Two Control Processes Associated with Multi-Digit Prehension

Mark L.LATASH, Jae Kun SHIM, Fan GAO, and Vladimir M. ZATSIORKY
Department of Kinesiology, The Pennsylvania State University,
University Park, PA 16801, USA mll11@psu.edu

Abstract. Different computational approaches have been applied to analyis of how the central nervous system (CNS) solves the problem of motor redundancy. We studied individual digit forces and points of their application (elemental variables) during planar static prehension tasks. The subjects held an instrumented handle against external load/torque combinations using prismatic grasps. Patterns of variability of elemental variables across many attempts at the same task showed the existence of two subgroups of the variables with strong covariations within each subgroup and no covariations across the subgroups. The covariations were partly necessitated by the mechanical constraints, and partly represented choice by the CNS. Two subgroups were associated with two task components: First, holding the handle statically and preventing it from slipping out of the hand; and Second, preventing the handle from rotating under the action of the external torque. The existence of two control processes was confirmed in another experiment when subjects held the handle against different external load/torque combinations. Elemental variables showed significant changes with the external load and with the external torque without interactions between these two factors. We conclude that static prehension tasks involve two control processes associated with two null-spaces based on subgroups of elemental variables.

1. Introduction

The coordination of redundant motor systems has been a hotly debated topic since the seminal works by Bernstein (1967) where he formulated the famous problem of motor redundancy. Recently, it has been suggested that the central nervous system (CNS) does not eliminate redundant degrees-of-freedom (we are going to refer to these as "elemental variables") but creates sub-spaces (uncontrolled manfolds, Scholz & Schöner 1999; reviewed in Latash et al. 2002; null-spaces, Todorov & Jordan 2002) corresponding to selective stabilization of particular performance variables. This approach has been applied to a variety of motor tasks including the coordination of finger forces in multi-finger force production tasks (Latash et al. 2001; Scholz et al. 2002). In particular, we have recently discussed possible applications of this approach to handwriting (Latash et al. 2003).

On the other hand, recent progress in robotics has suggested a principle of superposition for the control of multi-element systems (Arimoto et al. 2001; Doulgeri et al. 2002). According to this principle, some skilled actions can be decomposed into several elemental actions that are controlled independently by separate controllers. In particular, it has been shown that a dexterous grasp and manipulation of an object by two soft-tip robot fingers can be realized by a linear superposition of two commands related respectively to stable grasp and regulation of the orientation of the object. Such a decoupled control decreases the computation time.

When a task requires stabilization of more than one performance variable simultaneously, it can be accomplished by creating uncontrolled manifolds for each of the performance variables using all the elemental variables or by creating subgroups of elemental variables such that each subgroup deals with stabilization of only one performance variable. The latter solution would comply with the principle of superposition. The main purpose of the current study has been to investigate whether multi-digit prehensile tasks are organized according to the principle of superposition. In the experiments, we manipulated two task variables, external load and external torque, and studied patterns of changes of elemental variables, individual digit forces and points of their application, when the subjects performed the same task many times and when they performed tasks that differed in the magnitudes of the external load and torque.

2. Methods

In the experiments, the subjects held statically a handle using prismatic grips (Figure 1). The handle was instrumented with ATI six-dimensional transducers that measured three components of force and three components of moment applied by the digit. The T-shaped attachment allowed independent variation of external load and torque. In the first experiment, the subjects (n=6) exerted the supination (negative) and pronation torques of –1.0 Nm, –0.5 Nm, 0 Nm, 0.5 Nm and 1.0 Nm. The load was always 14.8 N. At each torque, the subjects performed 25 trials. Tthe instruction to the subjects was to grasp the handle by placing the fingertip centers at the centers of the sensors and always apply a minimal effort. Finger forces and moments were recorded and the coordinates of the points of force application were computed. The analysis was limited to the planar static case; the forces of the fingers opposing the thumb were reduced to one resultant force (the virtual finger, VF, force; MacKenzie & Iberall 1994; Baud-Body & Soechting 2001). The forearm, wrist and hand positions were fixed.

In the second experiment, subjects (n = 18) held a similar handle while both external load and torque varied. The loads were 14.7 N, 19.6 N, 24.5 N and 29.4 N and the torques were –1.5 Nm, -1.125 Nm, –0.75 Nm, –0.375 Nm, 0 Nm, 0.375 Nm, 0.75 Nm, 1.125 Nm and 1.5 Nm, in total 36 combinations. The instruction to the subjects was the same as in the first experiment. Multivariate ANOVA with the LOAD and TORQUE as factors was performed with tangential and normal digit forces as the outcome variables (10 variables in total). The task was similar to holding a glass filled with a liquid. The weight of the object and the magnitude of the resisted torque varied among the trials (we used similar experimental setups in previous studies, more detailed description can be found in Zatsiorsky et al. 2002).

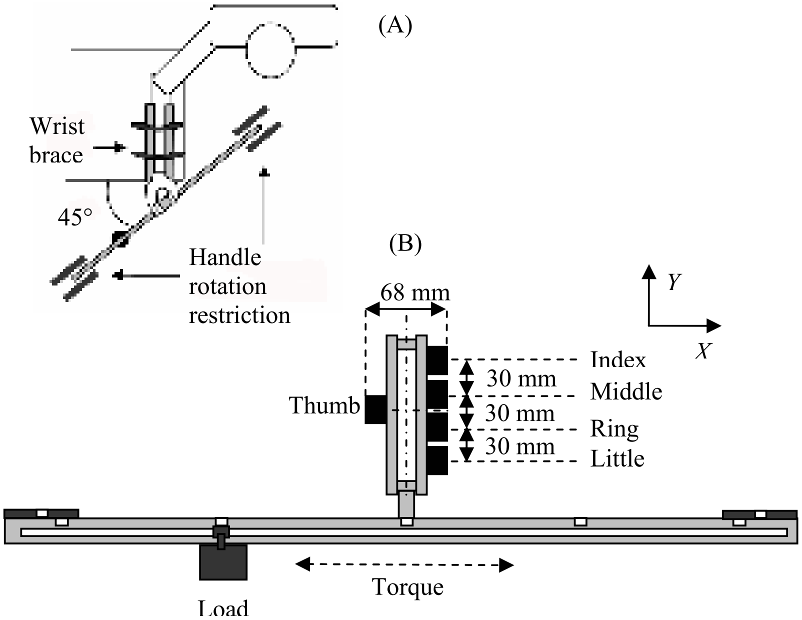

Figure 1. (A) The experimental settings and (B) the handle with the T-shape attachment and the digit placement.

3. Results

In the first experiment, repetitive trials at the same task were associated with variations in the performance variables that showed reproducible relations when analyzed at the level of forces and moments produced by the thumb and by the VF. Correlation analysis among the performance variables has shown that they formed two subsets (Figure 2A). The variables within each subset highly correlated with each other over repetitions of a task while the variables from different subsets did not show significant correlations. The first subset included normal forces of the thumb and VF (Figure 2Aa). The second subset included tangential forces of the thumb and VF, the moments produced by the tangential and normal forces, and the moment arm of the VF normal force, D_{vf}^{n} (Figure 2Ac-f). In particular, trial-to-trial changes of the VF normal force F_{vf}^{n} did not correlate with the variations of the VF moment of the normal force M_{vf}^{n} (Figure 2Ab). Because the moment of the normal force is simply the product of the VF normal force and its moment arm, this lack of correlation is counter-intuitive. On the other hand, a high correlation between M_{vf}^{n} and the tangential force of the thumb F_{th}^{t} was discovered (Figure 2Af). There was also a high correlation between F_{th}^{t} and D_{vf}^{n} (not illustrted in Figure 2A).

(A) (B)

Figure 2. (A) Interrelations among the experimental variables measured in a representative subject over repetitions of the same task. (B) The VF tangential forces at different magnitudes of the load and the resisted torque (averaged data).

In the second experiment, when both exteranl load and torque changed in a systematic manner, the effects of LOAD and TORQUE on all the finger forces, both normal and tangential, were highly significant ($p < 0.001$). In contrast, there were no significant LOAD×TORQUE interactions for any of the normal and tangential forces ($p > 0.6$). Figure 2B illustrates that the finger force changes associated with manipulation of one of the factors did not depend on the magnitude (level) of the other factor.

4. Discussion

The high interdependence among variables at the VF level of control is evident from Figure 2. Due to the static nature of the task, most of the relationships are very strong (with coefficients of correlation close to ≤1.0) and the compensations are transparent in the sense that variations in an elemental variable are nearly perfectly matched by variations in another variable(s) such that a functional performance variable, dictated by the task, is stabilized. Some of these relations are necessitated by the mechanical requirements of the task. For example the magnitudes of the normal forces of the thumb and the VF should be equal to prevent the object from moving. Similarly, the sum of the thumb and VF tangential forces should be equal to the external load. Other relations, however, are not obviously dictated by the mechanics of the task. In particular, the task mechanics does not prescribe the magnitude of either of the tangential forces, thumb or VF, only their sum. It also does not prescribe their trial-to-trial variations. The lack of correlation between the normal force F_v^n and the moment that the force generates (Figure 2b) suggests that the CNS does not use all mechanically possible options to control the moment of VF normal force M^n. Mechanically, the trial-to-trial tuning of the M^n can be achieved by variations of the F_v^n (i.e. by proportional changes of all normal finger forces) but the CNS does not use this option. Instead it mainly controls the moment arm by adjusting the sharing pattern of finger forces.

On the whole, the data show that elemental variables are organized in null spaces and thus support the uncontrolled manifold hypothesis (Scholz & Schöner 1999). The results of both experiments suggest that the principle of superposition (Arimoto et al. 2001) is valid for the control of multi-finger prehension in humans. Forces and moments of individual digits are defined by two independent commands: “Grasp the object stronger/weaker to prevent slipping” and “Maintain the rotational equilibrium of the object”. The effects of the two commands are summed up.

5. Acknowledgments

The study was supported in part by grants AG-018751 and NS-35032 from the National Institutes of Health, USA.

6. References

Arimoto S., Tahara K., Yamaguchi M., Nguyen P.T.A., and Han H.Y. (2001) Principles of superposition for controlling pinch motions by means of robot fingers with soft tips. *Robotica* 19, 21-28.

Baud-Bovy G. and Soechting J.F. (2001) Two virtual fingers in the control of the tripod grasp. *Journal of*

Neurophysiology 86, 604-615.

Bernstein N.A. (1967) *The Co-ordination and Regulation of Movement*. Pergamon Press, Oxford.

Doulgeri Z., Fasoulas J., and Arimoto S. (2002) Feedback control for object manipulation by a pair of soft tip fingers. *Robotica* 20, 1-11.

Latash M.L., Scholz J.F., Danion F., and Schöner G. (2001) Structure of motor variability in marginally redundant multi-finger force production tasks. *Experimental Brain Research* 141, 153-165.

Latash M.L., Scholz J.P., and Schöner G. (2002) Motor control strategies revealed in the structure of motor variability. *Exercise and Sport Science Reviews* 30, 26-31.

Latash M.L., Danion F., Scholz J.F., Zatsiorsky V.M., and Schöner G. (2003) Approaches to analysisof handwriting as a task of coordinating a redundant motor system. *Human Movement Science* 22, 153-171.

MacKenzie C.L. and Iberall T. (1994) *The Grasping Hand*. North Holland, Amsterdam.

Scholz J.P. and Schöner G. (1999). The uncontrolled manifold concept: Identifying control variables for a functional task. *Experimental Brain Research* 126, 289-306

Scholz J.P., Danion F., Latash M.L., and Schöner G. (2002) Understanding finger coordination through analysis of the structure of force variability. *Biological Cybernetics* 86, 29-39.

Todorov E. and Jordan M.I. (2002) Optimal feedback control as a theory of motor coordination. *Nature Neuroscience* 5, 1226-1235.

Zatsiorsky V.M., Gregory R.W., and Latash M.L. (2002) Force and torque production in static multi-finger prehension: Biomechanics and Control. Part I. Biomechanics. *Biological Cybernetics* 87, 50-57.

Zatsiorsky V.M., Gao F., and Latash M.L. (2003) Prehension synergies: Effects of object geometry and prescribed torques. *Experimental Brain Research* 148, 77-87.