

Human Hand as a Parallel Manipulator

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1. Introduction

When a human hand grasps an object the hand can be viewed as a parallel manipulator. In general, the mathematical analyses of the human hands and multi-fingered robot hands (Murray et al. 1994) are similar. In particular, concepts developed in robotics such as contact models, e.g. soft-finger model, grasp matrix, form and force closure grasps, internal forces, etc. can be applied to analyze the performance of the human hands. Multi-finger prehension is an example of a mechanically redundant task: the same resultant forces on the object can be exerted by different digit forces. People however do not use all the mechanically available options; when different people perform a certain manipulation task they use a limited subset of solutions.

Studies on human prehension deal with four main issues:

1. Description of the behavior: What are the regularities in force patterns applied at the fingertip-object interfaces when people manipulate objects?
2. Are the observed patterns dictated by the task and hand mechanics? The mechanical properties of the hand and fingers are complex, and it is not always evident whether the findings are direct consequences of the mechanical properties of the hand or they are produced by a neural control process.
3. If the observed facts/phenomena are not of mechanical origin are they mechanically necessitated? In other words, can the task be performed successfully in another way?
4. If reproducible phenomena are not mechanical and not mechanically-necessitated, the question arises why the central nervous system (CNS) facilitates these particular phenomena. This is a central question of the problem of motor redundancy in general: Why does the CNS prefer a certain solution over other existing solutions?

The present chapter briefly reviews some specific features of the human hand and the involved control mechanisms. To date, the experimental data are mainly obtained for the so-called *prismatic grasps* in which the thumb opposes the fingers and the contact surfaces are parallel (Figure 1). The contact forces and moments are typically recorded with 6-component force and moment sensors.

Experimental 'inverted-T' handle/beam apparatus commonly used to study the prismatic precision grip. Five six-component force sensors (black rectangles) are used to register individual digit forces. During testing, the suspended load could vary among the trials. The load displacement along the horizontal bar created torques from 0 N·m to 1.5 N·m in both directions. The torques are in the plane of the grasp. While forces in all three directions were recorded the forces in Z direction were very small and, if not mentioned otherwise, were

neglected. When the handle is oriented vertically the force components in the X and Y directions are the *normal* and *shear*, (or *tangential*) forces, respectively. The figure is not drawn to scale.

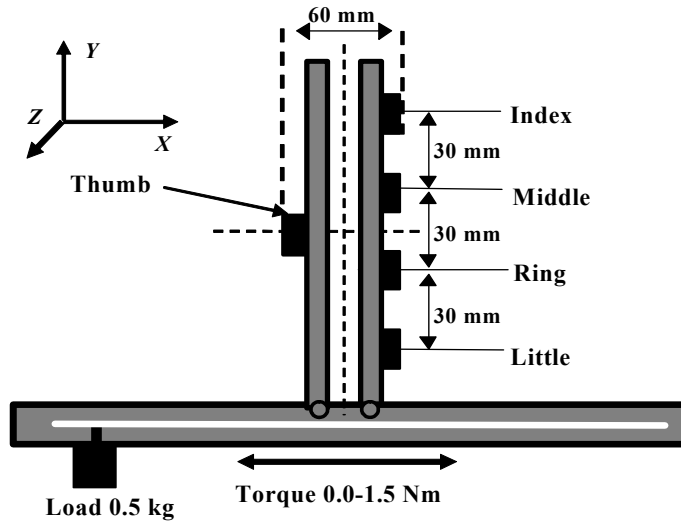


Figure 1. Experimental 'inverted-T' handle/beam apparatus

2. Digit contacts

During an object manipulation the finger tips deform and the contact areas are not constant (Nakazawa et al. 2000; Paré et al. 2002; Serina et al. 1997; Srinivasan, 1989; Srinivasan et al. 1992; Pataky et al. 2005). The fingers can also roll on the sensor surface. As a result, the point of digit force application is not constant: it can displace by up to 5-6 mm for the fingers and up to 11-12 mm for the thumb (Figure 2). Therefore the digit tip contacts should be as a rule treated as the soft-finger contacts (Mason & Salisbury, 1985).

When a soft-finger model of the digit-object contact is employed, the contact is characterized by six variables: three orthogonal force components (the normal force component is uni-directional and the two tangential force components are bi-directional), free moment in the plane of contact, and two coordinates of the point of force application on the sensor. To obtain these data the six-component force and moment sensors are necessary. The coordinates of the point of force application are not recorded directly; they are computed from the values of the normal force and the moment around an axis in the contact plane. Such a computation assumes that the fingers do not stick to the sensor surfaces, in other words the fingers can only push but not pull on the sensors. In such a case the moment of force about the sensor center is due to the application of the resultant force at a certain distance from the center. The displacements of the points of digit force application change the moment arms of the forces that the digits exert on the hand-held object and make the computations more cumbersome.

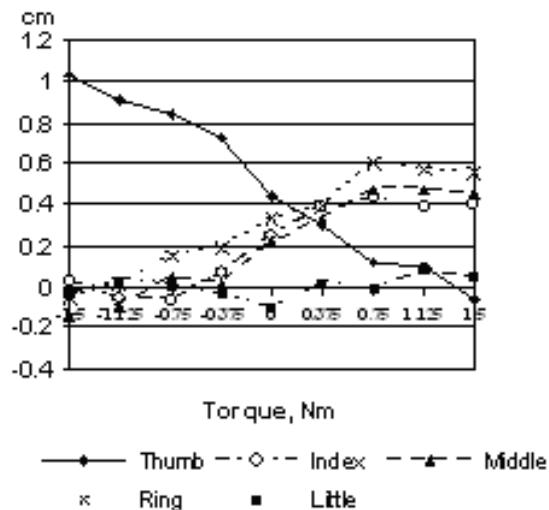


Figure 2. Displacement of the point of application of digit forces in the vertical direction at the various torque levels. The results are for an individual subject (average of ten trials). The positive direction of the torque is counterclockwise (pronation efforts), the negative direction is clockwise (supination efforts). Adapted by permission from V.M. Zatsiorsky, F. Gao, and M.L. Latash. Finger force vectors in multi-finger prehension. *Journal of Biomechanics*, 2003a, 36:1745-1749.

3. Hand asymmetry and hierarchical prehension control

Asymmetry in the hand function is an important feature that differentiates the hand from many parallel manipulators used in engineering as well as from some robotic hands (Fu & Pollard 2006). The functional hand asymmetry is in part due to the hand design (e.g. the thumb opposing other fingers, differences in the capabilities of index and little fingers, etc.) and in part is due to the hand control.

Due to the specific function of the thumb opposing other fingers in grasping, the forces of the four fingers can be reduced to a resultant force and a moment of force. This is equivalent to replacing a set of fingers with a *virtual finger*, VF (Arbib et al. 1985, Iberall 1987; Baud-Bovy & Soechting, 2001). A VF generates the same wrench as a set of actual fingers. There are substantial differences between the forces exerted by individual fingers (IF) and VF forces: (a) The IF force directions are as a rule dissimilar (for a review see Zatsiorsky & Latash 2008) while their resultant (i.e., VF) force is in the desired direction (Gao et al. 2005). (b) VF and IF forces adjust differently to modifications in task conditions (Zatsiorsky et al. 2002a, b). (c) IF forces are much more variable than VF forces (Shim et al. 2005a, b). The desired performance at the VF level is achieved by a synergic co-variation among individual finger forces at the IF level. The above facts support a hypothesis that multi-finger prehension is controlled by a two-level *hierarchical control* scheme (reviewed in Arbib et al. 1985; Mackenzie & Iberall 1994). At the upper level, the required mechanical action on the object is distributed between the thumb and the VF. At the lower level, action of the VF is distributed among individual fingers.

Functional hand asymmetry is also manifested in different responses to perturbations in the supination effort (SE) and pronation effort (PE) tasks. [The anatomical terms supination and pronation refer to the rotation of the forearm and hand along the longitudinal forearm axis in the clockwise and counterclockwise directions, respectively (as seen by the performer).] For instance, when subjects double their initial grasping force whilst maintaining the handle in the air in equilibrium, in the PE tasks the moment of normal forces exerted on the object increases while in the SE tasks it decreases (Figure 3). Such moment changes are not determined by the hand anatomy which is approximately symmetrical about the longitudinal axis of the hand (Li et al. 1998a). The changes in the moments of the normal forces are compensated by equal and opposite moments of the tangential forces such that the total moment exerted on the object does not change.

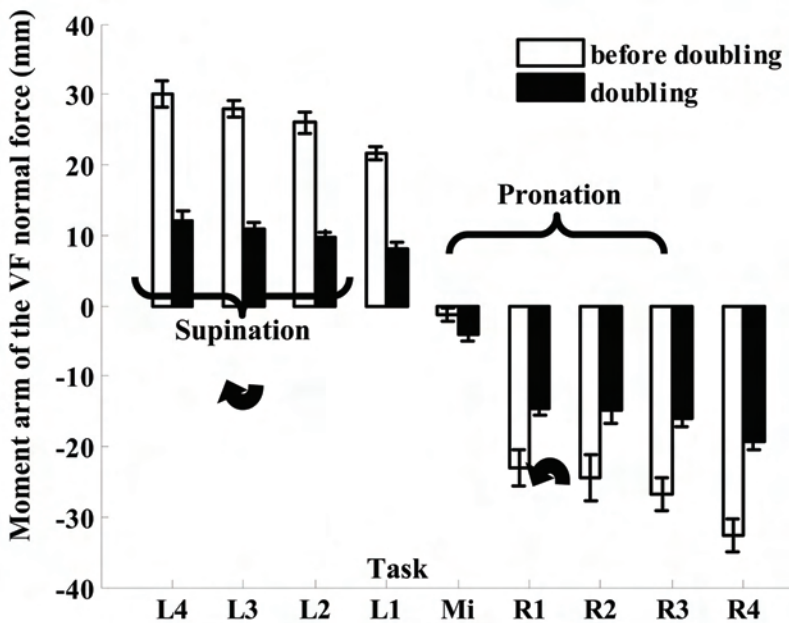


Figure 3. Changes of the moments of the normal forces after the doubling of the grasping force (From an unpublished study by X. Niu, M.L. Latash, V. Zatsiorsky, 2008)

Another example of the functional hand asymmetry in the SE and PE tasks comes from the experiments with transcranial magnetic stimulation (TMS). A single-pulse TMS applied over the hand projection in the left motor cortex (its descending pathways go to the segmental apparatus that controls the right hand) induced different reactions in the SE and PE tasks (Figure 4). Note that the changes in the total moment of force scale with the background moment of force (task moment of force in Figure 4), but supination responses dominate. The reasons behind the asymmetrical hand reactions to the TMS-induced perturbations in the SE and PE tasks are presently unknown.

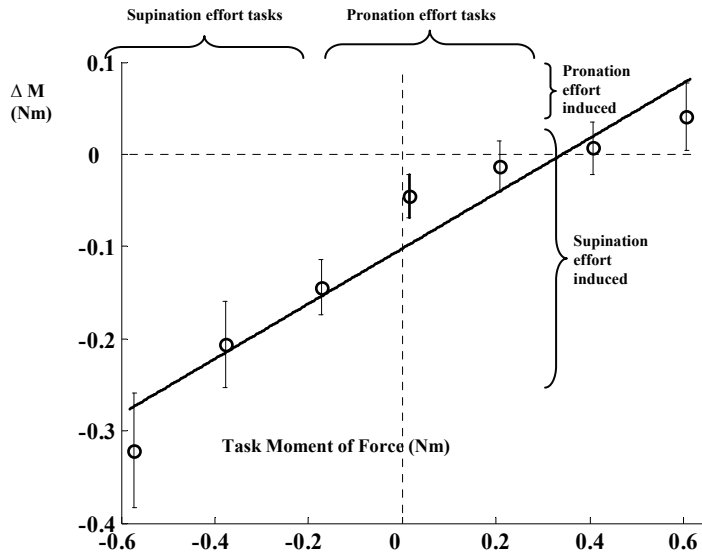


Figure 4. The dependence of the TMS-induced change in the total moment of force on the background moment of force required by the task. The grand average across subjects data ($n=6$) are presented with the linear regression line. (From an unpublished study by X. Niu, M.L. Latash, V. Zatsiorsky, 2008)

4. Finger interdependence and inter-finger connection matrices

In studies on parallel manipulators, the contacts are usually considered independent and identical in their properties. Consequently, all contact points are treated equally. Actions of human fingers are not independent (reviewed in Schieber, Santello, 2004; Zatsiorsky, Latash 2004; 2008). To demonstrate the finger interdependence turn your palm up and wiggle the ring finger. You will see that other fingers also move. This simple demonstration is an example of the so called *finger enslaving*—fingers that are not required to produce any force/motion by instruction are activated (Kilbreath & Gandevia 1994; Li et al. 1998b; Zatsiorsky et al. 2000; Kilbreath et al. 2002). Another type of the finger interdependence is *force deficit*— peak force generated by a finger in a multi-finger maximal voluntary contraction (MVC) task is smaller than its peak force in the single-finger MVC task. The deficit increases with the number of explicitly involved (master) fingers (Li et al. 1998a).

Finger interdependence is commonly described by *inter-finger connection matrices* (IFM) that relate the levels of commands to individual fingers with finger forces via a matrix equation (Zatsiorsky et al. 1998b; Li et al. 2002; Danion et al. 2003; Gao et al. 2003; Latash et al. 2003a):

$$\mathbf{f} = [\mathbf{W}]\mathbf{c} \quad (1)$$

where \mathbf{f} is a (4×1) vector of the normal finger forces, $[\mathbf{W}]$ is a (4×4) inter-finger connection matrix whose elements depend on the number of fingers involved in the task (i.e. they represent both the finger enslaving and force deficit), and \mathbf{c} is a (4×1) vector of *central (neural) commands*, representing by how much the person wants to involve individual

fingers. The elements of vector \mathbf{c} equal 1.0 if the finger is intended to produce maximal force (maximal voluntary activation), they are equal to zero if the finger is not intended to produce force (no voluntary activation). The inter-finger connection matrices can be computed by artificial neural networks based on experimental data involving finger force measurements (Zatsiorsky et al. 1998; Li et al. 2002; Gao et al. 2003, 2004; Latash et al. 2003a) or estimated by simple algebraic equations (Danion et al, 2003). The described approach led to the concept of finger *modes* that are arrays of finger forces caused by a single command to one of the fingers. If matrix $[\mathbf{W}]$ is known and actual finger forces in a prehension task are recorded, the vector of neural commands \mathbf{c} can be reconstructed by inverting equation (1): $\mathbf{c} = [\mathbf{W}]^{-1}\mathbf{f}$ (Zatsiorsky et al. 2002b). Matrix $[\mathbf{W}]$ is 4×4 and is always invertible.

When the vector \mathbf{c} is reconstructed, forces generated by individual fingers can be decomposed into components that are due to (a) direct commands to the targeted fingers, and (b) the enslaving effects, i.e. the commands sent to other fingers (Figure 5).

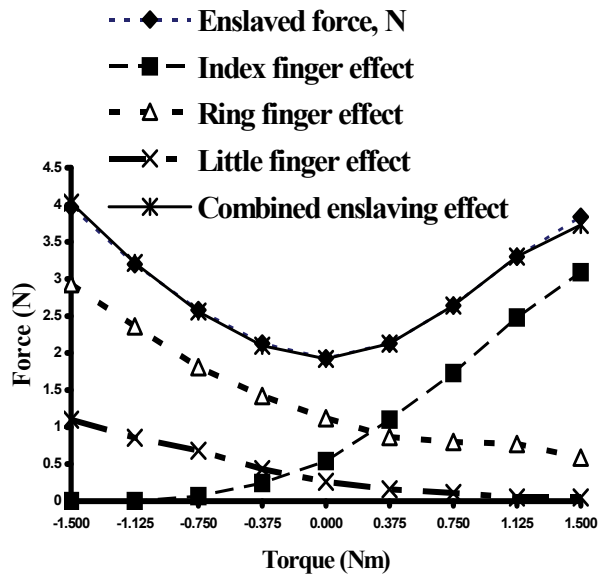


Figure 5. Decomposition of the normal force of the middle finger during holding a 2.0 kg load at different external torques. The data are from a representative subject. (Adapted from V.M. Zatsiorsky, R.W. Gregory, and M.L. Latash. (2002b) Force and torque production in static multifinger prehension. II. Control. *Biological Cybernetics*, 87: 40-49.)

5. Agonist and antagonist fingers

In multi-finger grasps, the finger forces generate the moments of force with respect to the thumb as a pivot. The fingers that are located above and below the thumb, for instance the index and the little fingers, generate moments in opposite directions (Li et al. 1998a, b). Moments in a desired direction – those that resist the external torque – have been termed the *agonist moments* while moments in the opposite direction – assisting the external torque – have been termed *antagonist moments* (Zatsiorsky et al. 2002a, b). The fingers that

generate agonist and antagonist moments with respect to a given task (external torque) are commonly addressed as the *agonist* and *antagonist fingers*, respectively.

Activation of the antagonist fingers increases the energy expenditure and can be mechanically unnecessary. Patterns of the antagonist moments depend on the load/torque combinations and can be described using a *3-zone model*, Zatsiorsky et al. 2002a): (A) *Large load-small torque* combinations. The antagonist fingers should be activated to prevent object slipping from the hand. In such tasks the antagonist moments are mechanically necessary. (B) *Intermediate load-intermediate torque* combinations. To prevent slipping, a performer has two options: (a) exert larger force by the agonist 'central' (middle or ring) finger while simultaneously decreasing the force of the agonist 'peripheral' (index or little) finger such that the VF normal force is above the slipping threshold, or (b) activate the antagonist fingers. (C) *Small load-large torque* combination. In such tasks, there is no need for the performer to be concerned about the object slipping from the hand because the force exerted by the agonist fingers is sufficient for the slip prevention. In this zone, antagonist moments are not mechanically necessary. They were however observed in all the tasks (Figure 6). One of the mechanisms causing the antagonist moments is enslaving; antagonist fingers are activated because strong commands are sent to the agonist fingers and the antagonist fingers are enslaved by these commands.

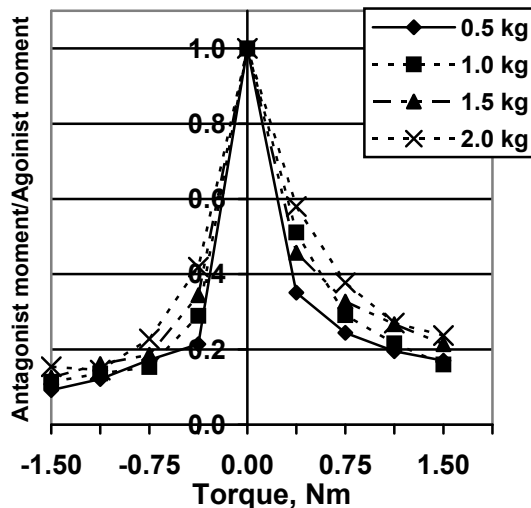


Figure 6. 'Antagonist/agonist moment' ratio in different tasks. Among the tasks, the load varied from 0.5 to 2.0 kg and the torque values were from -1.5 Nm to 1.5 Nm. The ratio for the zero torque conditions was estimated from the equilibrium requirements under the assumption that the normal forces of the two pairs of agonist and antagonist fingers were equal. Antagonist moments were observed over the entire range of load-torque combinations. (Adapted from V.M. Zatsiorsky, R.W.Gregory, and M.L.Latash. Force and torque production in static multifinger prehension: biomechanics and control. I. Biomechanics. *Biological Cybernetics*, 2002, 87:50-57.)

6. Grasp equation

The force-moment transformations from the digit tips to the hand-held object can be described with a *grasp equation*

$$\mathbf{F}=\mathbf{G}\mathbf{f} \quad (2)$$

For a planar task (see Figure 1), \mathbf{F} is a (3×1) vector of the resultant force and moment acting on the object, \mathbf{G} is a (3×10) *grasp matrix* (Mason & Salisbury 1985), and \mathbf{f} is a (10×1) vector of the digit forces. The elements of the first two rows of the matrix are the coefficients at the digit force values. Because in the position shown in Figure 1 the normal and tangential digit forces are along the X and Y axes of the global system of coordinates, the coefficients are either zeroes or ±1. When the normal and tangential digit forces are not parallel to the X and Y axes, e.g. when the handle is not oriented vertically, the coefficients equal the direction cosines, i.e. the projections of the unit vectors along the normal and tangential directions onto the X and Y axes. The elements of the last row in matrix \mathbf{G} are the moment arms of the digit forces about axis Z through the origin of the system of coordinates. \mathbf{G} is also known as the *matrix of moment arms*.

Equation (2) is a linear equation that allows for using the common methods of linear algebra. The equation is based however on a simplifying assumption that the elements of the grasp matrix are constant, i.e. the points of digit force applications do not displace during the period of observation. If they migrate, the elements of \mathbf{G} are not constant anymore and the equations become non-linear: variable values of digit forces are multiplied by the variable values of moment arms. In computations, this obstacle can be avoided if a (10×1) \mathbf{f} vector is expanded to a (15×1) vector where the added elements are the moments exerted by the individual digits with respect to the corresponding sensor centers. Matrix \mathbf{G} in this case is 3×15. For a general 3-D case, matrix \mathbf{G} is 6×30.

7. Internal forces during object manipulation

In multi-digit grasping, a vector of contact forces and moments \mathbf{f} can be broken into two orthogonal vectors: the resultant force vector \mathbf{f}_r (manipulation force) and the vector of the internal force \mathbf{f}_i ($\mathbf{f}=\mathbf{f}_r+\mathbf{f}_i$) (Kerr & Roth 1986; Yoshikawa & Nagai 1990, 1991). An *internal force* is a set of contact forces which can be applied to an object without disturbing its equilibrium (Mason & Salisbury 1985; Murray et al. 1994). The elements of an internal force vector cancel each other and, hence, do not contribute to the manipulation force (a resultant wrench exerted on the object). In human movement studies, the best known example of the internal forces is the *grasp force*, two equal and opposite normal forces exerted by the thumb and VF against each other. The resultant of these forces equals zero. An internal force is not a single force; it is a set of forces and moments that, when act together, generate a zero resultant force and a zero resultant moment.

In five-digit grasps in 3-D space, vector of individual digit forces and moments \mathbf{f} is a 30×1 vector. Its relation with a 6×1 vector \mathbf{F} of the resultant forces and moments acting on the object is described by equation (2) where \mathbf{G} is a 6×30 grasp matrix (Salisbury & Craig 1982; Kerr & Roth 1986). Vector of the internal forces \mathbf{f}_i lies in the null space of \mathbf{G} (the null space of a m by n matrix \mathbf{G} is the set of all vectors \mathbf{f} in \mathbb{R}^n such that $\mathbf{G}\mathbf{f}=\mathbf{0}$ $\{\mathbf{f}\in\mathbf{N}(\mathbf{G})|\mathbf{G}\mathbf{f}=\mathbf{0}\}$).

Because the rank of a 6×30 matrix is at most 6, the dimensionality of the null space of the

grasp matrix (its nullity) is at least 24. The dimensionality of each of these vectors equals the total number of the digit forces and moments, i.e. thirty in five-digit grasps (some of the elements of an internal force vector can be zero). Hence there exist many finger force-moment combinations that interact in such a manner that the individual forces and moments cancel each other and do not contribute to the manipulation force. For instance, if individual tangential finger forces are in opposite directions, ulnar and radial, these force components can cancel each other such that the resultant tangential force equals zero. Analysis of all the 24 basic vectors of $\mathbf{N}(\mathbf{G})$ would be a daunting task. The force elements can be of different magnitude (provided that they negate each other's effects) and the 24 independent sets of internal forces (basic vectors) can be combined in different linear combinations, so there can be many internal forces (Gao et al. 2005). A performer can choose innumerable combinations of the internal force elements provided that they cancel each other.

So far, the research was mostly limited to the planar tasks performed with mechanically unconstrained objects and analyzed at the VF level. According to the mathematical analyses (Kerr & Roth 1986; Gao et al. 2005), at this level there exist only three internal forces: the *grasp force*, the *internal moment* (about an axis parallel to axis Z, see Figure 1), and the *twisting moment* - due to the opposite twisting moments exerted by the thumb and VF around the axis normal to the surfaces of the contacts. The latter combination is mechanically possible due to the soft finger contacts but cannot be actually realized in single-hand grasping: people cannot twist the thumb and the finger(s) in opposite directions (in two-hand grasping this option can be realized). Because of that, the twisting moment is neglected in the studies on human prehension.

The manipulation force is prescribed by the task mechanics. The internal forces allow for much freedom. The manipulation force vector and the vector of the internal force are mathematically independent (Kerr & Roth 1986; Yoshikawa & Nagai 1991). Practically this means that the central controller can change manipulation force without changing the internal force and vice versa (Yoshikawa & Nagai 1990, 1991; Gao et al. 2005 b, c). This opportunity is realized in robotics manipulators where the manipulation force and the internal forces are commonly controlled separately (e.g., Zuo & Qian 2000); the control is said to be decoupled. The decoupled control requires less computational resources; the controller does not have to bother about on-line adjustments of the grasp force to object acceleration and/or orientation. This strategy requires, however, exerting unnecessarily large forces and is, in this sense, uneconomical. People do not use this option. Available data suggest that the CNS prefers to face larger computational costs rather than produce excessive forces. In contrast to robots, people adjust the internal forces to the manipulation forces during the object transport (Flanagan & Wing 1993, 1995; Smith & Soechting 2005; Zatsiorsky et al. 2005; Gao et al. 2005 b, c). The pattern of the adjustment depends on the performed movement.

Gao et al (2005 b, c) studied vertical and horizontal object movement at the three handle orientations, vertical, horizontal and diagonal (inclined 45°). In total, six combinations of handle orientation and movement direction were tested: (1) Parallel manipulations. (1a). VV task: Vertical orientation-vertical movement. (1b). HH task: Horizontal orientation-horizontal movement. (2) Orthogonal manipulations. (2a) VH task: Vertical orientation-horizontal movement. (2b) HV task: Horizontal orientation-vertical movement (3) Diagonal manipulations. (3a.) DV task: Diagonal orientation-vertical movement. (3b). DH task:

Diagonal orientation-horizontal movement. In the above description the following terminology is used: When the handle orientation and the direction of manipulation are along the same axis (e. g. a vertically oriented handle is being moved in the vertical direction or a horizontally oriented handle in the horizontal direction) the manipulation is called the *parallel manipulation*. The *orthogonal manipulation* corresponds to the object motion at the right angle to the handle orientation, e.g. a vertically oriented handle is being moved in a horizontal plane or a horizontally oriented handle is moved in a vertical plane.

The summary results on the coordination of internal forces in various manipulation tasks are presented in Table 1. The following terminology is used. *Grasping synergy* (GS) is a conjoint change of the normal digit forces (Zatsiorsky & Latash 2004). The coordination pattern characterized by a simultaneous (in-phase) increase or decrease of the normal forces of the thumb and VF is called *symmetric GS* (in the VV task a symmetric GS was used, see Figure 7 below). The reciprocal thumb force-VF force changes when the normal forces of the thumb and VF change in opposite directions are called *anti-symmetric GS*, see Figure 8 where the internal force demonstrated an 'inverted V' pattern with respect to the handle acceleration.

| Manipulation | | Coupling of the thumb and VF normal forces (Grasping synergies) | Internal force-manipulation force (acceleration) coupling |
|-------------------|----|---|---|
| <i>Parallel</i> | VV | Symmetric | Positive |
| | HH | Symmetric | Positive (the internal force increases slightly with the acceleration magnitude) |
| <i>Orthogonal</i> | VH | Anti-symmetric | Inverted -V pattern (symmetric) |
| | HV | Depends on the frequency. Approximately anti-symmetric at high frequencies. | Depends on the frequency. At high frequencies an asymmetric inverted-V pattern with the peak at 1 g |
| <i>Diagonal</i> | DV | Symmetric | Positive |
| | DH | Anti-symmetric | Positive (for the selected direction of the coordinate axes) |

Table 1. Internal forces during different manipulations of the hand-held objects

Consider the cases of symmetric GS and anti-symmetric GS. When people move a vertically oriented object in the vertical direction (the VV tasks) the grip force F_G increases in parallel with the object acceleration and hence the load force F_L ($F_L = W + ma$ where W is the object's weight, m is its mass and a is acceleration), apparently to prevent slip (Johansson & Westling 1984; Flanagan & Wing 1993, 1995; Flanagan et al. 1993; Flanagan & Tresilian 1994; Nakazawa et al. 1996; Kinoshita et al. 1996, Gordon et al. 1999; Gysin et al. 2003; see also Flanagan & Johansson 2002 for a review). The $F_G - F_L$ coupling is so strong that people increase F_G in parallel with F_L even when F_G is already much above the slipping threshold, e.g. when before lifting the object a performer purposefully grasps the object with a high

force (Flanagan & Wing 1995). Figure 7 illustrates the finding. Note that the grasping force is larger for larger object acceleration.

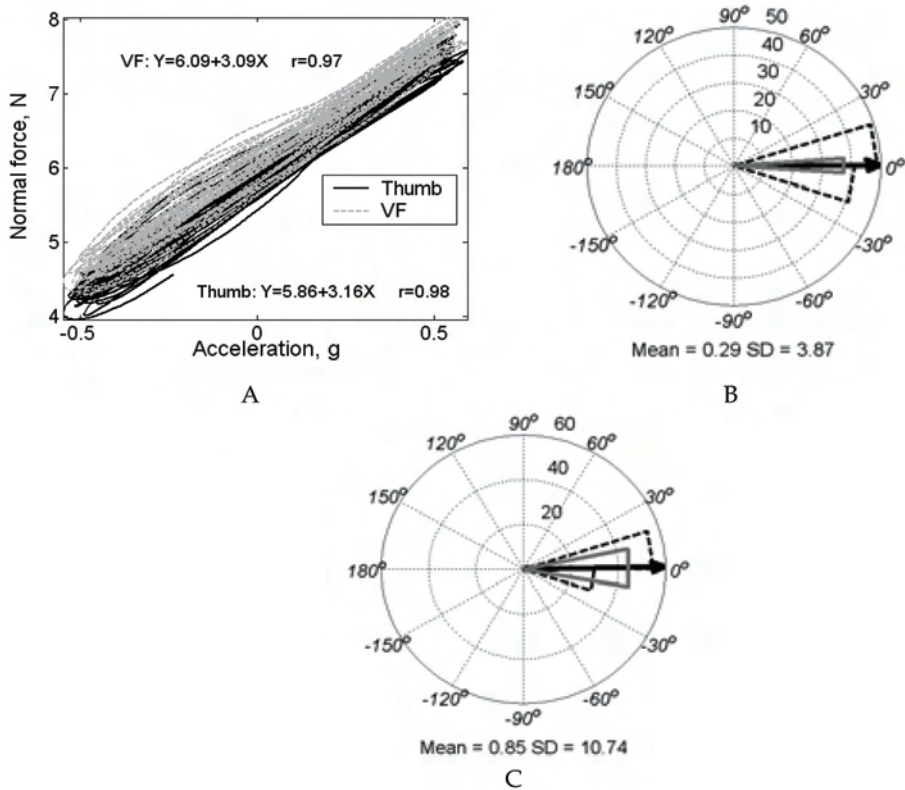


Figure 7. VV manipulation. (A) Normal forces of the thumb and VF (N) versus the handle acceleration in the vertical direction. A representative trial, weight (W) 8.8 N, frequency 1.5 Hz, representative subject. With the acceleration from approximately -0.5 g to 0.5 g the tangential force L (load) varied from approximately 4.4 to 13.2 N ($L = W + ma$). The range of the internal force fluctuations was approximately 4.0 N, from 4.0 to 8.0 N. (B) The VF normal force - acceleration phase angles (circular histogram). The phase angles cluster around zero degree. (C) The VF normal force - thumb normal force phase angles (circular histogram). Thick black arrow represents the mean phase angles and the gray triangle represents the angular standard deviation, The dashed lines illustrate the data for individual bins, the bin size is 20° . $n = 90$ (6 subjects \times 5 loads \times 3 frequencies). Adapted from Gao, F., Latash, M. L., Zatsiorsky, V. M. (2005) Internal forces during object manipulation. *Experimental Brain Research*, 165 (1): 69-83.

Quite a different coordination is observed in the VH tasks (horizontal movement of a vertically oriented object). In these tasks, the maximal grasping force is observed at the instances of maximal speed, and hence zero acceleration (Smith & Soechting 2005; Gao et al. 2005a, b), Figure 8.

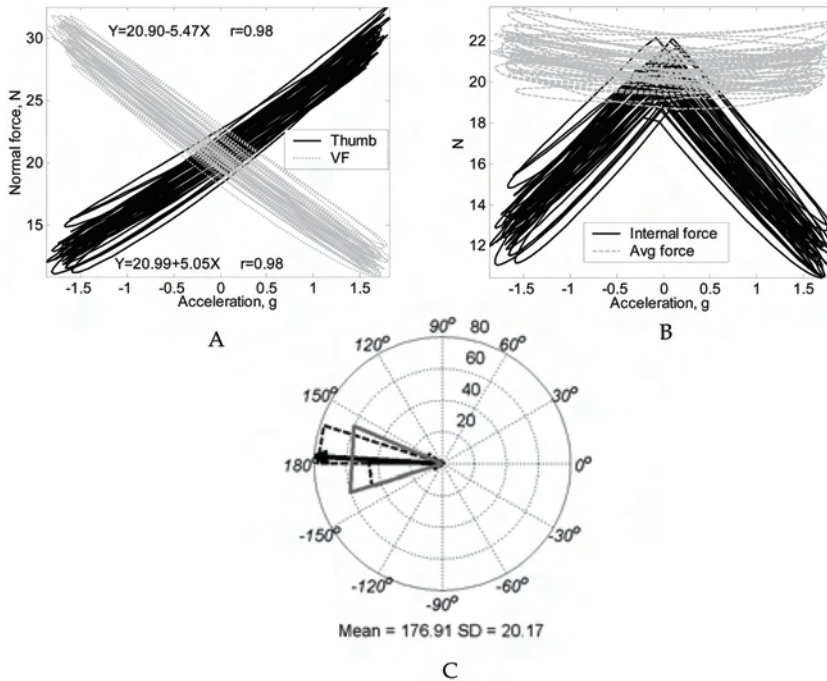


Figure 8. VH manipulation. (A) Normal forces of the thumb and VF versus the handle acceleration in the horizontal direction. A representative trial, the load was 11.3 N, the frequency was 3 Hz, representative subject #1. (B) Internal force and average normal force versus the handle acceleration. The range of the internal force fluctuations was approximately 8.0 N, from 12.0 N to 21.0 N. (C) The thumb normal force-VF normal force phase angle [circular histogram, $n = 150$ (6 subjects \times 5 loads \times 5 frequencies)]. Adapted from Gao F, Latash ML, Zatsiorsky VM (2005) Internal forces during object manipulation. *Experimental Brain Research*, 165 (1): 69-83.

In addition to the grasping force changes, the moments exerted by the normal and tangential digit forces also change during object manipulation while compensating for each other's changes and preserving the object orientation (Figure 9).

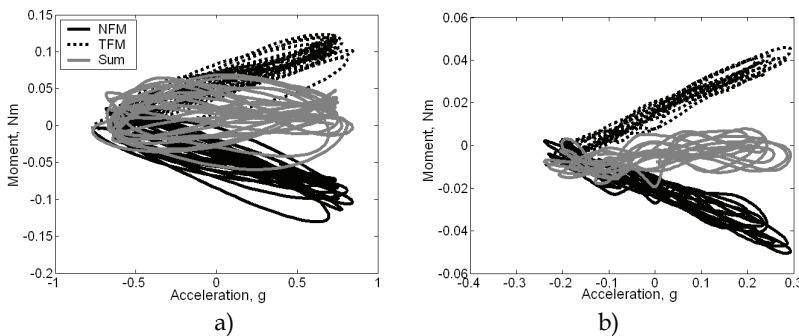


Figure 9. Internal and resultant moments in various tasks. Representative examples. Abbreviations: NFM-Moment of normal force; TFM-Moment of tangential force; Sum =

(NFM+TFM) = resultant moment. (A) VV: 2 Hz, 13.8 N, representative subject; (B) HH: 1 Hz, 6.3 N, representative subject. Adapted from Gao, F., Latash, M. L., Zatsiorsky, V. M. (2005) Internal forces during object manipulation. *Experimental Brain Research*, 165 (1): 69-83.

8. Local and synergic reactions to perturbations

When grasping different objects performers adjust digit forces to the object features. Two types of the adjustments are distinguished, local and synergic. The term *local* describes the responses that start and end at the same digit, i.e. an effect of friction at a given digit on the force exerted by this digit. The term *synergic* refers to changes in a finger's force in response to changes in friction under other finger(s) (Aoki et al. 2006, 2007; Zatsiorsky et al. 2006).

An example of the local and synergic reactions could be seen in experiments in which the friction under each digit was different, either high or low, resulting in eight friction conditions (for the three-digit grasps, Niu et al. 2007) or 32 friction conditions (Aoki et al. 2007). The difference between the high and low friction was three-fold. When friction under a digit was low, its tangential force decreased and the normal force increased (local effects). Digit forces were also adjusted to friction at other digits (synergic effects). The synergic effects were directed to maintain the handle equilibrium. For instance, to keep the total tangential force constant, the tangential forces of the thumb and fingers changed in opposite directions (Figure 10).

Not only the VF tangential force but also the tangential forces of the individual fingers are affected by the local friction conditions (Aoki et al. 2007; Niu et al. 2007). The tangential force adjustments to the local friction support the notion that the VF tangential force sharing is under neural control; the sharing percentage is not determined solely by the passive mechanical properties of the individual fingers and joints. In other words, the metacarpal joints cannot be modeled as simple hinges.

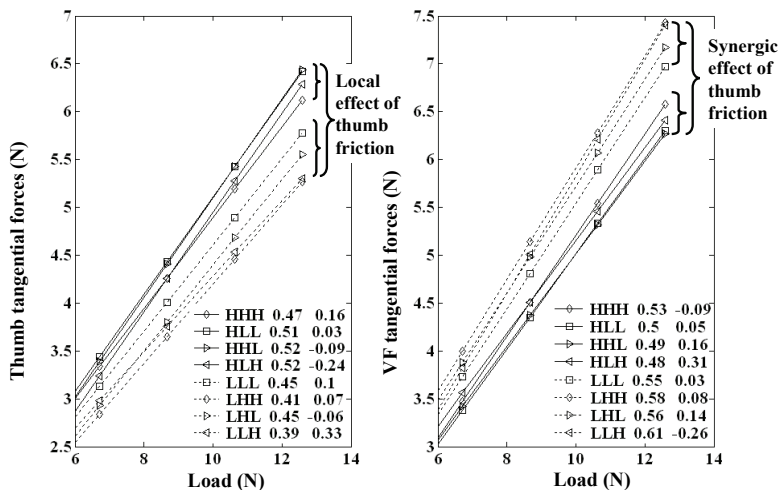


Figure 10. Tangential forces of the thumb and VF in the three-digit grasps as a function of the load and friction, high (H) or low (L). The eight friction conditions were HHH, HLL, HHL, HLH, LLL, LHH, LHL, and LLH, where the letters correspond to the friction condition

for the thumb, index and middle fingers, respectively. The friction sets with the thumb at a low friction contact (LLL, LHH, LHL and LLH) are printed with dotted lines. The solid lines represent the tasks with the high friction contact at the thumb. In the left panel, LFE is the *local friction effect*, i.e. the difference induced by the high or low friction contact at the thumb. Two other smaller figure brackets show the synergic effects, i.e. the effect of friction at other digits on the thumb force. The numbers in the bottom right insets are the regression coefficients and intercepts (the regression model $f_i^t = a_i + k_i^{(1)}L$ was used for computations). Note the small values of the intercepts. Cf. the right and the left panels: the thumb friction, H or L, induced opposite changes of the thumb and VF forces. (The figure is from X. Niu, M. Latash, V.M. Zatsiorsky (2007) Prehension synergies in minimally redundant grasps & the triple-product model of digit force control, *Experimental Brain Research*, 98 (1): 16-28.)

Local and synergic reactions are not limited to adjustments to local friction. For instance, similar reactions were observed when performers were holding a motorized handle while the handle width was forcibly either increased or decreased (Zatsiorsky et al. 2006). Handle expansion/contraction did not perturb the handle equilibrium; both the resultant force and moment acting on the handle remained the same. However, when the handle width increased each digit was perturbed (the length of the flexor muscle increased), and a restoring force tending to return the digit to its previous position arose (the local digit force adjustment). The local mechanisms, e.g. stretch reflexes, were directed to resist the imposed digit displacement. These mechanisms violated the object equilibrium, whilst the synergic force adjustments restored the equilibrium.

9. Principle of superposition in human prehension

The *principle of superposition* refers to decomposition of complex skilled actions into several elemental actions, which can be controlled independently by several controllers. The principle was first suggested in robotics (Arimoto et al. 2001; Arimoto & Nguyen 2001) and was verified for the dexterous manipulation of an object by two soft-tip robot fingers. Such a control can be realized via a linear superposition of two commands, one command for the stable grasping and the second one for regulating the orientation of the object. In robotics, such a decoupled control decreases the computation time.

When applied to multi-finger grasps in humans, the principle claims that at the VF level the forces and moments during prehension are defined by two independent commands: "Grasp the object stronger/weaker to prevent slipping" and "Maintain the rotational equilibrium of the object". The commands correspond to the two internal forces discussed previously, the grip force and the internal moment. The effects of the two commands are summed up. The validity of the principle was confirmed in a set of diverse experiments (for the review see Zatsiorsky et al. 2004; see also Shim et al. 2005 and Shim & Park, 2007)). The principle allows explaining the digit force adjustments to different factors such as (a) the load force and its modulation associated with the handle acceleration; (b) the external torque and its modulation; (c) the object orientation in the gravity field; (c) friction at the digit tips; and some other variables. The variations of the above factors may require similar or opposite adjustments. For instance, an increase of the object weight and a decrease in friction both require a larger gripping force while, a decrease of the load and a decrease in friction require opposite grasp force changes, a force decrease and increase, respectively. It has been

suggested that the CNS responds to a mixture of similar or opposite requirements follows a rule: *Adjustment to the sum equals the sum of the adjustments* (reviewed in Zatsiorsky & Latash 2008).

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