a_{z'}$$
 Next, from all the half-cycles available for analysis (between 200 and 235 movements for flexion and extension for each subject), those with handle tilt less than 30° were selected for further analysis. The number of selected half-cycles varied from 133 to

227 across subjects and movement type (flexion and extension). Apart from one condition for subject 1 (0.75 Hz with 500 g weight in flexion) that had only one valid half-cycle, all other subjects and conditions had at least 5 valid movement half-cycles available for further analysis.

For each selected half-cycle, the *effective normal acceleration* along $\widehat{e}_z'$ and the acceleration along $\widehat{e}_y'$ were computed as,

$$A_{z'} := r\alpha\sin\theta + r\omega^2\cos\theta - b, \quad (1)$$

$$a_{y'} = -r\alpha\cos\theta + r\omega^2\sin\theta, \quad (2)$$

where ω and α are the wrist angular velocity and angular acceleration, respectively, obtained by differentiating the wrist angle φ (potentiometer reading). Note that the angle between the lever and the vector $\mathbf{r}$ (Fig. 2) is assumed constant. The parameter b represents the contribution of the net finger force along $\widehat{e}_x$ to the acceleration of the handle along $\widehat{e}_z'$ (see Appendix 1). The acceleration of the handle that would have resulted from the $\widehat{e}_z'$ component of the net normal force alone is $A_{z'}$. Furthermore, the *effective normal forces* for the VF and TH are defined as the components of the normal forces along $\widehat{e}_z'$:

$$F_{z'}^{TH} := F_z^{TH}\cos\beta, \quad (3)$$

$$F_{z'}^{VF} := F_z^{VF}\cos\beta. \quad (4)$$

A linear regression model was fitted to the mean traces of the effective acceleration, acceleration along $\widehat{e}_y'$ and effective normal forces computed separately for flexion and extension, for each frequency-weight combination and for each subject:

$$F_{z'} = \pm F_r + F_t \pm F_{BG},$$

$$F_{z'}^{TH} = -km|a_{y'}| + Cm A_{z'} - D, \quad (5)$$

$$F_{z'}^{VF} = km|a_{y'}| + (1 - C)m A_{z'} + D. \quad (6)$$

Note that Equations 5 and 6 individually do not represent the dynamic equations of motion since the coefficients k , C and D are under neural control. The model is designed to understand the elements that contribute to the generation of the TH and VF normal forces. Based on the work of Slota et al., 2011, who developed a similar model for manipulation of grasped objects using the whole arm and with a (mostly) rigid wrist, we surmise that the normal forces of the TH and VF reflect the additive effects of

1. F_r proportional to the radial acceleration of the object $a_{y'}$ which acts as an external load,

2. F_b proportional to the tangential acceleration of the object A_z' . The net (effective) normal force produces acceleration A_z' , and the grip force component CmA_z' is assumed to be proportional to the tangential acceleration.
3. $F_{BG} = D$, the base grasping force estimated as the average force for holding the object. It is the constant term in Equations 5 and 6.

The acceleration in the radial direction must be countered by friction to avoid object slip. Therefore, the first term in the model F_r is proportional to the radial acceleration and it accounts for the required radial frictional force.

The acceleration along $\hat{e}_z'$ is achieved by the normal forces, and adding Equations 5 and 6 yields the equation of motion in the $\hat{e}_z'$ direction. The multipliers C and $1 - C$ adjust the ratio of the TH and VF contributions to the force changes that accompany movement along $\hat{e}_z'$.

The last term in the model F_{BG} (coefficient D) is a constant that reflects the summed effects of the static and the stato-dynamic fractions (Zatsiorsky et al., 2010) of the grasping force. The static fraction represents the basic grip force required to hold the object without slipping, and it accounts for the object's weight. The stato-dynamic fraction is an additional internal force that increases the grip force and allows a safe range of force oscillation due to the dynamic fraction, which is represented by the first two terms of the model.

The quality of the regression was assessed by computing the correlation, the RMS error normalized by the mean of the absolute value of the corresponding effective normal force, and the variability accounted for (VAF) by the fit as

$$VAF = \left(1 - \sum \frac{[actual(t) - predicted(t)]^2}{actual(t)^2} \right) \times 100.$$

The grip force mean value and amplitude and the model coefficients were analyzed with a 3-way repeated measures ANOVA with factors WEIGHT (300 g, 500 g, 700 g), FREQUENCY (0.75 Hz, 1.0 Hz, 1.25 Hz) and DIRECTION (flexion, extension). Data were pooled across subjects. Post-hoc analysis was conducted when necessary using pairwise comparisons with Bonferroni corrections.

All statistics for the quasistatic and the dynamic tests were performed with SPSS statistical software using α -level of 0.05. Mauchly's sphericity tests were performed to verify the validity of using repeated measures ANOVA. The Greenhouse-Geisser adjustment to the degrees of freedom was applied whenever departure from sphericity was observed.

Results

Grip force in static and quasistatic tests

In the static MVC test, the grip strength showed an inverted 'U'-shaped variation across wrist angles with the highest grip strength occurring when the wrist was slightly extended. Also, the grip strength at the extreme flexion position was smaller than that at the extreme extension position for all subjects. A quadratic function was fitted to the grip strength vs. wrist angle relation. Fig. 3. shows the discrete maximal grip force measurements at seven wrist angles and the quadratic fit to the data. The R^2 values for the fits ranged from 0.7 to 0.98, with a median value of 0.91. The maximum of the quadratic functions occurred at wrist angles ranging from 0.5° to 50° in extension, with a median value of 16.5°.

The movements during the quasistatic test (Test 3) were justifiably quasistatic (average wrist angular velocity less than 10 °/s). The grip force during this task remained approximately constant over most of the range of the wrist angle. Fig. 3 shows the mean $\pm$ standard deviation (SD) of the grip force for each handle weight for extension and flexion. The negative of the grip force during flexion is plotted for clarity. Data are for a representative subject. The 3-way ANOVA on the grip force showed significant effect of WEIGHT ($F_{(2,16)} = 59.15$; $p < 0.01$) and POSITION ($F_{(4,32)} = 6.72$; $p < 0.05$). The effect of DIRECTION was not significant ($F_{(1,8)} = 0.80$; $p = 0.39$). Post-hoc analysis revealed that higher handle WEIGHT always elicited higher grip force and the effect of POSITION on grip force was significant for 'flexion' - 'maximum flexion' position pair. This was true for flexion movement only, which was reflected in a significant interaction POSITION $\times$ DIRECTION ($F_{(4,32)} = 6.97$; $p < 0.01$). Finally, the increase in grip force from the 500 g to 700 g weight was steeper from 'flexion' to 'maximum flexion' positions than for all other pairs. This was reflected in the significant interaction POSITION $\times$ WEIGHT ($F_{(8,64)} = 2.19$; $p < 0.05$).

Cyclic movement test

The results of the cyclic movement study are described in two parts: (a) characterization of the measured grip force and (b) the correspondence between the actual normal forces and those predicted by the regression model (model validation).

The subjects reproduced the prescribed frequencies well: the measured frequencies were (mean $\pm$ SD) 0.75 ± 0.04 Hz, 1.00 ± 0.04 Hz, and 1.24 ± 0.04 Hz. The subjects moved the handle significantly faster at higher frequencies, and consequently, higher radial and tangential accelerations were induced. A detailed statistical analysis of the movement kinematics is provided as supplementary material to this paper (available online).

Grip force—Two patterns of grip force variation with wrist angle were observed across subjects. The most common grip force pattern was a figure-8 shape, with the maximum grip force within a flexion or extension cycle occurring towards the end of that movement cycle. This pattern is illustrated in the left panel of Fig. 4. The data for the 1.0 Hz and 1.25 Hz movements are rotated by 120° and 240°, respectively, for better visualization. For some subjects, the grip force during extension remained greater than that during flexion, and then the grip-force curve resembled a bent oval. This pattern is shown in the right panel of Fig. 4.

The mean grip force for 1.25 Hz was significantly greater than that for the 0.75 Hz FREQUENCY ($F_{(2,14)} = 12.34$; $p < 0.01$), and it always increased with WEIGHT ($F_{(2,14)} = 40.97$; $p < 0.01$). There were also significant interactions FREQUENCY $\times$ WEIGHT ($F_{(4,28)} = 7.23$; $p < 0.01$) and FREQUENCY $\times$ DIRECTION ($F_{(2,14)} = 8.57$; $p < 0.05$). The first interaction reflects the fact that the increase in mean grip force with FREQUENCY was more pronounced for higher weight. The second interaction appears because the increase in the mean grip force with FREQUENCY was greater for flexion half cycles than the extension half cycles. The amplitude of the grip force also always increased with WEIGHT ($F_{(2,14)} = 9.87$; $p < 0.01$), and it was significantly higher for flexion than extension movements ($F_{(1,7)} = 8.79$; $p < 0.05$). There were no significant INTERACTION effects.

Regression model—The regression model successfully approximated the time course of the averaged effective normal force of TH and VF. Fig. 5 shows the boxplots of the normalized RMS errors, the correlations, and the VAF values for the model. The RMS errors of the fits were less than 7% of the mean effective normal force. The correlation between the regression result and data was greater than 0.99, and the model accounted for more than 99% of the variance in the data. Additional validation for the model is provided in Appendix 2.

Once the coefficients of the model were determined, the model predicted the time course of the effective normal forces of the TH and the VF given the object accelerations. Fig. 6 shows the measured and model-predicted time series for one frequency-weight combination for one subject. The grip force, which is the minimum of the TH and VF normal forces, is also predicted with high fidelity.

Confidence intervals on the regression coefficients suggested that the coefficients were significantly different from zero. In Fig. 7, each box plot displays coefficient values for the nine frequency-weight combinations for one subject. Coefficients C and D are mostly positive, and the coefficient k assumes positive as well as negative values. In 24 (twelve flexion-extension pairs) out of 144 cases (8 subjects $\times$ 2 directions $\times$ 9 frequency-weight combinations) the coefficient k was not significantly different from zero, perhaps because the amplitude of a_y' was low compared to that of A_z' (see Supplementary material).

The model coefficients k , C and D were affected by task parameters. The coefficient k was significantly affected only by the interaction DIRECTION $\times$ FREQUENCY ($F_{(2,14)} = 4.61$; $p < 0.05$). The interaction reflects the fact that the change in the mean k value with FREQUENCY shows opposite trends for flexion and extension half cycles. The coefficient C was significantly affected by DIRECTION ($F_{(1,7)} = 13.06$; $p < 0.01$), with a higher mean value for flexion movement. The coefficient value decreased with WEIGHT and FREQUENCY, and the effects were close to significance: FREQUENCY ($F_{(2,14)} = 2.95$; $p = 0.085$), WEIGHT ($F_{(2,14)} = 3.31$; $p = 0.07$). There were no INTERACTION effects. Finally, the coefficient D increased significantly with FREQUENCY ($F_{(2,14)} = 12.41$; $p < 0.01$) for the 0.75-1.0 Hz and 0.75-1.25 Hz pairs, and WEIGHT ($F_{(2,14)} = 29.14$; $p < 0.01$) for the 300-500 g and 300 – 700 g pairs. The DIRECTION effect was close to significance ($F_{(1,7)} = 4.76$; $p = 0.06$), with a higher mean value for flexion movements. There were no INTERACTIONS. The values for the model coefficients suggest the following strategy for movement production. First, the low values for k , coupled with low amplitudes of the radial acceleration a_y' suggest that the component F_r did not play a significant role in the model for some subjects and conditions. Furthermore, whenever k is negative, the normal forces reduce with increase in $|a_y'|$. Next, the C values are mostly between 0 and 1 (Fig. 7). So, the component F_t of normal force acts in the opposite direction of the tangential acceleration for the TH and in the direction of tangential acceleration for VF. This implies that for $A_z' > 0$, the grip force drops by CmA_z' and for $A_z' < 0$, it drops by $(1 - C)mA_z'$. When $C > 1$, the grip force drops by CmA_z' for $A_z' < 0$, and it increases by $(1 - C)mA_z'$ when $A_z' > 0$. The overall strategy of the CNS is to raise the base grasping force D and then generate movement by differentially modulating the TH and VF normal forces. Another reason for increasing D may be to account for the drop in grip strength in extreme wrist positions (Fig. 3). This way, it is ensured that the grip force magnitude always remains greater than that required to avoid slip.

Discussion

The first hypothesis (H1) was that the grip force measured during static holding and/or slow movement (quasistatic task) will vary with wrist angle just as grip strength does. As expected, maximum grip strength occurred at a slightly extended wrist position, and it decreased with wrist flexion and extension. However, constant grip force was observed across all wrist positions barring one. Our data thus refutes hypothesis H1. Wrist position affects the FDP muscle length, the primary contributor to grip force production (Platzer, 2004), and the drop in grip strength with wrist angle modulation follows from the shape of the classical isometric force-length curve (Zatsiorsky & Prilutsky, 2012). In contrast, no major modulation of grip force was observed during slow wrist motion with the hand-held

object gripped naturally. The only exception was that during flexion movement, the grip force increased as the wrist approached the extreme flexion position.

The second hypothesis (H2) on the predictability of grip force from wrist kinematics was based on an earlier regression model (Slota et al., 2011) predicting grip force modulation. The model handled the data in this experiment successfully. Further, we interpret the results within two theoretical paradigms on the neural control of movement: the referent-configuration hypothesis and the idea of control with internal models. This choice is based on our personal understanding of the current state of the field of motor control.

Grip force and wrist position coupling: interpretation within the referent configuration hypothesis

The constancy of grip force magnitude with wrist FE position can be interpreted within the referent configuration (RC) hypothesis (Feldman & Levin, 1996; Feldman, 2011) which is a recent development of the classical equilibrium-point hypothesis (Feldman, 1986) to multi-effector actions. The RC hypothesis assumes that the central nervous system uses changes in neural variables that, given the external force field, produce changes in the body (effector) referent configuration. Referent configurations are commonly not accessible to the effector because of anatomical and external constraints. As a result, equilibrium states are observed with non-zero muscle activations and active forces produced on the environment.

According to the referent-configuration hypothesis (Pilon et al., 2007), to produce grip force, the central controller specifies a referent aperture (distance between the tips of opposing digits, TH and VF in our case) that is smaller than the object-shape-dependent actual aperture. Grip forces emerge as the muscles are activated in proportion to the difference between the referent configuration and actual configuration. Grip-force modulation is then a matter of modulating the referent aperture. Furthermore, the relation between the force generated by a finger and its referent position depends on the force-length characteristic (a stiffness-like property termed “apparent stiffness”, see Latash & Zatsiorsky, 1993 for a discussion). This mode of control has been shown to lead to co-adjustments of the TH and VF normal forces addressed as grip-stabilizing synergies (Latash et al., 2005; Latash, 2010).

The lack of dependence of the grip force on wrist position is not a trivial finding. Note that, for a given distance between the referent and actual configurations, moving the wrist into flexion (extension) is expected to benefit force production by the extensors (flexors) as compared to their antagonists. The lack of changes in the grip force suggests that referent coordinates for the flexors and extensors are modified independently, and that this process cannot be reduced to manipulation of a single variable such as the referent aperture. This interpretation is compatible with the idea that grasping an object can be described as two independent pointing actions of the opposing digits, not a single change in the hand aperture (Smeets & Brenner, 1999).

The increase in grip force as the wrist approached extreme flexion during flexion movements was an exceptional observation. It suggests that the sub-maximal grip force during the quasistatic movements depends on the wrist position when the object is first grasped. A possible explanation is that approaching extreme wrist flexion is an unusual condition in which some physiological constraints may interfere with any control strategy employed by the motor system. For example, in order to generate a constant grip force close to extreme wrist flexion - an inefficient place on the length-tension curves of the extrinsic flexors - the firing rates of already recruited motor units may be increased, and larger units may be recruited (recall that digit flexors assist in wrist flexion as well). So rather than being an emergent property of a control strategy, rising grip force may have another origin, and it

is ignored at some level unless its effect is large enough to affect the task, demand too much energy, damage the object/hand, etc. This phenomenon deserves further investigation.

Predicting internal (grip) forces from movement kinematics

The grip force is an internal force: the force that does not perturb the movement kinematics (performers can grasp the object weaker or stronger without affecting the movement kinematics). Hence, its magnitude—provided that the magnitude exceeds the slipping threshold—cannot be determined from the kinematics alone. The determination of the internal force is a motor control and not a biomechanics problem. So, the demonstrated ability to predict the grip force from the movement kinematics is a non-trivial phenomenon suggesting that the apparently free grip force is modulated by performers based on the kinematics in a reproducible fashion: performers choose a grip force pattern that can be described with a simple mechanical model. The pattern is still however a matter of choice made by the central controller.

Inverse dynamic models predict the forces and moments required to produce observed kinematics of a dynamical system. As per one opinion in the motor control community, the human central nervous system employs internal inverse dynamic models to specify muscle forces required to execute intentional movement (Ambike & Schmiedeler, 2013; Hollerbach, 1982). Within this paradigm, grip-force-load-force coupling during arm movement is explained by positing that an efference copy of the inverse dynamic model output is utilized to predict the additional inertial load on the hand-held object, thus allowing anticipatory grip force adjustment (Kawato, 1999). This normative explanation, however, cannot predict the magnitude of grip-force change. The problem of predicting grip force cannot be reduced to the inverse dynamic problem since any grip force larger than the minimum required to prevent object slip is a valid solution, and internal-models-based explanations of motor behavior do not address this issue.

The model offered in this paper predicts the grip force from movement kinematics. Furthermore, in contrast to existing theories on grip control, it views grip force as an emergent phenomenon rather than a directly controlled quantity. In general, the TH and VF force magnitudes during object manipulation are different. Therefore, the model assumes that the commands to the digits are different (due to the coefficients C and $1 - C$ in Equations 5 and 6), and grip force is the consequence of the digit forces, object acceleration, and the passive mechanical properties of the digits and digit joints. The grip-force-load-force coupling can be viewed as a consequence of feed-forward adjustments of the digit commands.

It can be surmised that the observed pattern of the grip force changes during the wrist movements follows some optimization principles. (Although, there may be phenomena, e.g. rising grip force at the extreme wrist flexion in quasistatic conditions, that might originate from sources other than optimality.) The optimization approach to motor control assumes that the organization of human movement follows from the minimization of some perceived cost of the movement and provides a resolution of redundancy problems in motor control (Prilutsky & Zatsiorsky, 2002; Todorov & Jordan, 2002). Presumably, the movements in this study were also optimal, and the central controller could have chosen the values for the model coefficients k , C and D that minimize some cost. However, we have not addressed this issue.

The regression model and its interpretation

Wrist FE movement causes object rotation about the vertical axis passing through the wrist (assume zero handle tilt for simplicity). This feature of the present experiment was absent

from the study of Slota et al., 2011. The object's angular acceleration is caused by the moments of the finger forces in the $\hat{e}_y$ and the $\hat{e}_z$ directions. The finger normal forces cause object rotation when their lines of action do not pass through the object's center of gravity. Similar to the finger forces, there can exist: (1) *internal moment* which does not affect object equilibrium, and (2) *manipulation moment* which causes the object's angular acceleration (Gao et al., 2005). This paper does not study the internal moment. The success of the regression model suggests that the grip force is independent of object rotation, and can be predicted from the translational kinematics even in the presence of significant manipulation moment.

The constant D in the model has been interpreted by Slota et al., 2011 as the base grip force, to which forces proportional to kinematic terms are added. We explored the dependence of D on movement frequency and added load. Given the relatively few conditions, the results of this analysis should be viewed as pilot. A linear increase in D with movement frequency was observed for each of the loads; the coefficients of determination (R^2) range between 0.59 and 0.97. D also increased with the load. However, the linear dependences of D on frequency did not show a consistent intercept that could be interpreted as a reflection of a "base force" grasping the object in static conditions; the intercept varied nearly two-fold, from 4.2 to 7.0 N. Hence, the results do not allow a simple interpretation of the coefficient D .

The model is based on the hypothesis that the effect of efferent commands can be represented as the additive effect of three model elements –parallel manipulation component, orthogonal manipulation component and base grasping force. The parallel and orthogonal manipulation components were represented as radial and tangential accelerations, respectively, and the observed good correspondence between the model predictions and the actual results support the hypothesis. While the model coefficients (k , C , D) are found through curve fitting, once they are set, the model predicts the time history of the force changes quite well. The changes in the coefficients are then dependent on the task conditions.

One of the advantages of using multi-finger prehension as an object of motor control research is the opportunity to broadly vary the task conditions. In several studies, it was observed that the combined effect of varying two factors was essentially the sum of individual effects. This effect was observed, for example, when simultaneously varying supported load and resisted torque (Zatsiorsky et al., 2002a; Zatsiorsky et al., 2002b), and handle orientation (Pataky et al., 2004a, 2004b). The observed effects agreed with the *principle of superposition* according to which some complex actions, e.g., prehension, can be decomposed into elemental actions controlled independently (Zatsiorsky & Latash, 2004). It was surmised that additivity of the command effects, as well as the principle of superposition, are general phenomena of motor coordination, which are manifested in many motor tasks. Recently, Slota et al., 2011 showed the applicability of this principle to grip force patterns during whole-arm movements, and the present study extend that finding to movements involving object rotation and significant changes in the lengths of the grip-force producing muscles.

In the end, we acknowledge the limitations of the present study: (1) no measurement of the handle kinematics, (2) limited range of loads and frequencies of motion, (3) no analysis of internal moment production, (4) no muscle electromyographic measurements, and (5) analysis of only self-induced movements. We plan to resolve these limitations in the future.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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APPENDIX 1

Estimation of unmeasured kinematic variables using Newton's second law

Fig. 2 depicts three coordinate frames located at the handle's CG. The first frame $\{\widehat{e}_x - \widehat{e}_y - \widehat{e}_z\}$ is fixed to the handle. The second frame $\{\widehat{e}_r - \widehat{e}_t - \widehat{e}_{x'}\}$ is attached to the lever of the support mechanism. Along the lever is the vector $\widehat{e}_r$, $\widehat{e}_{x'}$ points vertically upwards, and $\widehat{e}_t$ is perpendicular to both $\widehat{e}_r$ and $\widehat{e}_{x'}$. The third frame $\{\widehat{e}_{x'} - \widehat{e}_{y'} - \widehat{e}_{z'}\}$ is attached to the palm. The unit vector $\widehat{e}_{x'}$ is common to the palm-fixed and lever-fixed frames. Any tilt of the handle is assumed to be due to variable finger configuration, and the palm maintains its vertical orientation. Also, the angle between the lever and vector $\mathbf{r}$ is assumed to be constant, so that the angular velocity and acceleration of the lever and the hand are equal.

The handle tilt was fairly constant during majority of the movement away from extreme wrist flexion and extension positions. Therefore, the portions of a half-cycle wherein the angular velocity was below 10% of the peak angular velocity during that half-cycle were excluded from this analysis. To confirm these observations, we repeated the cyclic movement test at all weight and frequency levels and measured the handle kinematics for one subject using a vision tracking system (Qualisys Motion Capture Systems). During these trials, the maximum variations in the parameters θ , β and r (the magnitude of vector $\mathbf{r}$) were 10.6° , 5.2° and 7.2 mm, respectively, and the vertical displacement of the CG was 8.5 ± 2.1 mm. The parameters r , θ and β for each movement half-cycle are assumed as constant, and the vertical movement of the handle was assumed considered insignificant.

The inertial forces acting on the handle in the lever-fixed frame are,

$$\bar{F}_{rad} = mrw^2 \widehat{e}_r, \quad (7)$$

$$\bar{F}_{tang} = mr\alpha \widehat{e}_t, \quad (8)$$

where m is mass of the handle. These forces are transformed into the palm-fixed frame. The finger forces measured by the sensors in their respective coordinate frames are also transformed into the palm-fixed frame. Then, the equation of motion along the $\widehat{e}_{z'}$ direction is written as

$$(F_z^{TH} + F_z^{VF}) \cos \beta - (F_x^{TH} + F_x^{VF}) \sin \beta = F_{tang} \sin \theta + F_{rad} \cos \theta,$$

$$(F_z^{TH} + F_z^{VF}) \cos \beta - (F_x^{TH} + F_x^{VF}) \sin \beta = mr(\alpha \sin \theta + w^2 \cos \theta), \quad (9)$$

where F_i^{TH} is the force along direction i for the thumb, and F_i^{VF} is the sum of the forces along direction i measured by the other four finger sensors, both expressed in the handle frame.

Next, a non-linear, constrained optimization routine (MATLAB function `fmincon`) was utilized to minimize the squared error between the left and the right hand sides of Equation 9 summed over all time instants t :

$$\min J := \sum_t \left[\left(F_{z_t}^{TH} + F_{z_t}^{VF} \right) a + mb - (m\alpha_t) r \sin\theta - (m\omega_t^2) r \cos\theta \right]^2,$$

subject to

$$0.86 \leq a \leq 1,$$

$$-\infty \leq b \leq \infty,$$

$$r_0 - 0.03 \leq r \leq r_0 + 0.03,$$

$$0 \leq \theta \leq \pi,$$

where r_0 is the radial distance (meters) from the wrist center to the handle CG measured in a static pose before the start of the cyclic movement trials for each subject. The constraints on r take into account the physically possible change in finger configuration that would change its value. The parameter a represents the term $\cos \beta$ in Equation 9, and it is constrained such that β lies between zero and 30 degrees. The parameter b represents the contribution of the net finger force along $\hat{e}_x$ to the acceleration of the handle along $\hat{e}_z$.

The optimization yielded values for the parameters a , b , r and θ , which were then used to compute the left and the right hand sides of Equation 9 for each movement half-cycle. These two time series were used to compute the RMS error normalized by the mean of the absolute value of the net finger force along $\hat{e}_z$ and the correlation between the two series. The movement cycles with correlation greater than 0.9 and normalized RMS error less than 0.25 were selected for further analysis. This procedure effectively rejects the movement half cycles that have excessive handle tilt.

APPENDIX 2

Additional validation fo the regression model

We followed a two-step analysis for further validation of the regression model (see Equations 5 and 6). First, 67% of the movement half cycles available for each task condition (frequency and weight) were chosen at random and the model parameters were obtained via regression. Next, the predictive ability of the model was tested on the remaining 33% of the half cycles. The accelerations a'_y and A'_z for these tests were inputs to the model, and the forces output by the model, $F_{z'}^{TH}$ and $F_{z'}^{VF}$, were compared with the measured forces by

computing the normalized RMS error, the correlation coefficient and the VAF for the time series.

Fig. 8 shows the histograms of the three metrics used to compare the predicted and the measured force time series. The figure combines data for all movement half cycles for all subjects (114 movement half cycles in all). The normalized RMS error is less than 10 % for 68 half cycles, the correlation coefficient is greater than 0.98 for all half cycles, and VAF is greater than 85%, for 110 half cycles. The model successfully predicts the TH and VF normal forces from task kinematics.

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Fig. 1.
 (a) Instrumented handle with 5 six-component force sensors. (b) Visual feedback provided for the quasistatic test

Fig. 2.

All coordinate frames are located at the handle CG. Each figure shows two of the three axes of each coordinate frame. Fig. (a) shows the handle viewed from the top. It assumes that the handle is vertical and shows frame $\hat{e}_r - \hat{e}_t - \hat{e}_z$ attached to the lever r , the frame $\hat{e}_x - \hat{e}_y - \hat{e}_z$ attached to the handle, and the frame $\hat{e}_x' - \hat{e}_y' - \hat{e}_z'$ attached to the palm. The wrist-joint angle is ϕ , and θ is the angle between vectors $\hat{e}_z'$ and $\hat{e}_r$. Fig. (b) shows a side view of the handle, and the x axes of the frames appear in this figure. The angle between the handle-fixed frame and the palm-fixed frame is β , and it measures the tilt of the handle from the vertical.

Fig. 3. Grip MVC force and the grip force is plotted against wrist angle for flexion and extension quasistatic movements for a representative subject. The grip strength characteristic is a quadratic function fit to the maximal grip force vs. wrist angle data. The mean $\pm$ SD of the grip force is plotted for each handle weight. The negative of the grip force during wrist flexion is plotted for clarity

Fig. 4.

The most commonly observed distributions of the grip force across wrist angles. The force (N) is plotted in the radial direction. Flexion movement is counter-clockwise. The data for 0.75 Hz, 1.0 Hz and 1.25 Hz are rotated by 0°, 120° and 240°, respectively. For each frequency, 0° corresponds to wrist position with the palm and forearm aligned. The left plot is for subject 7, and the right plot is for subject 2

Fig. 5. Diagnostics for the regression model for all subjects are displayed. The RMS error is normalized by the mean of the absolute value of the corresponding effective normal force. Each boxplot contains metric values for the subject's nine frequency-weight combinations

Fig. 6.

Example of the experimental data and the regression model predictions of the TH and VF effective normal forces and the grip forces for one cycle. Data are for Subject 8, frequency 1 Hz and weight 700 g. For the effective normal forces, the light thick curve and the light shaded band represent mean and SD. The dark thick curve is the corresponding model prediction. The grip forces are displaced vertically towards the center of the figure to enhance visualization. The vertical centerline corresponds to extreme extension for the flexion movement (left part of the plot) and extreme flexion for the extension movement (right part of the plot)

Fig. 7. Boxplots of the coefficients for the regression model are shown. Each box displays data for the nine frequency-weight combinations

Fig. 8. Histograms of the various metrics used to quantify the predictive power of the regression model are shown. The metrics are computed from the time series of the measured forces and those predicted using the regression model. Data is for all subjects