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Prehension Stability: Experiments With Expanding and Contracting Handle

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Abstract

We studied adjustments in digit forces and moments during holding a vertically oriented handle under slow, externally imposed changes in the width of the grasp. Subjects ($n = 8$) grasped a customized motorized handle with five digits and held it statically in the air. The handle width either increased (expanded) or decreased (contracted) at a rate of 1.0, 1.5, or 2.0 mm/s, while the subjects were asked to ignore the handle width changes, and their attention was distracted. External torques of 0.0, 0.25, and 0.5 Nm were applied to the handle in two directions. Forces and moments at the digit tips were measured with six-component sensors. The analysis was performed at the virtual finger (VF) and individual finger (IF) levels (VF is an imagined finger that produces the same wrench, i.e., the force and moment, as several fingers combined). In all the tasks, the normal VF and thumb forces increased with the handle expansion and decreased with the handle contraction. Similar behavior was seen for the thumb tangential force. In contrast, the VF tangential force decreased with the handle expansion and increased with the handle contraction. The changes in the tangential forces assisted the perturbations in the tasks requiring exertion of the supination moments and annulled the perturbation in the pronation effort tasks. In the former tasks, the equilibrium was maintained by the changes of the moments of normal forces, whereas in the latter tasks, the equilibrium was maintained by the changes of the moments of the tangential forces. Analysis at the IF level has shown that the resultant force and moment exerted on the object could arise from dissimilar adjustments of individual fingers to the same handle width change. The complex adjustments of digit forces to handle width change may be viewed as coming from two sources. First, there are local spring-like adjustments of individual digit forces and moments caused by both mechanical properties of the digits and the action of spinal reflexes. These stiffness-like reactions mainly assist in perturbing the rotational equilibrium of the object rather than in maintaining it. Second, there are tilt-preventing adjustments defined by the common task constraints that unite the digits into a task-specific synergy. The “virtual springs theory” developed in robotics literature is insufficient for describing the phenomena observed in human grasping.

INTRODUCTION

To manipulate hand-held objects, such as utensils or a glass, the grasps must be stable, i.e., the objects should not be dropped, and their orientation in space should be properly controlled. Grasp stability—both slip prevention and tilt prevention—has been examined both in human movement science and in robotics.

In humans, the studies mainly addressed slipping prevention (Eliasson et al. 1995; Flanagan and Wing 1995; Johansson and Westling 1984, 1988; Johansson et al. 1992; Salimi et al.

1999; Westling and Johansson 1984). It has been shown that, when performers grasp a vertically oriented handle, they increase the grip force if the load force increases (Johansson and Cole 1994; Kinoshita et al. 1995; Monzee et al. 2003; Winstein et al. 1991); this diminishes the risk of slipping. Only recently, rotational equilibrium became an object of research (Goodwin et al. 1998; Latash et al. 2004; Pataky et al. 2004a,b; Shim et al. 2003, 2005a,b; Zatsiorsky and Latash 2004; Zatsiorsky et al. 2002a,b, 2003a,b). It has been reported that during prehension, all the individual digit force variations—whether they occur in response to changes in the motor task, e.g., load and torque magnitude, or because of trial-to-trial or in-trial variability—are always interrelated, i.e., they manifest the prehension synergies (Baud-Bovy and Soechting 2002; Pataky et al. 2004a,b; Rearick and Santello 2002; Santello and Soechting 2000; Shim et al. 2003, 2005a,b; Zatsiorsky and Latash 2004; Zatsiorsky et al. 2003a). The cause–effect relations among the observed changes of the forces and moments are described by the chain effects (Shim et al. 2005a,b; Zatsiorsky et al. 2003b).

The common goal of the above research has been to understand how people control digit forces and moments to achieve stable grasps. In contrast, the goal of robotic research is to achieve the stable grasps with the technical means/grippers (for review, see Cutkosky and Wright 1986; Shimoga 1996; Svinin et al. 1999, 2000). In principle, the strategies used by humans and robots may be similar or they can be different.

The main tenets of the grasp stability theory developed in robotics literature (Al-Gallaf et al. 1993; Choi et al. 1993; Cutkosky 1985; Hanafusa and Asada 1977; Nguyen 1986a,b, 1987a,b, 1989) can be briefly described as follows.

Behavior of an individual finger i at the contact with the object is characterized by a stiffness matrix ($\mathbf{S}_i$), which represents an instantaneous static relation between contact forces and compliant deflections

$$\mathbf{S}_i = \frac{\partial \mathbf{f}_i}{\partial \mathbf{x}_i} \quad (1)$$

where $\partial \mathbf{f}_i = (\partial f_x, \partial f_y, \partial f_z, \partial m_x, \partial m_y, \partial m_z)^T$ includes the linear force and moment with respect to the local coordinates, and $\partial \mathbf{x}_i$ is a small change in the position and orientation of the contact. The elements of $\mathbf{S}_i$ are the coefficients (stiffness) of linear relation between the small linear and rotational displacements of the grasped object and the accompanying changes in force and torque. The diagonal elements of $\mathbf{S}_i$ represent the resistance in the direction of the perturbation, whereas the off-diagonal elements represent the increase in force/torque in one direction in response to the perturbation in another direction, e.g., increase in the normal force as a result of a small displacement in a tangential direction. In the planar case, the $\mathbf{S}_i$'s are 3×3 matrices (if only linear forces and displacements are considered the $\mathbf{S}_i$ is a 2×2 matrix); in three dimensions, a full $\mathbf{S}_i$ is a 6×6 matrix. Instead of stiffness, its inverse—compliance—can be used.

Individual $\mathbf{S}_i$'s form one concatenated matrix $\mathbf{S}_c$ of a grasp. For five-digit grasps, the dimensionality of the grasp concatenated $\mathbf{S}_c$ is 30 (5 digits $\times$ 6 force/torques). For the planar grasps, the $\mathbf{S}_c$ dimensionality is 15. The $\mathbf{S}_c$ is composed of diagonal $\mathbf{S}_i$'s and the interfinger coupling off-diagonal matrices. The coupling matrices represent the effect of the perturbation of one finger on the force/torque exerted by another finger, e.g., the effect of the lateral displacement of the little finger on the normal force of the middle finger. The $\mathbf{S}_c$ is computed at the contact reference frames.

The grasp stiffness, i.e., its resistance to small perturbations, is represented by the stiffness matrix $\mathbf{S}_o$ computed with respect to the object reference frame. The grasp stiffness matrix $\mathbf{S}_o$

in the object frame can be obtained by applying a congruent transformation to the concatenated stiffness matrix $\mathbf{S}_c$. Matrix $\mathbf{S}_o$ is 6×6 in three dimensions, and it is 3×3 in planar case (2×2 if only linear displacements and forces are considered).

For the grasp to be stable, the stiffness matrices $\mathbf{S}_i$, $\mathbf{S}_c$, and $\mathbf{S}_o$ should be positive definite. This requirement assures that all the eigenvalues of the above matrices are positive numbers. Note that the requirement does not specify precisely the digit forces; they can be of any value provided that the requirement is satisfied.

An essential feature of the above theory is that on-line control is not necessary for the prehension stability: if the stiffness matrices satisfy the required conditions, the grasp will be stable both in terms of the contact stability (slip prevention) and the orientation stability (tilt prevention). In other words, the grasp stability is an inherent property of a given grasp. Such a theory essentially assumes that the digits and their interconnections can be replaced by “virtual springs” (Kao 1994), this is the virtual springs theory. Maintaining the grasp stability without the on-line control is convenient for robotic applications: it allows freeing the computational resources for manipulation control.

An imperative part of the above theory is that, for the grasp to be stable, the stiffness matrices should be symmetric, i.e., $s_{ij} = s_{ji}$, where s is an element of the stiffness matrix. For the concatenated matrix $\mathbf{S}_c$, this requirement, as an example, means that an increase of the normal force of one finger in response to a lateral perturbation of another finger should be equal to an increase of the tangential force of the second finger in response to a perturbation of the first finger in the normal direction. It has been shown experimentally that the symmetry requirement is satisfied for the human arm: the matrix of the endpoint stiffness of human arm is approximately symmetric (Dolan et al. 1993; Flash and Mussa-Ivaldi 1990; Gomi and Kawato 1997; Lacquaniti et al. 1993; Mussa-Ivaldi et al. 1985; Tsuji 1997). The symmetry of the stiffness matrices $\mathbf{S}_c$ and $\mathbf{S}_o$ has not been studied.

Testing the virtual springs theory of the grasp stability on human subjects in its entirety is technically difficult: for five-digit grasps in three dimensions, each of the 30 kinematic/dynamic variables should be independently perturbed, and the resulting 30 reactions to the perturbation should be measured. Thus far, simpler paradigms have been used in the literature. Milner and Franklin (1998) measured the stiffness of the index finger in the flexion–extension plane under the instruction to the subjects “not to respond to the displacement.” The computed 2×2 matrix was approximately symmetric. The finger stiffness was anisotropic with the direction of greatest stiffness being approximately parallel to the proximal phalanx of the finger. In contrast to the previous studies that examined finger joints in isolation and found that the joint stiffness increases with the joint torque (Akazawa et al. 1983; Becker and Mote 1990; Capaday et al. 1994; Carter et al. 1990, 1993; Hajian and Howe 1997), Milner and Franklin (1998) did not find a monotonic relation between joint stiffness and joint torque.

Several authors have attempted to explore the grasp stiffness, limiting the research to 1) planar tasks, 2) pinch (mainly 2-digit) grasp, 3) mechanically constrained handles (i.e., the handle cannot move in all the directions freely), and 4) zero external torque conditions. Either the stiffness matrices were 2×2 (only linear displacements and forces were considered; Kao 1994) or the reaction to the perturbation was recorded in only one direction (Hermsdörfer et al. 1992, 1994; Van Doren 1998). Kao (1994) perturbed the pinch grasp in two directions, proximal–distal and radial–ulnar, and computed the 2×2 stiffness matrix with and without the assumption on its symmetry. It was found that the matrix was approximately symmetric. Similar results were reported by Kao et al. (1997). By studying the effect of grasp force and finger span on the grasp stiffness, Van Doren (1998) found that stiffness increased significantly in proportion to initial force but was changed only slightly by initial span. In the latter study,

the stiffness was understood as a scalar rather than a matrix and was measured in the direction of the linear perturbation, the change of the handle width. A three-digit grasp was used, but only the thumb normal force was measured.

In this study, we are interested in how the grasp stability—both slip prevention and tilt prevention—are preserved during slow changes in the task constraints. We used a customized handle to change the grasp width during the manipulation—increase or decrease it—and studied 1) five-digit grasps; 2) the normal and tangential digit forces as well as the points of digit points application, in total 15 outcome variables; and 3) both the zero-torque and non-zero-torque tasks. Because of the novelty of the experimental paradigm, we did not formulate testable hypotheses; this is an exploratory study. However, we expected to find that 1) rotational equilibrium in prehension is maintained by the elastic-like properties of the digits (i.e., the properties that depend solely on the deformation magnitude but not on other factors such as speed) and 2) the CNS uses an economical reaction to the perturbation, making minimal adjustments to cope with the changing task constraints. For instance, a change in the handle width leads to a change in the moment arm of the tangential digit forces. A straightforward, minimal adjustment would be to covary the difference between the tangential forces of the thumb and the fingers to keep the moment of tangential forces constant. We have to admit that we were wrong in both expectations: The real picture is much more complex.

METHODS

Subjects

Eight right-handed male university students served as subjects (age, 30.5 ± 3.74 yr; weight, 74.5 ± 9.5 kg; height, 1.786 ± 0.095 m; hand length from the middle fingertip to the distal crease of the wrist with the hand extended, 19.1 ± 1.3 cm; hand width, 9.2 ± 0.53 cm). The subjects had no previous history of neuropathies or trauma to the upper limbs. All subjects gave informed consent according to the procedures approved by the Office for Regulatory Compliance of The Pennsylvania State University.

Equipment

A customized motorized handle was attached to the top edge of an aluminum beam ($5.0 \times 85.0 \times 0.6$ cm) at the midpoint of the beam in the medio-lateral direction (Fig. 1). Five six-component force/moment transducers (mass 9.1 g; Nano-17, ATI Industrial Automation, Garner, NC) were mounted on the handle. An eyehook hanger was located along the bottom edge of the beam and was used to suspend a weight. The position of the hook in the medio-lateral direction could be varied by sliding the hook in the slot that ran the length of the beam. A level was attached to the top of the handle to monitor its orientation and avoid rotation of the handle/beam unit about the x and z axes.

The center points of the index and middle finger sensors were located 37.5 and 12.5 mm, respectively, above the midpoint of the handle. The center points of the ring and little finger sensors were located 12.5 and 37.5 mm, respectively, below the midpoint. The surfaces of the transducers were covered with 100-grit sandpaper (the friction coefficient at the sensor-fingertip interface was between 1.4 and 1.5; Gao 2002).

The output cables from the five sensors were connected to a custom-made breakout box that separated individual signals. There were 30 force/moment signals in total (6 signals $\times$ 5 sensors). The analog signals were sent to a customized signal conditioning box and were used as input to two 64-channel 12-bit analog-digital converters (PCI-6031, National Instrument, Austin, TX). The sampling frequency was 100 Hz.

The moving assembly was fixed within a rigid frame. A stepper motor (IMS M-1718-1.5S, Intelligent Motion Systems, Marlborough, CT) controlled by a control box was connected through worm gears to the branches of the handle that can move outward (expand) or inward (contract). A laser displacement sensor (resolution, 0.015 mm; AR200-50M, Schmitt Measurement Systems, Portland, OR) was used to record the displacement of the handle branches under expansion or contraction. The uneven weight of the right and left halves of the handle—caused by the right side location of the laser sensor and the three extra sensors—was counterbalanced by a piece of metal fixed to the left of the midline of the handle (data not shown), such that the center of gravity of the handle without a suspended load was at the midline.

Testing procedure

Before testing, the subjects were given an orientation session to become familiar with the experimental apparatus and to ensure that they were able to accomplish the tasks. Their height, weight, and hand dimensions were measured. Before the experiment, the subjects cleaned their fingertips with the alcohol prep swabs.

Subjects sat in a chair alongside a table with the right upper arm positioned at $\sim 45^\circ$ abduction in the frontal plane and 45° flexion in the sagittal plane. The elbow joint was flexed $\sim 45^\circ$. The forearm, but not the wrist and hand, was constrained by a brace and rested on the table. The forearm was supinated 90° so that the hand was placed in a natural grasping position. Special attention was given to digit placement on the sensors such that the center of the digit surface coincided with the center of the sensor.

During the experiment, a 0.285-kg load was suspended from the beam at different positions with respect to the middle of the beam. Suspending the load at different positions produced “external” torques of 0.25 and 0.5 Nm in both clockwise and counterclockwise directions with respect to the middle of the handle. Suspending the load in the middle corresponded to a zero torque. The total weight of the apparatus including the load was 14.1 N.

Subjects were requested to hold the handle statically in the air while maintaining the horizontal orientation of the level located on the top of the handle. The subjects were instructed to hold the handle “naturally with minimal force exertion.” When the subjects reported that they were holding the handle comfortably, the handle branches either expanded or contracted at one of the three prescribed speeds: 1.0, 1.5, or 2.0 mm/s. The different speeds were used to establish whether the stiffness-like behavior of the digits [their apparent stiffness (AS)] was affected by the speed. Note that in classical mechanics, stiffness—by definition—does not depend on the speed. The starting grip widths were 80 and 100 mm for handle expansion and handle contraction, respectively. A “do-not-intervene” paradigm was used; i.e., the subjects were told “do not adjust your commands to the hand” during changes in the handle width. To further reduce the voluntary intervention and distract the subject's attention from the motor task, the subjects were asked to count down from a large number in their mind.

The signals were recorded for 10 s. The signals were set to zero before each trial. During a single experimental session, each subject performed 90 trials in total (5 torques $\times$ 3 speeds $\times$ 2 directions $\times$ 3 repetitions). The order of the trials was pseudorandomized. Breaks of ≥ 1 min were provided between trials to avoid fatigue. The total duration of each experiment was ~ 2 h.

Data analysis

Customized data acquisition software written in LabVIEW (National Instruments) was used to convert the digital signals into force and moment values. The working motor induced slight

oscillations of the handle. Because of that, the data were digitally low-pass filtered at 1.0 Hz with a fourth-order Butterworth filter. The cut-off frequency was determined based on the power spectrum analysis of the kinematics data of the handle (the peak spectral density was at ~2.0 Hz). The kinematic measurements were collected only for one subject. A ProReflex Motion Capture Unit 240 (Qualisys Medical AB) was used and located 1 m away from the subject. Three reflective 20-mm markers were placed evenly on the horizontal bar. With such a setup, the accuracy of the measurement was 0.02 mm. The recorded oscillation was mainly in the vertical direction (~1–1.5 mm in amplitude), and it was much smaller in the horizontal direction (<0.5 mm). Data reduction was performed by using Matlab (Mathworks, Natick, MA).

In the transducer-fixed reference system, the forces normal to the transducer surface corresponded to the z -direction, F^z . In this experiment, F^z was oriented horizontally with respect to the environment. The transducers were mounted on the handle such that the y -axis was aligned with vertical axes. Thus the force F^y exerted in y -directions was computed as the tangential force. Because the task was static, the tangential force always acted in the vertical direction. Upward tangential forces and counterclockwise moments (as seen from the subject) were defined as positive. Hence, the pronation torques exerted by the subject were positive and supination torques negative. Suspending the load to the right of the middle of the handle (these tasks are labeled with letter R) produced an external torque in the clockwise (negative) direction; this torque was negated by a positive torque (pronation, counterclockwise) exerted by the subjects. In L tasks, when the load was suspended to the left of the middle of the handle, the subjects exerted negative torque (in the clockwise direction, the direction of supination). In the text, if not specified otherwise, when angular direction of moment of forces is mentioned, it always refers to efforts exerted by the subject (not to the external torque generated by the suspended load). The digit contacts with the sensors were modeled as the soft finger contacts (Mason and Salisbury 1985), in particular the rolling of the fingers on the sensor surfaces was allowed. The y coordinates of the digit force application with respect to the sensor center were computed as $y_i = m_i^x / f_i^z$ ($i=1, 2, 3, 4, 5$) where m_i^x represents the moment of the i th digit with respect to x -axis and f_i^z represents the normal force of the i th digit. The obtained values were then used to compute the moment arms of the digit forces in the handle reference frame. The moments of the normal finger forces were computed with respect to the y coordinate of the point of application of the thumb normal forces.

All analyses were performed at two levels: at the level of individual fingers (IF) and the virtual finger (VF) level. The VF is an imaginary finger that produces a wrench equal to the sum of wrenches produced by all the fingers (Arbib et al. 1985; Iberall 1987). To determine the VF normal and tangential forces— F_{vf}^n and F_{vf}^t , respectively—the IF forces were summed up. The vertical coordinate of the point of VF normal force application Y_{vf} was determined based on the theorem of moment (the Varignon theorem) as $Y_{vf} = \sum F_i^n Y_i / F_{vf}^n$ ($i=1, 2, 3, 4$), where Y_i is the vertical coordinate of the force application point of finger i ($Y_i = d_i + y_i$, where d_i is a projected vertical distance between the sensor centers of finger i and the thumb). The capital Y is used to designate a coordinate in the handle fixed reference system, whereas the lowercase y_i designates the coordinate with respect to a sensor center i .

At the VF level, the moment of the normal forces M^n and the moment of the tangential forces M^t were computed. M^n is caused by normal forces of the thumb and the VF. These forces are equal, opposite, and not collinear. Hence, they form a force couple. Because the moment of a couple is a free moment, i.e., it is the same for all moment centers and remained unchanged under parallel displacements (Zatsiorsky 2002), the M^n can be added to the M^t to obtain the total moment exerted by the subject.

At each instant of time during the trial, the moment of the VF normal force was computed as

$$M^n = F_{vf}^n (Y_{vf} - Y_{th}) \quad (2)$$

and the moment of tangential forces was computed as

$$M^t = (F_{vf}^t - F_{th}^t) w / 2 \quad (3)$$

where superscripts n and t represent the normal force and tangential force, respectively; subscripts th and vf represent the thumb and virtual finger, respectively; the difference $(Y_{vf} - Y_{th})$ is the moment arm of the normal digit forces, and w stands for the current width of the handle.

Determination of apparent stiffness

The term stiffness is greatly misused in human science literature (for a discussion, see Latash and Zatsiorsky 1993; Zatsiorsky 2002). It is often applied with a meaning that has little in common with the connotation accepted in mechanics. To avoid an ambiguity, we will use the term AS, understanding under it the change in force or moment per unit of an externally imposed handle width change. We associate with this term neither mechanical factors affecting the force (e.g., the perturbation speed; in classical mechanics, stiffness by definition does not depend on speed) nor specific physiological mechanisms (e.g., passive, intrinsic, or reflex stiffness components as it done in some studies; Carter et al. 1990).

A small displacement (width perturbation) can be represented by a vector $\Delta \mathbf{w} = (\Delta w_1 \Delta w_2 \Delta w_3 \Delta w_4 \Delta w_5)^T$, where the superscript T designates the vector transpose. In planar case, the effect of the above perturbation on the digit forces and moments can be described by a (15×5) stiffness matrix $\mathbf{S}_c$ such that

$$\begin{bmatrix} \Delta \mathbf{f}^n \\ \Delta \mathbf{f}^t \\ \Delta \mathbf{m} \end{bmatrix} = [\mathbf{S}_c] [\Delta \mathbf{w}] \quad (4)$$

where $\Delta \mathbf{f}^n$, $\Delta \mathbf{f}^t$, and $\Delta \mathbf{m}$ are the (5×1) vectors of the changes of the normal digit forces, tangential forces, and moments, respectively. The $\Delta \mathbf{m}$ are changes in the local moments, i.e., the moments exerted on the sensor surfaces by the individual digit tips. To retain the object equilibrium, the concatenated vector $[\Delta \mathbf{f}^n, \Delta \mathbf{f}^t, \Delta \mathbf{m}]^T$ should be in the null space of the (6×15) grasp matrix $[\mathbf{G}]$, i.e., the matrix product

$$[\mathbf{G}] \begin{bmatrix} \Delta \mathbf{f}^n \\ \Delta \mathbf{f}^t \\ \Delta \mathbf{m} \end{bmatrix} = [0] \quad (5)$$

Equation 5 represents an equilibrium constraint on the variations of the digit forces and moments.

Changes in the local moments $\Delta \mathbf{m}$ are not influenced by the tangential forces, which act in the plane of the sensors and hence do not generate moments about axes in this plane. Also, the digits do not stick to the sensors and can only push but not pull on them; hence they do not generate force couples (free moments) about the plane of contact. Therefore $\Delta \mathbf{m}$ is only caused by changes in the magnitude of the normal forces $\Delta \mathbf{f}^n$ and the points of their application on the

sensors Δp . Because Δp is mathematically independent on the normal digit forces and Δf_i^n effects are already accounted for in equilibrium Eq. 5, we analyzed the effects of the handle expansion/contraction on Δp rather than on Δm . The Δp data were used to compute the moment arms of the VF normal forces.

We will use the symbol ASn to describe the change of the normal force per unit of the handle width change, $\Delta f_i^n / \Delta w$, where Δf_i^n is the change in the normal force of a single digit. The symbol AS_t will be used to characterize the “tangential apparent stiffness,” i.e., the observed changes in the tangential force per unit of displacement. For uniformity, we will take the liberty of using the symbol AS_p with the meaning “displacement of the point of digit force application per unit of handle width change.” Note that the AS_p is dimensionless. Besides computing the AS for individual digits, the AS_n, AS_t, and AS_p for the VF were computed. The AS_p for the VF was computed as the displacement of the vertical coordinate of the point of application of the resultant normal forces of the four fingers. The difference between the AS_p for the VF and thumb—i.e., the change in the moment arm of the normal forces per unit of handle width change—was calculated and further designated as ΔAS_p . The M^n and M^t (Eqs. 2 and 3) variations per unit of handle width change were also computed and designated as the ASM_n and ASM_t, respectively (the apparent stiffness of the moments).

Based on the preliminary data, it was shown that a linear pattern (Fig. 2) between grip force and displacement (grip width) was sufficient to capture the force–displacement relation, regardless of the handle movement direction. Hence the AS of individual digits was quantified by the slopes of linear regression (the intercepts of the relations clustered around 0; they are not analyzed in detail here). Because the motor did not reach a prescribed speed immediately, the starting point was set at 1.5 mm from the initial grip width. The average time from the instant when the motor started working to the 1.5-mm threshold was 2.5 ± 0.22 s. Six different windows—4, 5, 5.5, 6, and 6.5 mm and the whole course—were chosen and compared. The linearity, i.e., the measure of the departure from a straight line response, served as a criterion (Sirohi and Krishna 1991). No significant differences among windows were revealed by ANOVA and multiple comparison [$F_{5,24177} = 1.78$, $P > 0.1$; Tukey's HSD test (post hoc)]. Therefore a 6.5-mm window was chosen for the analysis. This window magnitude was close to those used in other studies— ≤ 7 mm in Van Doren (1998) and 4 mm in the study of Milner and Franklin (1998).

Statistics

Three-way repeated-measures ANOVA with the factors DIRECTION (2 levels), SPEED (3 levels), and TORQUE (5 levels) was performed. Because the handle expansion occurred at the starting handle width of 80 mm while the initial width for the handle contraction was 100 mm, the factor DIRECTION should be more properly called DIRECTION and RANGE. For brevity, we will, however, call it simply DIRECTION. Traditional statistical measures were also used. When computing coefficients of correlation, we sometimes pooled all the trials of all the subjects together. We understand that such a procedure—which implicitly assumes that intersubject and intrasubject variabilities are similar—is not recommended; we did it to increase the number of observation points to 24 (8 subjects $\times$ 3 trials). The conclusions about the statistical significance of such correlation coefficients should be viewed with caution. The average values of the coefficients of correlation were computed using the z-transform. Statistical analysis was performed in Minitab (Minitab, State College, PA) and Matlab.

RESULTS

The results are presented in the following sequence: 1) the initial digit forces (before the perturbation); 2) maintaining rotational equilibrium; 3) the AS at the VF level (effects of task

conditions and intertrial/task correlations); and 4) effects of task conditions on the AS: individual fingers.

Initial digit forces

Digit forces before the perturbation are shown in Fig. 3, *A* and *B*. The results are in good agreement with the previously published data (Zatsiorsky et al. 2002a) and are presented here only for easy reference and comparison with the modulation-induced by the grip width change. The grip force (the thumb and VF) changed with the torque in a V-like fashion, whereas the tangential forces of the thumb and VF increased/decreased in opposite directions. The moment arm of the normal forces changed in a systematic manner from negative in the L tasks to positive in the R tasks (Fig. 3C).

Maintaining rotational equilibrium

During the trials, the rotational equilibrium of the handle was preserved (i.e., the total moment exerted on the handle was approximately constant); however, the moments of the normal and tangential forces changed in opposite directions (Fig. 4). As seen in the graphs, with the handle expansion, the M^n values changed in the direction of pronation, i.e., positive moments increased, negative moments decreased or changed to positive, whereas the M^t values changed in the direction of supination, i.e., the negative moments increased, the positive moments decreased or changed to negative. For instance, at a zero-torque task M_i , the magnitudes of M^n (it was positive) and M^t (it was negative) both increased.

Because the moment of the tangential forces is proportional to the difference between the tangential forces of the thumb and VF (see Eq. 3), an increase of the magnitude M^t within a trial may be caused by the increase of the moment arm (the handle width) and/or the change of the tangential forces in opposite directions (Fig. 5). The VF tangential force decreased with the handle expansion and increased with the handle contraction. The thumb tangential force changed in opposite way: increased with the handle expansion and decreased with the handle contraction.

AS at the VF level

We discuss first the ASMn and ASMt data and then the results obtained on other variables.

In all tasks, the ASMns were positive, whereas the ASMts were negative (Fig. 6). The ASMt values almost ideally mirrored the ASMn values (with a minus sign). In the handle expansion trials (with the exception of L2), the systematic effects of speed factor were seen. In the handle contraction trials, the L1 and M_i tasks did not follow this rule. The ANOVA results showed that the effects of all three studied factors, TORQUE, SPEED, and DIRECTION, on the ASMn and ASMt were highly significant ($P < 0.01$).

Mechanically, the observed ASMn and ASMt changes represent the following effects: 1) the moments of the normal forces in the counterclockwise (pronation, positive) direction increase—and the moments in the clockwise direction decrease—with the handle expansion and decrease with the handle contraction, and 2) the moments of the tangential forces adjust in opposite direction to the above changes, the counterclockwise (pronation) moments decrease during the handle expansion and increase with the handle contraction. The M^n behavior follows a simple algebraic rule; it can be represented as a product of plus and minus entries (Table 1). The changes of M^t are opposite the M^n changes. In Table 1, the pronation and handle expansion entries are considered positive, and the supination entries are considered negative. Hence, the expression (+,+) signifies handle expansion in pronation tasks; it yields the M^n increase. The (+,-) combination, i.e., a handle increase during supination tasks, results in decreasing the M^n magnitude. In the latter case, M^n is negative; hence the decrease in the M^n magnitude

corresponds to positive values of ASMn (cf. Fig. 6). The values in other cells are interpreted in a similar way.

Changes in the ASn, ASt, and ASp indices with task conditions were complex and not always intuitive. All three main factors, TORQUE, SPEED, and DIRECTION, showed significant effects on some of these indices. The ANOVA results are presented in Table 2. The following effects did not reach the level of statistical significance: for the ASn, the TORQUE effects (both for the thumb and VF); for the ASt, only the DIRECTION effects for the thumb (however, $P = 0.07$); and for the ASp, the SPEED effects (both for the thumb and VF). Among the interaction effects, only DIRECTION $\times$ TORQUE effects on the ASt and ASp (both for the thumb and VF) and DIRECTION $\times$ SPEED interaction effect on the thumb ASp were statistically significant.

In Fig. 7, the values of ASn, ASt, and ASp for the VF (*right*) and the thumb (*left*) are presented. Note the similarity of the ASn values for the VF and the thumb (2 *top panels*) and equal symmetric values of the ASt (negative for the VF and positive for the thumb; 2 *middle panels*). The observed ASt values signify equal increases/decreases of the thumb and VF tangential forces. As a result, the total tangential force stays the same, because it should be to maintain the equilibrium; the clockwise (negative, supination) moment of tangential forces increases (in the Mi, L1, and L2 tasks) or the pronation moment decreases (in the R1 and R2 tasks). With the torque changes from L2 to R2, Δ ASp systematically decreased (with the only exception for L1 at the speed 1.5 mm/s), and for the largest pronation torque R2 during the expansion tasks, it became negative (at the speed 2.0 mm/s; Fig. 8).

Intertrial/task correlations

Among the tasks, ASn did not show any correlation with the initial grip force, whereas ASt correlated with the initial level of the tangential force. The correlation between ASt and the initial force was negative both for the thumb ($r = -0.71$, Fig. 9) and VF ($r = -0.72$, data not shown). To check whether the correlations were statistically significant, the slopes of regression lines between initial forces and ASt were also calculated for individual subjects. All the slopes had the same sign across all the subjects, and hence we concluded that the correlations were statistically significant (sign rank test, $P < .005$). Note that for the thumb the increase of the initial tangential force was accompanied by the decrease of the ASt magnitude, whereas the ASt magnitude for the VF increased (because the ASt itself was negative). The independence of the ASn on the initial value of the normal force should be emphasized. The lack of correlation between ASn and the initial grip force does not agree with the study by Van Doren (1998). In the latter study, however, maintaining rotational equilibrium of the object was not an issue. The different relations of ASn and ASt with the initial force levels suggest that their changes may be mediated by different mechanisms.

The ASp correlated negatively with the ASt values (Table 3): in the trials where the tangential forces changed to a larger degree (the trials with larger ASt), the displacement of the point of application of the VF normal force was smaller.

The coefficients of correlation between the ASn and ASp were positive for the L2, L1, and Mi tasks (with the only exception for the L1 task at 1.5-mm speed, where the coefficient was -0.02), and they were negative for the R1 and R2 tasks (with the only exception for the R2 task at 1.5-mm speed, where the coefficient was 0; Table 4). Examples of the relations are presented in Fig. 10.

Effects of task conditions on the AS: individual fingers

The group average data on the ASn and ASt of individual fingers are presented in Fig. 11.

As follows from the ANOVA results (Table 5), the ASn did not depend significantly on the TORQUE but depended on SPEED for the index, middle, and ring fingers. For the little finger, the effects were opposite: significant for the TORQUE and insignificant for the SPEED (however, in the latter case, the effects were close to the statistical significance level, $P = 0.06$). The effects of DIRECTION (whether the handle is expanding or contracting) were different for different fingers: significant for the index and ring fingers and insignificant for the middle and little.

The AS_t of the index finger depended significantly on all three factors, DIRECTION, SPEED, and TORQUE. The AS_t of the middle, ring, and little fingers did depend on the SPEED. The effects of the TORQUE did not reach the level of statistical significance for the middle and ring fingers. Only the following interaction effects were statistically significant: the DIRECTION $\times$ SPEED interaction, the AS_p of the ring finger; DIRECTION $\times$ TORQUE, the AS_n of the middle finger, AS_t of the ring and little fingers, and the AS_p of the middle finger; the SPEED $\times$ TORQUE interaction, only the AS_p of the little finger; and the DIRECTION $\times$ SPEED $\times$ TORQUE interaction, only the AS_p of the little finger.

A general conclusion from the AS_n and AS_t analysis of the individual fingers (cf. Figs. 7 and 11) is that some of them can behave differently from the VF, i.e., the resultant force and moment exerted on the object may arise from dissimilar adjustments of individual fingers to the same perturbation. However, for the AS_p of the individual fingers, the effects were similar to those observed for the VF: significant effects of the DIRECTION and TORQUE and insignificant effect of SPEED (with the exception of the little finger where the SPEED effect was significant). Such a similarity between the VF and individual fingers AS_p tunings is interesting because the VF AS_p alterations occur mainly because of the modification of the finger force sharing pattern, whereas the AS_p for individual fingers is caused by the displacements of the points of finger force applications on the sensor surfaces.

DISCUSSION

Handle expansion/contraction does not affect the load force and external torque acting on the handle, i.e., it does not immediately perturb the handle equilibrium. The simplest strategy for the performer to prevent slip and tilt, e.g., in the zero-torque tasks, would be to do nothing (to not change the digit forces). However, as follows from the presented data, in all the tasks, numerous inter-related adjustments of the individual digit forces and moments to the perturbation are made. Such conjoint coordinated variation is an identifiable sign of a prehensions synergy. The observed changes cannot be explained solely by reactions of individual digits to their forced displacements, i.e., by their tendency to resist the perturbation. In other words, the reactions cannot be explained by the digit apparent stiffness without extending the meaning of this term beyond reason. For instance, when the handle width increases or decreases, the point of application of the VF force changes in a regular way (goes up or down). Such a change can barely be explained by spring-like reactions of digits alone.

Tilt prevention: maintaining rotational equilibrium

The handle width represents the moment arm of the tangential forces. Hence, if in the nonzero torque tasks, the width changes and the tangential forces were to stay put, the M^t would change and unless adjustments of other moment components are made, the rotational equilibrium of the object would be broken. It seems that the simplest possible solution for the central controller is 1) to keep M^t constant by adjusting the tangential forces to the handle width changes and 2) not to change anything else, in particular the normal digit forces. However, the central controller does not use this “simplest” option preferring instead multiple adjustments of all the involved variables.

We hypothesize that this happens because of the perturbing effects of the stiffness-like reactions of the individual digits to their forcible displacement. In this task, such reactions may not be mechanically necessary (because the load force does not change) but are still unavoidable because of both biomechanical (e.g., Jacobian change) and neurophysiological (e.g., stretch reflex action) factors. As a result, the central controller should ensure the object equilibrium while facing both the handle expansion (a pure geometric factor) and the increase of the gripping forces caused by the mentioned built-in mechanisms. In other words, the stiffness-like reactions of the individual fingers assist mainly in perturbing the rotational equilibrium rather than in restoring it. Consider as examples, the L2 and R2 tasks.

In both tasks, when the handle expands 1) the moment arm of the tangential forces increases (this should increase the magnitude of M^t , which is negative in the L2 task and is positive in the R2 task) and 2) the normal forces increase, by assumption because of the built-in spring-like reactions of the fingers to their forced displacement (the ASn 's are positive; Fig. 7, A and B). If these two factors are not compensated, the magnitudes of M^t and M^n are expected to increase, thus disrupting the rotational equilibrium. To maintain the equilibrium, either M^n or M^t should decrease in magnitude.

The tangential force of the thumb in both tasks goes up while the VF force goes down: the ASt is positive for the thumb and is negative for the VF in all the tasks (cf. Fig. 7, C and D; see also Fig. 5 for an example of a single trial). The similar tangential force changes lead, however, to opposite mechanical effects in the L2 and R2 tasks. In the L2 task, the tangential force of the thumb is larger than the tangential VF force (Fig. 3B) and, hence, the M^t is negative (the supination moment, in clockwise direction). Because of the tangential force changes the difference between the forces increases and the M^t magnitude rises, i.e., the negative moment increases ($ASMt$ is negative, Fig. 6C). Therefore in the L2 task, the tangential force changes do not restore the rotational equilibrium; instead they assist the perturbation. In contrast, in the R2 tasks the similar changes of the thumb and VF tangential forces lead to a decrease in the difference between the forces as well as to a decrease in M^t . Thus while the thumb and VF tangential forces change in the same directions in the L and R tasks (ASt are positive for the thumb and negative for the VF in all the tasks; Fig. 7, B and C)—and $ASMt$'s are always negative (Fig. 6, C and D)—the mechanical effects of these responses in the L and R tasks are opposite: they increase the M^t magnitude in the L tasks and decrease it in the R tasks.

Because in the L and R tasks the thumb and VF normal and tangential forces change similarly—producing, however, opposite mechanical effects—the only mechanism that can be used to maintain the rotational equilibrium is a change of the moment arm of the normal digit forces ($Y_{vf} - Y_{th}$), mainly by a redistribution of the normal forces among the fingers. Because, in the L2 task, where the subjects produce the negative (supination) moments, the M^t magnitude increases (the $ASMt$ is negative; Fig. 6C), to compensate for this increase, the changes of the moment arm of the normal digit forces should be positive and large (Fig. 8). On the contrary, in the R tasks where the M^t magnitude decreases during the handle expansion—and hence compensates for the equilibrium perturbations—changes of ($Y_{vf} - Y_{th}$) can be small, as seen in the R1 task, or even negative, as in the R2 task. $ASMn$ is always positive, i.e., the magnitude of the moment of the normal forces decreases in the L tasks (where the moment itself is negative) and it increases in the R tasks. Figure 12 shows the described sequence of events.

In summary, in the L2 task, only one tool of rotational equilibrium control is used, namely an increase of the moment arm of the normal digit forces. In the R2 task, the equilibrium is maintained by the changes of the tangential forces that decrease M^t (in the L2 task analogous changes increase the M^t magnitude). In addition, the moment arm of the normal digit forces decreases, negating to some extent the rotational effect of the increased normal forces. However, $ASMn$ in the R2 task still remains positive (Fig. 6A), i.e., the M^n increases with the

handle expansion, and consequently, the rotational equilibrium is maintained solely by the decreased M^t (ASMt is negative; Fig. 6, C and D).

Some dependencies and correlations

We admit that at this time we cannot explain all the relations reported in Tables 1, 3, and 4 and Figs. 9 and 10. The following discussion addresses only some of them.

For the ASn, the lack of dependence from the initial normal force levels (Fig. 9A) is mechanically advantageous: scaling the ASn with the initial forces would change the M^n . Because the normal forces of the VF and thumb systematically increase with the torque magnitude (Fig. 3A), the same is valid for the absence of scaling of the ASn with the torque (Table 1). The positive correlations of the ASn with the ASp in the L2, L1, and Mi tasks and the negative correlations in the R1 and R2 tasks (Table 4; Fig. 10) are related with the fact that in the first group of tasks, the ASp is positive, whereas in the R2 task, it is negative (at speeds of 1.5 and 2.0 mm/s; see Fig. 7F). In the R1 task, the ASp is positive but very small. The dependence of the ASn on SPEED is not dictated by the task mechanics and will be discussed later in the text.

For the ASt, its correlations with the initial force levels are negative (Fig. 9B), but they have different meanings for the thumb where ASt are positive and for the VF where the ASt are negative. For the thumb, with the handle width expansion, the larger the initial tangential force, the smaller the tangential force increase; for the VF, the larger the tangential force, the larger the tangential force decrease. Because for the VF, the ASt values are negative, their negative correlation with the ASp means that, when the ASt magnitudes are larger, the ASp is also larger, i.e., in the tasks where the VF tangential force decreases to a larger extent, the point of force application displaces upward by a larger amount or displaces downward by a smaller amount.

In general, the differences in the ASn and ASt dependencies/correlations on the initial force levels and TORQUE (Table 1; Fig. 9) support an idea that the normal and tangential forces are influenced by different control mechanisms with the substantial contribution of local elastic-like (but SPEED dependent) mechanisms in the normal force control (stretch reflexes, changes in the digit Jacobians, passive stiffness of the constitutive tissues, e.g., the fingertips) and the lack of it in the control of tangential forces.

Elemental (local) versus synergy (global) reactions

We would like to suggest that the equilibrium maintenance in prehension is defined by two types of reactions, “local” (elemental) and “global” (synergy). In the present context, the term local (elemental) is used to designate the responses that start and end “at the same place,” e.g., at the same finger: if the finger equilibrium is perturbed a restoring force arises that tends to return the finger to its previous position.

When behavior of individual fingers at the contact with the object is characterized by stiffness matrices (S_i), the matrices depend on 1) the structural properties of the finger, e.g., on the deformability of the fingertip; 2) finger configuration, i.e., the finger joint angles represented by the finger Jacobian; and 3) individual joint stiffnesses that in turn depend on mechanical properties of the joint tissues, e.g., the tendon elasticity, and—what is most important—on the stiffness control (Cutkosky and Kao 1989). In robots, the control is realized through the joint servocontrol; in humans it may involve several mechanisms including but not limited to 1) changes in muscle activation levels produced through autogenic spinal reflexes triggered by changes in the activity of peripheral receptors located in the same muscles, 2) changes in

supraspinal commands to muscles, and 3) changes in muscle activity through nonlocal neural circuits related to task-specific organization of multidigit synergies.

In this study, the ASn, both at the VF level and IF levels (with the exception of the little finger at L 2 task), were positive (Figs. 7, A and B, and 11, A and B), i.e., the digit force increased with the handle expansion and decreased with the handle contraction. Such a behavior can be explained by a combination of passive mechanical resistance and the action of the stretch-reflex (Akazawa et al. 1983; Capaday et al. 1994; Cook and McDonagh 1996; Kanosue et al. 1983; Wallace and Miles 1998, 2001; but see Wessberg and Vallbo 1996). A more general explanation is provided by the equilibrium-point hypothesis. According to the equilibrium point hypothesis (Feldman 1966, 1986), voluntary muscle control is done by changing the threshold (λ) of the tonic stretch reflex for the involved muscles. For a fixed set of λ s to participating muscles, reactions of effectors to external displacements are expected to lead to muscle behavior defined by the tonic stretch reflex characteristics of the participating muscles. Because characteristics of the tonic stretch reflex within typical physiological ranges of muscle length have positive slopes (Gottlieb and Agarwal 1988; Latash and Gottlieb 1990; Nichols and Houk 1976), all ASn values defined by this mechanism are expected to be positive.

The ASn's (as well as ASts) depended statistically significantly on the SPEED; this means that, strictly speaking, they cannot be called "stiffness." The speed effect was also reported by Van Doren (1998). To distinguish the cases when the resistive force depends solely on the deflection magnitude from the cases when it depends also on the deflection speed, such terms as static stiffness and dynamic stiffness were used (Hajian and Howe 1997; Milner and Franklin 1998). If these terms are adopted, the ASn can be classified as a dynamic stiffness measure. The well-known velocity sensitivity of the primary endings of muscle spindle is expected to lead to a velocity-dependent component in the tonic stretch reflex. These effects have been incorporated into the equilibrium point hypothesis (Feldman 1986; Feldman and Levin 1995). They are expected to lead to velocity-dependent changes in AS. Such changes were actually observed in the reported experiments, both for the ASn and ASt.

The ASn values did not correlate with the initial grip force level. In the literature, it is usually either reported or assumed that stiffness increases with muscle force (e.g., Goubel 1978; Goubel et al. 1971; Hunter and Kearney 1982; Perreault et al. 2001; Zhang et al. 1998). However, it seems that the relations between the stiffness and the initial force levels are different at the different levels of musculoskeletal organization. In particular, for the fingers and grasping 1) at individual joints, the relations are positive (Akazawa et al. 1983; Becker and Mote 1990; Capaday et al. 1994; Carter et al. 1990, 1993; Hajian and Howe 1997); 2) for individual finger (s), the relations are not monotonic; the stiffness is lower for higher values of joint torques than for the smaller values (Milner and Franklin 1998); the decrease of the stiffness at the high levels of forces was attributed to the activation of the multi-joint muscles that perform antagonist functions in neighboring joints (e.g., interossei are the metacarpo-phalangeal joint (MCP) flexors and proximal interphalangeal joint extensors); and 3) for the grasps, stiffness increased in proportion to initial force (Van Doren 1998). In the latter study, the handle was not completely free to move, the rotational equilibrium was not addressed, and only the normal force of the thumb was measured. In this study, the maintenance of the rotational equilibrium was required and, hence, the task was quite different from those used in other studies.

The handle width change was accompanied by the changes in the tangential forces (Fig. 5). With the handle expansion, the thumb tangential force increased (ASt was positive; Fig. 7C), whereas the VF tangential force decreased (ASt was negative; Fig. 7D). Evidently the VF force decrease with the handle expansion cannot be explained by the stretch reflexes, e.g., by the reflexes initiated by the finger forcible abduction or adduction. With respect to possible MCP

abduction/adduction angle changes in the trials, we mention that these changes 1) are very small; 2) for the radial fingers (e.g., the index finger) and ulnar fingers (e.g., the little finger) are in opposite directions; and 3) generate opposite forces that should negate each other. These forces also should not depend on the initial torque, whereas ASt does (Fig. 7D).

The usual representation of the endpoint limb stiffness with 2×2 stiffness matrices (Dolan et al. 1993; Flash and Mussa-Ivaldi 1990; Gomi and Kawato 1997; Lacquaniti et al. 1993; Mussa-Ivaldi et al. 1985; Tsuji 1997; Zatsiorsky 2002) is also irrelevant because the matrices describe the stiffness in a flexion-extension plane and the tangential force in this study was exerted in the radial-ulnar plane. The orderly displacement of the point of application of the VF normal force, manifested in high correlations between the ASp and other variables (Tables 3 and 4; Fig. 10) cannot also be explained by the stretch reflexes acting on individual digits.

In general, our observations of changes in digit forces in directions orthogonal to the direction of displacement, i.e., changes in tangential forces, cannot be explained by local effects of changes in the muscle length. As such, they go beyond the equilibrium point hypothesis for control of individual muscles, and changes in commands to other muscles need to be postulated, particularly to muscles that produce adduction-abduction finger forces. These changes may get contribution from intermuscle spinal reflexes (Nichols 1989, 2002) and/or from changes in descending supraspinal commands to motoneurons innervating those muscles. Currently, we cannot separate these two factors. We suggest that changes of activation of muscles whose length is not affected by the imposed changes in the handle width are defined by multidigit synergies and can be partly predicted from chain effects (Shim et al. 2003).

Other facts whose explanation goes beyond the equilibrium point hypothesis include the observed changes in the ASp (Table 2; Fig. 7, *bottom*), the numerous correlations between the experimental variables (Tables 3 and 4), the high correlation between the ASt, and the initial levels of the tangential forces and the lack of such a correlation for the ASn (Fig. 9). While not all of these facts can be presently explained (both from the biomechanical and physiological perspectives), it seems that invoking the concept of synergy is a natural way of thinking about such complex relations.

The core of the prehension synergy is a necessity to maintain the rotational equilibrium of the handle. In particular, the following can be mentioned. 1) In the non-zero-torque tasks, the individual normal digit forces cannot increase in proportion to the initial force levels because such a proportional increase will increase the moment M^n exerted by the fingers on the handle and, hence, can breach the rotational stability of the object. 2) The change of the handle width changes the moment arm of the tangential digit forces (Eq. 3). Therefore any change of the handle width at constant values of the tangential forces modulates the moment of tangential forces M^t exerted on the handle. 3) Because the sum $M^n + M^t$ has to stay constant, a series of adjustments in the digit forces is necessary. Such adjustments should also account for the changes of the normal forces induced by the digit local reactions (e.g., by the stretch reflexes). Note that, in this study, changes of the normal digit forces in response to the perturbations are mechanically not necessary: the load is constant and there is no need in changing the grip force to prevent the object slipping.

Summing up the following explanation of the observed modulations of the digit forces is offered. At the local level, 1) the normal digit forces change because of the stretch reflexes and other local mechanisms (e.g., the change in the finger Jacobians) and 2) the moment arms of the tangential forces vary. At the synergy level, to attenuate the effect of the 1) and 2) from above, the tangential finger forces change (Fig. 5), M^n and M^t change in opposite directions (Fig. 4), and the normal digit forces are adjusted to the torque equilibrium requirements (Table 4). Metaphorically speaking, the local digit reactions are harnessed by the prehension synergy.

The interaction between the local and synergy mechanisms of maintaining grasp stability is not limited to effects of grasp width changes. Another example of a similar interaction is the finger force adjustments to the local friction at the fingertip interfaces when an object should be at equilibrium (Aoki et al. 2006). Although such adjustments arise from the independent networks controlling each engaged digit (Burstedt et al. 1997; Edin et al. 1992), the central controller is still able to maintain the object equilibrium, which requires coordinating activity of all involved digits.

What solutions does the CNS prefer?

The most economical solution to the handle expansion or contraction (in the sense of the minimal number of performed adjustments) would be changing the tangential digit forces to accommodate for the perturbation in the handle width and not changing anything else, e.g., the M^n . Instead the CNS prefers a “global” solution such that all the involved forces and moments (except of the resultant tangential force and moment) are changed. Also, if the change of M^n is desired, it can be done by 1) changes of the normal digit forces, 2) changes of the point of VF normal force application, or 3) both. Again, the CNS changes “everything.” In turn, changes of the point of VF normal force application can be achieved by 1) the different distribution of the total normal force among individual digits, 2) displacement of the points of application of the finger force application on the sensor surface, or 3) both. Once again, the CNS prefers to change everything. It seems that activation of a minimal number of the contributing elements is not what bothers the central motor controller. This fact should be taken into consideration in the studies that attempt to use mathematical methods of optimization in the prehension control research (e.g., Pataky et al. 2004b; Zatsiorsky et al. 2002b). Bernstein (1967) was right again: “The system never reacts locally to a local change.”

Is the virtual springs theory applicable to human prehension?

Only as a first approximation. The observed effects of the perturbations on the digit forces do not follow a simple pattern, but in general, they do not support the virtual springs theory according to which the digit action during prehension is similar to an action of a set of interacting springs. The theory assumes hard finger contacts with the objects (point contacts with friction); in such a contact, the point of finger point application does not displace. This is not valid for human grasps (Zatsiorsky et al. 2003a,b. As follows from this study, the points of force application displace and the ASps are carefully controlled. Another difference between the human and robot hands is in the MCP joints: in robots, the joints are usually simple hinges (1 degree of freedom joints) and the tangential fingertip forces are supported passively by the hand structure; in humans, the tangential forces at the MCP joints require active control. (The virtual spring theory allows for including the tangential forces and MCP moments into consideration, but this is typically not done.)

In general, the theory provides a nice computational tool and a formal framework to discuss the grasp stability, but it lacks the explanation power: it does not explain it describes. For instance, the simple cause-effect relations such as 1) changing the handle width changes the moment arms of the tangential forces→, 2) the moment of tangential forces changes→, 3) to maintain the total moment constant the M^1 should be changed→, and 4) the individual normal finger forces change cannot be deduced readily from the theory.

The strongest feature of the theory is that it describes stability conditions for all possible perturbations provided that proper coefficients of the stiffness matrix are established and the perturbation does not exceed a certain limit. In this case, the stability maintenance does not require on-line control or a special task adjustment. The CNS, however, does not use this option: all the recorded variables change between the tasks. It seems that the theory provides sufficient but not necessary conditions for the grasp stability, i.e., the grasp stability can be

maintained according to the theory, but it can also be maintained in other ways. This is what the CNS does.

Delimitations of the study

We have to acknowledge the numerous delimitations of this study. In particular, 1) only planar tasks were studied, 2) the perturbations were applied in only one normal direction, 3) all the digits experienced the same perturbation, 4) the changes in the digit Jacobians have not been identified (including the changes in the ab/adduction angles at the MCP joints), and 5) an EMG was not recorded, and the relation between the stiffness control and corresponding muscle activity remains unknown. As a result of 2) and 3), we were not able to determine all the elements of the stiffness matrices. Because of 3), the possible effects of finger enslaving and force deficit (Li et al. 1998a,b; Zatsiorsky et al. 1998, 2000) have not been identified. Because of the technical delimitations, we were not able to separate the DIRECTION and RANGE effects. Also, it seems that the handle width (80–100 mm) was too big for the convenient placement of the little finger, and during the perturbation in some subjects, the finger visibly rolls on the sensor such that the force was exerted by its medial side. Despite our efforts, we were not able to decrease the handle width because we had to use a powerful motor to displace the moving assembly and the digits at a prescribed rate. The handle expansion/contraction is rather unusual in everyday living and was new for naïve subjects. The effects of learning in such a task can be substantial, but we did not study them. We hope that these shortcomings will be overcome in the future studies.

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Fig. 1.

Schematics of the motorized handle. A system of gears is meshed together to control the speed of movement of 2 branches to which force sensors for the thumb and the fingers are attached. Rotation of a stepper motor is transmitted through the vertical threaded worm to the 2nd threaded horizontal worm that in turn meshes with the toothed discs fixed to the 2 branches. Rotation of the stepper motor results in equal displacement of the branches such that their positions with respect to the midcentral line of the handle remain symmetric. Because of this symmetry, location of the center of gravity of the handle and hence the external moment did not change during the handle expansion or collapse (with the exception of the effect induced by the weight of the 3 finger sensors; the weight of each sensor was 0.09 N; hence during the trial the moment was changed by only $0.09 \text{ N} \times 0.00325 \text{ m} \times 3 \text{ sensors} = 0.0009 \text{ Nm}$; this effect was neglected in the analysis). The distance of 1 of the branches from the external frame of the handle (and hence the instant values of the handle width) is controlled with a laser sensor. ψ_i designates the vertical coordinate of the point of force application with respect to the sensor center i .

Fig. 2.

Selecting the 6.5-mm windows; digit grip forces in relation to handle width in individual trials are shown. Representative examples, 0-torque tasks. *A*: expansion at 3 different speeds (index finger). *B*: contraction at 3 different speeds [virtual finger (VF)].

Fig. 3.

Digit forces before the grip width change, handle width 80 mm. Group averages and SE. *A*: normal forces. *B*: tangential forces. *C*: moment arm of the normal forces, $Y_{vf} - Y_{th}$. In this and other figures, the torques are described by the load location with respect to the center of the beam: R, right; L, left; Mi, middle; 1, 0.25 Nm; 2, 0.5 Nm. As an example, the symbol R2 represents the load location to the right of the center that results in the moment of -0.5 Nm. Such a moment—as seen from the subject—is in the clockwise direction (negative). To counterbalance this external moment/torque, the subject should exert a counterclockwise (pronation, positive) moment of equal magnitude.

Fig. 4.

Profiles of moments in time domain under different torque conditions (a representative example, subject 7, expansion at 2 mm/s). M^t is the moment of tangential forces and M^n is the moment of the normal forces. Note that, in the L1 and L2 tasks, the resultant moments exerted on the handle ($M^t + M^n$) are negative. In the 0-torque L1 and R1 tasks, the M^n and M^t moments are in opposite directions: the moments of the normal forces are positive while the moments of the tangential forces are negative (i.e., the normal forces tend to rotate the object in counterclockwise direction, whereas the tangential forces tend to rotate the object in clockwise direction). In the R2 task, both the M^n and M^t are positive, i.e., they are in the counterclockwise (pronation) direction.

Fig. 5. Tangential force (N) vs. displacement (a representative example, a 0-torque task, subject 1, expansion at 2 mm/s).

Fig. 6.
The apparent stiffness (AS)Mn and ASMt values in different tasks. Note that the ASMn and ASMt mirror each other. Group means, the vertical lines designate the SE.

Fig. 7.

Apparent stiffness at the VF level during the handle expansion. Group means, the vertical lines designate the SE. A: ASn (thumb). B: ASn (VF). C: ASt (thumb). D: ASt (VF). E: ASp (thumb). F: ASp (VF).

Fig. 8.
Changes of the moments arms of the thumb and VF normal forces per unit of the handle width change, ΔASp .

Fig. 9.

The intertask correlations between the level of the initial force (abscissa) and the AS for the thumb. Group averages, SE of both initial force, and AS are shown. *A*: ASn vs. initial grip force level. *B*: ASst vs. initial tangential force levels. Handle expansion, initial width 80 mm, $n = 15$ (5 torques $\times$ 3 speeds). For $n = 15$, empirical coefficients of correlation equal or exceeding 0.514 (2-tailed test) are statistically significant at $P = 0.05$. Correlations for the VF were similar.

Fig. 10.

Scattergrams of the relations between the VF ASp and ASn examples. *Left:* L1, handle expansion at 2 mm/s. *Right:* R2, handle contraction at 2 mm/s. For the computation, the data for 8 subjects and 3 trials per subject were combined (totally $8 \times 3 = 24$ cases, different symbols represent individual subjects).

Fig. 11. Apparent stiffness of individual fingers. *A* and *B*: ASn. *C* and *D*: ASst. Group average and SE, expansion at 2 mm/s.

Fig. 12.

Maintaining the rotational equilibrium of the object during handle expansion, a schematic. *A*: L2 task. *B*: R2 task. $(F_{vf} - F_{th})$ is the difference between the tangential forces of the VF and the thumb (see Eq. 3). In the L2 task, equilibrium is maintained because of the M^n changes opposing the perturbation, specifically because of the changes of the moment arm of the normal digit forces. In the R2 task, the equilibrium is maintained by the M^t changes. Note that in both tasks, the M^t changes are similar; they are in the same (negative) direction. Figure is not drawn to scale.

TABLE 1

Effects of the handle expansion and contraction on the magnitudes of the moments of the normal (M^n) and tangential (M^t) forces in the pronation (+) and supination (−) effort tasks

Initial torque effort	Handle expansion (+)		Handle contraction (−)	
	Moment of normal forces	Moment of tangential forces	Moment of normal forces	Moment of tangential forces
Pronation (positive, +)	Increases, (+, +)	Decreases, −(+, +)	Decreases, (+, −)	Increases, −(+, −)
Supination (negative, −)	Decreases, (−, +)	Increases, −(−, +)	Increases, (−, −)	Decreases, −(−, −)

TABLE 2

Effects of the task conditions on the AS of the thumb and VF

	ASn		ASt		ASp	
	Thumb	VF	Thumb	VF	Thumb	VF
Direction (<i>D</i>)	0.00	0.02	0.00	0.07	0.00	0.00
Speed (<i>S</i>)	0.00	0.00	0.00	0.00	0.60	0.24
Torque (<i>T</i>)	0.21	0.29	0.00	0.00	0.00	0.00
<i>D</i> × <i>S</i>	0.06	0.06	0.19	0.15	0.00	0.58
<i>D</i> × <i>T</i>	0.21	0.21	0.00	0.00	0.00	0.00
<i>S</i> × <i>T</i>	0.63	0.63	0.06	0.09	0.60	0.31
<i>D</i> × <i>S</i> × <i>T</i>	0.62	0.62	0.07	0.10	0.46	0.53

The results of the 3-way repeated-measure ANOVA. To save space, only the significance levels are shown and the interaction effects are not presented. The number of degrees of freedom for the factors DIRECTION, SPEED, and TORQUE is 1, 2, and 4, respectively. Statistically significant ($P < 0.05$) cases are printed in bold italics. The complete ANOVA results can be provided on request sent to fan-gao@northwestern.edu. AS, apparent stiffness; VF, virtual finger.

TABLE 3
Coefficients of correlation between the ASp and ASi values for the VF (n = 24; 8 subjects × 3 trials)

Direction of Perturbation	Speed	Torques				
		L2	L1	Mi	R1	R2
Expansion	1 mm/s	-0.84	-0.89	-0.82	-0.70	-0.48
	1.5 mm/s	-0.81	-0.63	-0.87	-0.57	-0.63
	2 mm/s	-0.63	-0.88	-0.89	-0.45	-0.29
Contraction	1 mm/s	-0.86	-0.80	-0.83	-0.69	-0.76
	1.5 mm/s	-0.74	-0.87	-0.78	-0.39	-0.61
	2 mm/s	-0.76	-0.75	-0.81	-0.53	-0.24

For n = 24, the empirical coefficients of correlation equal or exceeding 0.404 are statistically significant at P = 0.05 (2-tailed test). See Fig. 3 for abbreviations.

TABLE 4
Coefficients of correlation between the ASp and ASn values for the VF (n = 24; 8 subjects × 3 trials)

Direction of Perturbation	Speed	Torques				
		L2	L1	Mi	R1	R2
Expansion	1 mm/s	0.56	0.28	0.25	-0.32	-0.38
	1.5 mm/s	0.66	0.58	0.29	-0.15	-0.26
	2 mm/s	0.58	0.88	0.32	-0.31	-0.36
Contraction	1 mm/s	0.66	0.52	0.49	-0.29	-0.22
	1.5 mm/s	0.38	-0.02	0.29	-0.41	0.00
	2 mm/s	0.50	0.17	0.07	-0.44	-0.51

See Table 2 for abbreviations.

TABLE 5

Effects of the task conditions on the AS of individual fingers

	DIRECTION	SPEED	TORQUE	D × S	D × T	S × T	D × S × T
ASn	Index	0.03	0.00	0.11	0.15	0.37	0.33
	Middle	0.94	0.02	0.26	0.23	0.00	0.98
	Ring	0.02	0.04	0.26	0.24	0.30	0.98
	Little	0.97	0.06	0.00	0.23	0.69	0.72
ASi	Index	0.01	0.01	0.00	0.17	0.20	0.83
	Middle	0.05	0.73	0.10	0.65	0.15	0.68
	Ring	0.98	0.61	0.19	0.81	0.00	0.99
	Little	0.00	0.28	0.00	0.99	0.00	0.68
ASp	Index	0.01	0.14	0.00	0.38	0.45	0.32
	Middle	0.00	0.38	0.03	0.83	0.04	0.24
	Ring	0.00	0.63	0.03	0.05	0.10	0.96
	Little	0.00	0.01	0.00	0.77	0.10	0.00

The results of the 3-way repeated-measure ANOVA. To save space, only the significance levels are shown and the interaction effects are not presented. The number of degrees of freedom for the factors DIRECTION (D), SPEED (S), and TORQUE (T) is 1,2, and 4, respectively. Statistically significant ($P < 0.05$) cases are printed in bold italics. The complete ANOVA results can be provided on request to fan-gao@northwestern.edu See Table 2 for abbreviations.