SUPERPOSITION AND HIERARCHICAL ORGANIZATION OF STATIC PREHENSION IN HUMAN

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INTRODUCTION

Holding a grasped object in the field of gravity requires the CNS to specify six mechanical variables for each digit; three forces and three moments. A question arises whether changes in the normal forces (‘grip control’ intended to prevent the slipping) correlate with changes in the moment of these forces (‘torque control’). If they do not correlate, there are two null spaces (Zatsiorsky *et al*. 2002) or uncontrolled manifolds (UCM, Latash, 2002) representing the grip control and torque control, respectively. Such a finding would support the principle of superposition in robotics (Arimoto *et al*. 2001).

METHODS

Equipment: Four six-component (three forces and three moments) transducers (Nano-17, ATI Industrial Automation, Garner, NC, USA) were attached to an aluminium handle which had an aluminium beam (5.0cm ×85.0 cm × 0.6cm) affixed to the bottom. A load was attached to the beam at different positions to create different external torques.
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. The forearm was strapped with Velcro strips. The brace prevented wrist flexion/extension and adduction/adduction. Each subject performed 25 trials at each torque condition; –1.0 Nm, –0.5 Nm, 0 Nm, 0.5 Nm, and 1.0 Nm. Subjects were instructed to stabilize the handle with the thumb and three fingers without the little finger. The total load was always 14.9 N. A planar static task was chosen with a prismatic grip.
Model: *F, M,* and *d* designate the force, moment, and moment arm; *n* and *t* are the normal and tangential force components. *th, i, m, r,* and *vf* are the thumb, index, middle, ring, and virtual finger (a finger whose mechanical action is equal to that of the three fingers).

1. The sum of the normal forces of the three fingers equals the normal force of the thumb.

$$F^n_{th} = F^n_i + F^n_m + F^n_r = \sum_{f=1}^{3} F^n_f \qquad (1)$$

2. The sum of the digit tangential forces equals the weight (*L*) of the hand-held object.

$$L = F^t_{th} + F^t_i + F^t_m + F^t_r \qquad (2)$$

3. The total moment produced by the digit forces, *M*, is equal and opposite to the external torque exerted on the hand-held object.

$$M = \underbrace{F^n_{th}d_{th} + F^n_i d_i + F^n_m d_m + F^n_r d_r}_{\text{Moment of the normal forces} \equiv M^n} + \underbrace{F^t_{th}r_{th} + F^t_i r_i + F^t_m r_m + F^t_r r_r}_{\text{Moment of the tangential forces} \equiv M^t} \qquad (3)$$

Statistics: The true coefficients of correlations (without error propagation) were computed from equation 4.

$$\frac{r_x}{r_{x+n}} = \sqrt{\left(1+\frac{\sigma^2_{n1}}{\sigma^2_{x1}}\right)\left(1+\frac{\sigma^2_{n2}}{\sigma^2_{x2}}\right)} \qquad (4)$$

where r_x is a coefficient of correlation between the variables x_1 and x_2 measured without errors (a ‘true’ coefficient), r_{x+n} is the coefficient of correlation between these variables when they are measured with errors (noise), σ_{n1} and σ_{n2} are the SD of the errors of the first and second variables, respectively, and σ_{x1} and σ_{x2} are the SD of the first and second variables measured without errors.

RESULTS AND DISCUSSION

In spite of the variability of individual finger forces and points of their application, the stable performance was achieved by the fine-tuning among force components (prehension synergies). Some of the observed phenomena (e.g. a V-like relationship between the tangential force and its variability) can be predicted from the equilibrium equations. Other phenomena probably represent solutions preferred by the CNS. Among the latter: (a) different locations of the clusters of the tangential force in various tasks and in different subjects, (b) the lack of correlation between the total normal force and the moment that the force generates, and (c) a significant correlation between the thumb tangential force and the point of application of the normal virtual finger force. We have found that individual performance variables are organized in two null spaces (A and B in Figure 1). Variables within each null space highly correlate with each other while there is no correlation among variables from different null spaces. The discovery of the two null spaces supports the principle of superposition for human prehension. We conclude that the prehension synergy is comprised of two sub-synergies; *grasp control* and *torque control*. The data support the theory of hierarchical organization of prehension synergies.

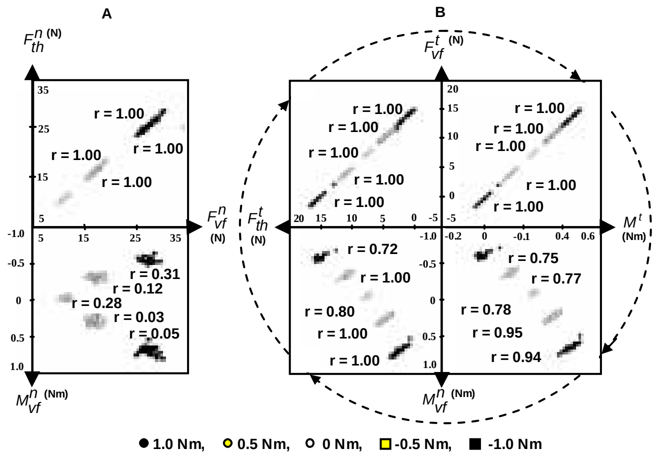

Figure 1. Interrelations among the experimental variables. Representative examples.

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