FORCE VARIABILITY AND NULL SPACES IN HIERARCHICAL ORGANIZATION OF STATIC HUMAN PREHENSION

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INTRODUCTION

Both theoretical analyses (Iberall, 1997) and experimental evidence (Santello, Soechting 1997; Zatsiorsky et al., 2002) have suggested that prehension is controlled in a hierarchical fashion. The hierarchical organization is based on a virtual finger which is an imaginary finger that generates the same mechanical effect as a set of actual fingers. This study employed two hierarchical levels of finger control; virtual finger level (VF) and individual finger level (IF). The accuracy and stability of static force production has been the object of many research efforts. However, little is known about trial-to-trial variability in human prehension under different external torque conditions. We hypothesized that a) the variability of the variables would differ in different subjects and tasks, b) the variability of forces would depend on their magnitudes and c) there would exist more than one null space in the prehension tasks.

METHODS

Equipment: Four six-component (three forces and three moments) transducers (Nano-17, ATI Industrial Automation, Garner, NC, USA) were attached to an aluminum handle which had a beam affixed to the bottom. A load was attached to the beam at different positions to create different external torques: –1.0 Nm, –0.5 Nm, 0 Nm, 0.5 Nm, and 1.0 Nm.

Experimental Procedure: Subjects (n=6, male, right-handed) sat on a chair and positioned the right upper arm on a wrist-forearm brace fixed on the table. Subjects performed 25 trials at each torque condition. Subjects were instructed to stabilize the handle with the thumb and three fingers without the little finger. A planar static task was chosen with a prismatic grip.

Accuracy Measurement: The error propagation and uncertainty of indirect measurements were estimated from the data reported by the producer for individual sensors. The propagation of uncertainty in the elemental errors u_i to the uncertainty of the result u_R was computed as (Taylor 1997):

$$u_R = \pm\sqrt{\sum_{i=1}^{n}\left(\frac{\partial R}{\partial x_i}u_i\right)^2} \quad (1)$$

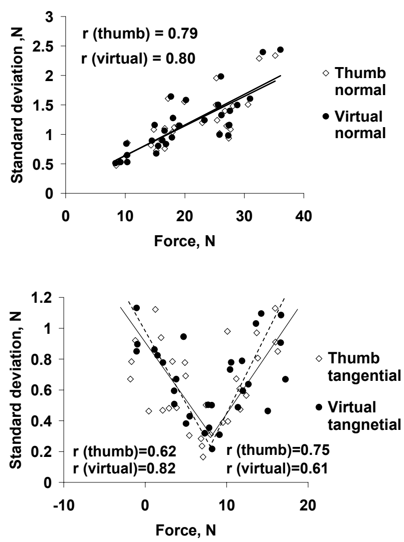
Statistics: Levene's homogeneity tests were performed to determine whether the trial-to-trial variability is affected by tasks and subjects. S.D. was used as a force variability measure. Pearson coefficients of correlation were computed and corrected for the noise and error propagation using the equation 2.

$$\frac{r_x}{r_{x+n}} = \sqrt{\left(1+\frac{\sigma_{n1}^2}{\sigma_{x1}^2}\right)\left(1+\frac{\sigma_{n2}^2}{\sigma_{x2}^2}\right)} \quad (2)$$

Principal component analyses were performed to reduce the dimension of variables and verify the null spaces.

RESULTS AND DISCUSSION

Trial-to-trial variability: The trial-to-trial variability of all the VF-level variables was affected by the tasks (P<0.001). The variability was also different in various subjects (P<0.001). The variability of the virtual finger normal force increased with the increased force magnitude as could be expected from earlier studies (Slifkin and Newell, 1999) (Figure 1). The variability of the tangential force showed a V-shape dependence on the force magnitude, which can be explained by the constant total load constraint. The variability of individual finger normal forces also showed increase with the increased magnitudes (r ranged from 0.72 to 0.86) although the tangential forces showed low correlations (r ranged from 0.01 to 0.36).



(A)

(b)

Figure 1. Variability of the thumb and virtual normal (a) and tangential (b) forces versus the force magnitude. Representative example.

It was found that individual performance variables are organized in two null spaces (Figure 2). Variables within one null space highly correlate with each other while there is no correlation among variables from the other null space. The discovery of the two null spaces supports the principle of superposition for human prehension (Arimoto, 2001). The variables in Figure 2a prevent the handle from slipping off the hand while the variables in Figure 2b are associated with the control of hand held object orientation. Principal component analyses confirmed that more than 90% of variability can be explained by two groups of VF-level variables (two null spaces) in all subjects.

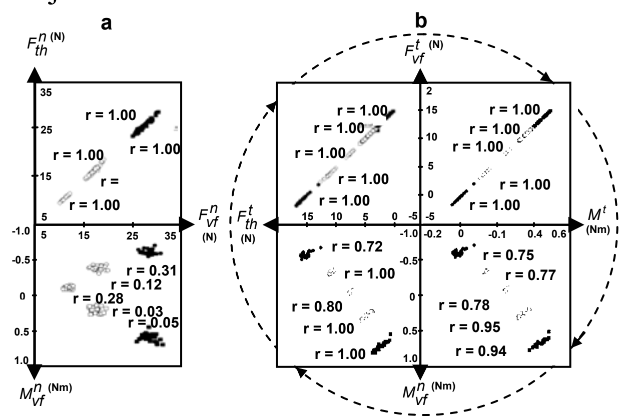


Figure 2. Interrelations among the VF-level variables. Representative example.

SUMMARY

In general, people do not perform the same prehension static task in an identical way. However, the variability of normal forces increases with their magnitude increase in both IF and VF levels of human prehension. The prehension synergy is comprised of two sub-synergies; *grasp control* and *torque control*.

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