Unlike robots, people modulate internal forces during object manipulation

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Abstract. Internal force is a set of contact forces that does not disturb object equilibrium. The mathematical independence of the internal and manipulation forces allows for their independent (decoupled) control realized in robotic manipulators. As this study shows, the central nervous system uses another strategy: the internal forces change with the manipulation forces. During the parallel manipulations, the internal (grip) force increases or decreases in phase with the manipulation force. During the orthogonal manipulations, the internal changed out of phase with the manipulation force; the plots of the internal force vs. object acceleration resembled an inverted V letter.

Key words: Internal force, Manipulation force, Grasping, Fingers, Prehension synergy, Robots

1 Introduction

In multi-digit grasping, a vector of contact forces and moments **f** can be broken into two orthogonal vectors: the resultant force vector $\mathbf{f}_\mathbf{r}$ (manipulation force) and the vector of the internal force $\mathbf{f}_\mathrm{i}$ ($\mathbf{f} = \mathbf{f}_\mathbf{r} + \mathbf{f}_\mathrm{i}$) [1, 2]). The elements of the internal force vector $\mathbf{f}_\mathbf{i}$ cancel each other and, hence, do not contribute to the manipulation force. A performer can choose innumerable combinations of the force elements provided that they cancel each other, for instance, the performer can grasp an object stronger or weaker. The mathematical independence of the internal and manipulation forces allows for their independent (decoupled) control which is realized in robotic manipulators [e.g. 3]. Such a control saves computation resources. In daily life, people commonly manipulate hand-held objects. It is unknown whether they, similar to robots, use the decoupled control.

2 Terminology

Virtual Finger (VF) is an imaginary finger that produces a wrench (the force and moment) equal to the sum of wrenches produced by all the fingers The *handle orientation* is defined by the angle between the longitudinal axis of the handle and the vertical. At the vertical handle orientation, the angle is zero. *The direction of manipulation* is defined with respect to either vertical or the horizontal axes. 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. *Grasping synergy* (GS) is a conjoint change of the normal digit forces.

3 Problem formulation

This study addresses the following general problem: How is the internal force-manipulation force coupling —if it exists—affected by such factors as grasp orientation and direction of manipulation? Specifically, we are interested in two questions: (1) Is the internal force coupled with the manipulation force? To answer this question we analyzed whether the internal forces/moments change conjointly with the handle acceleration (the handle acceleration is representative of the manipulation force acting on the object)? (2) Do grasping synergies depend on the type and parameters of object manipulation?

4 Methods

4. 1 Experiment

A customized aluminum handle instrumented with five six-component force/torque transducers (Nano-17, ATI Industrial Automation, Garner, NC, USA) was used. The subjects performed vertical (V) and

horizontal (H) cyclic movements at the three handle orientations: vertical (V), horizontal, and diagonal (D, inclined 45°) were used. The following six tasks were performed: (1-2) Parallel manipulations: VV task (vertical orientation-vertical movement) and HH task.
(3-4) Orthogonal manipulations: VH and HV tasks. (5-6) Diagonal manipulations:DV and DH tasks. In each task, five loads were used: 3.8 N, 6.3 N, 8.8 N, 11.3 N and 13.8 N (including the weight of the handle with the sensors). The oscillations were performed at three frequencies, 1.0 Hz, 1.5 Hz and 2.0 Hz.

4.2 Determining the internal forces

In five-digit grasps, vector of individual digit forces and moments **f** is a 30×1 vector. Its relation with a 6×1 vector **F** of the resultant forces and moments acting on the object is described by – **F**=**Gf,** where **G** is a 6×30 grasp matrix [4]. Vector of the internal forces $\mathbf{f}_i$ lies in the null space of **G.** The null space of a *m* by *n* matrix **G** is the set of all vectors **f** in R^n such that $\mathbf{Gf} = \mathbf{0}$

$\{\mathbf{f} \in \mathbf{N(G)} | \mathbf{Gf} = \mathbf{0}\}$. Because the rank of a 6×30 matrix is at most 6, the nullity of the grasp matrix is at least 24. Analysis of all the 24 basic vectors of **N(G)** would be a daunting task. Therefore, only the normal and tangential components of the VF and thumb forces were analyzed. The two orthonormal basis vectors spanning the null space of **G** were then calculated by using the singular value decomposition with function, *null*, in Matlab 6.1. The two internal forces are the *grip force* and the *internal moment* (the moment of normal forces can be canceled by the moment of the tangential forces).

5 Results

The examples of the obtained results for the two tasks are presented in Fig. 1 and 2.

Fig. 1. VV manipulation. Top panel. 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. Bottom panel. The VF normal force – thumb normal force phase angles (circular histogram). The phase angles cluster around zero degree.

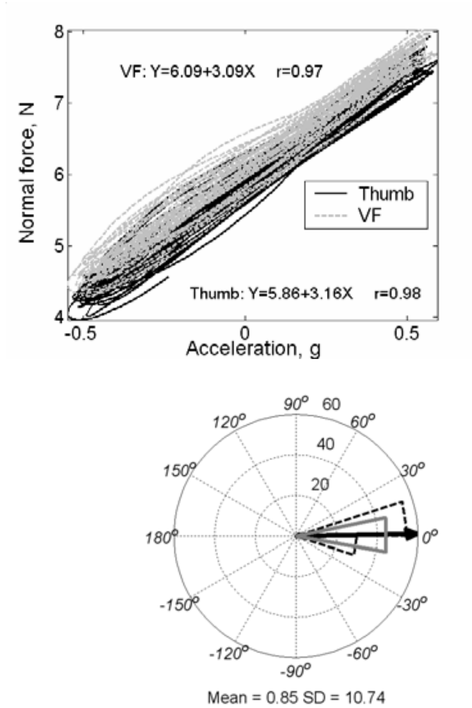
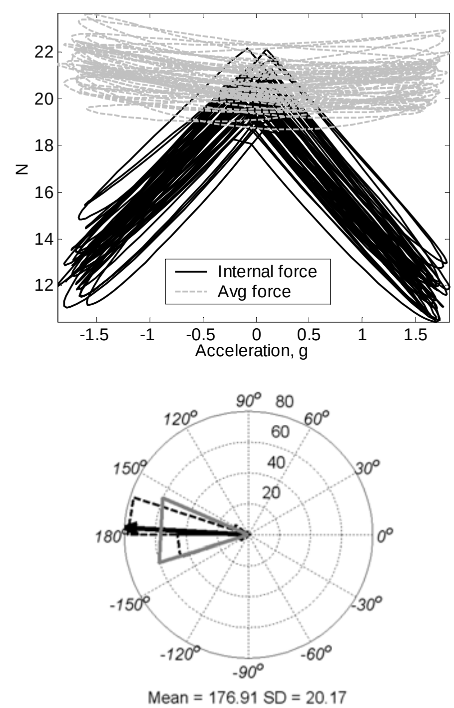


Fig. 2. VH manipulation. Top. Internal force and average normal force versus the handle acceleration. Bottom panel. The thumb normal force-VF normal force phase angle, a circular histogram. The phase angles cluster around 180 degrees.



(b)

In general, during the parallel manipulations, the internal (grip) force was coupled with the manipulation force (producing object acceleration) and the thumb-VF forces increased or decreased in phase: the thumb and VF worked in synchrony to grasp the object stronger or weaker. During the orthogonal manipulations, the thumb-VF forces changed out of phase; the plots of the internal force vs. object acceleration resembled an inverted V letter. The HV task was the only task where the relative phase (coupling) between the normal forces of the thumb and VF depended on oscillation frequency. During the diagonal manipulations, the coupling was different in the DV and DH tasks.
Substantial internal moments have been observed in all the tasks: the moments produced by the normal finger forces were counterbalanced by the moments produced by the tangential forces such that the resultant moments were close to zero.

6 Discussion

Internal forces do not affect equations of motion and hence control of manipulation can be broken up into two sub-tasks—'holding' and 'tracking'—which can be controlled independently. For instance, the performers in our tests could grasp the object with a large force and then keep this force constant during the performance. Such a control strategy (which is commonly used in robotic grippers) simplifies the control —the controller does not have to bother about on-line adjustments of the grip force to the object acceleration and/or orientation. This strategy requires, however, exerting unnecessarily large forces and is in this sense uneconomical. Available data suggest that at least in some tasks the central nervous system prefers to face larger computational costs rather than produce excessive forces.
To summarize the results on the internal force during the object manipulation we conclude that the CNS uses different patterns of the thumb-VF coordination when the manipulation force is in a tangential direction as compared with the manipulation in the normal direction. When the manipulation force is in a tangential direction, the symmetric pattern of the thumb-VF coordination is used: The thumb and VF work in synchrony to grasp the object stronger or weaker. In contrast, when the manipulation force is in the normal direction the anti-symmetric force changes are recorded: When the normal force of either thumb or VF increases, the force exerted by the opposing digits decreases.

7 Conclusion

In contrast to robotic controllers, the central nervous system adjusts the internal forces to the manipulation force. Such a strategy increases the computational cost but decreases excessive force production.

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