

PREHENSION SYNERGY: PRINCIPLE OF SUPERPOSITION DURING MULTI-FINGER TORQUE PRODUCTION ON MECHANICALLY FIXED- AND FREE-OBJECTS

^{1,2}Jaebum Park, ¹Vladimir M. Zatsiorsky, ²You-Sin Kim, ⁵Yoon-Hyuk Kim and ^{2,3,4,5}Jae Kun Shim

¹Department of Kinesiology, The Pennsylvania State University, University Park, PA, USA

²Department of Kinesiology, University of Maryland, College Park, MD, USA

³Department of Bioengineering, University of Maryland, College Park, MD, USA

⁴Neuroscience and Cognitive Science (NACS) Graduate Program, University of Maryland, College Park, MD, USA

⁵Department of Mechanical Engineering, Kyung Hee University, Global Campus, Korea 130-701
email: jzp12@psu.edu, web: <http://www.kinesiology.psu.edu/research/laboratories/mcl>

INTRODUCTION

In order to maintain a stable static grasp of hand-held objects, the central nervous system (CNS) needs to satisfy a set of external static constraints [1]. In this study we used a free-object and mechanically fixed-object to investigate the effect of static constraints during a multi-digit prehension and to investigate how the CNS controls digits' forces and moments against the imposed static constraints within tasks. Specifically, we were interested in whether the principle of superposition (i.e., decoupling of grasping force control and rotational equilibrium control) is valid in fixed-object prehension when the scalar sums of individual finger (IF) normal forces and the total sum of the tangential forces are not necessarily required to be equal to the thumb normal force and the weight of object, respectively [1-3]. If the grasping stabilization, which is achieved via a high correlation between the normal forces of thumb and fingers in trial-to-trial changes, is still maintained, and the other elemental variables are grouped into an independent subset, then the principle of superposition in static human hand prehension is valid regardless of static constraints within tasks.

METHODS

Equipment: Five six-component transducers (three force and three moment components) were attached to an aluminum handle to measure forces/moment produced by individual fingers and thumb. One six-component (three position and three angle components) magnetic tracking device was

mounted to the top of the handle in order to provide real-time feedback on linear and angular movements of the handle.

Experimental Procedure: There were twelve experimental conditions: 2 prehension types (fixed- and free-objects) \times 6 torque conditions (supination efforts: $-0.70, -0.47, -0.24$ Nm; pronation efforts: $0.24, 0.47, 0.70$ Nm). For the fixed-object condition, the handle was mechanically fixed to a vertical aluminum plate so that the handle could not be translated or rotated. The subjects were instructed to produce an assigned torque for 6-s while watching the feedback of torque being produced on a computer screen. For the free-object condition, the task for the subjects was to hold the handle while maintaining its pre-set constant linear and angular position against the given external torques. The task for the subjects was to hold the handle while maintaining the handle at equilibrium (i.e., quasi-static grasping). For a given condition, twenty five consecutive trials were performed.

Model: For a static prehension, the following three task constraints (i.e., mechanical constraints) in a two-dimensional grasping plane should be satisfied during a free-object prehension.

$$-F_{th}^n = F_i^n + F_m^n + F_r^n + F_l^n \quad (1)$$

$$F_{th}^t + F_i^t + F_m^t + F_r^t + F_l^t = -w \quad (2)$$

$$\sum_k (M_k^n + M_k^t) = -Tq, k = \{th, i, m, r, l\} \quad (3)$$

where F and M represent the force and moment, respectively; n and t refer to the normal and tangential force components; w and Tq represent the weight of the object and external torque; subscripts $th, i, m, r,$ and l indicate the thumb, index, middle,

ring and little finger, respectively. Eq. 3 (i.e., rotational constraint) should be satisfied in both fixed- and free-object conditions while Eq. 1 and 2 should additionally be satisfied in the free-object condition.

Analysis: For the 25 trials in each condition, Pearson's coefficients of correlation between selected experimental variables were calculated. The analysis was performed at the virtual finger (VF) level. The variables at the VF level (e.g., F_n^{vf} and F_n^{th}) were computed as the vector sums of individual fingers' variables. The variables at the VF level included $F_n^{th}, F_n^{vf}, F_t^{th}, F_t^{vf}, F_t, M_n^{vf}, D_n^{vf}$, and M_t , where D_n^{vf} stands for the moment arm of the VF normal force. A principal component analysis (PCA) with a variance maximizing rotation (varimax) was performed.

RESULTS AND DISCUSSION

For both free- and fixed-object conditions, the thumb normal force was highly correlated with the VF normal force across the 25 trials for each condition ($r > .8$, pairs of variables F_n^{th} vs F_n^{vf} ; $r = \{0.87, 1.00\}$: range of correlation coefficients across all experimental conditions), while the VF normal force was not significantly correlated with the moment of VF normal force ($r < .3$, pair of variables F_n^{vf} vs M_n^{vf} : $r = \{0.04, 0.32\}$) in any of the torque conditions (Fig. 1). In addition, the thumb and VF normal forces had large loadings ($|loading| > 0.7$) in the same PCs and small loadings in other PCs for both fixed- and free-object conditions (Table 1). Although the large loadings in the same PCs for other variables (e.g., thumb and VF tangential forces and the moment arm of VF normal forces) were only observed in the free-object condition (PC2), it was commonly observed that normal forces and tangential forces were decoupled during both fixed- and free-object conditions (Table 1).

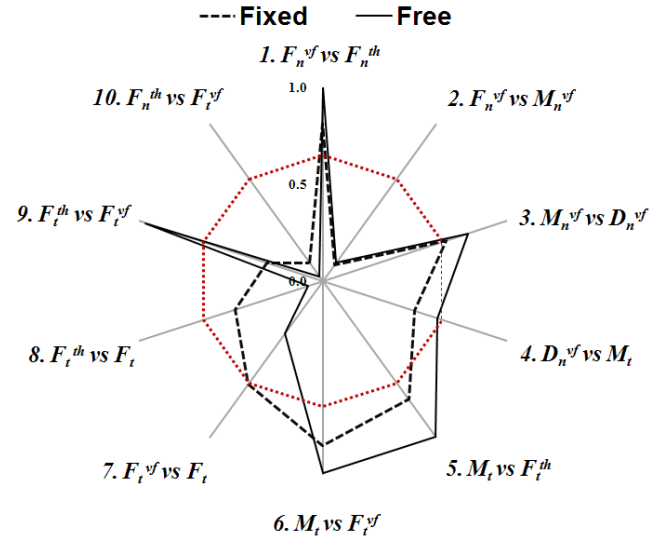


Figure 1: The correlation coefficients between ten pairs of elemental variables at the VF level. Averaged data across subjects and experimental conditions in prehension types (i.e., fixed- and free-objects) are presented. Red dotted line indicates the significant level of correlation coefficients ($r = .5$) with 25 of sample size.

Table 1: Groups of elemental variables at the virtual finger (VF) level which showed high loadings ($|loading| > 0.7$) on the same PCs.

	PC1	PC2	PC3	PC4
Free	$\{F_n^{th}, F_n^{vf}\}$	$\{F_t^{th}, F_t^{vf}, D_n^{vf}\}$		
Fixed	$\{F_n^{th}, F_n^{vf}\}$	$\{F_t^{th}, D_n^{vf}\}$ or $\{F_t^{vf}, D_n^{vf}\}$	$\{F_t^{vf}\}$ or $\{F_t^{th}\}$	$\{D_n^{vf}\}$

CONCLUSIONS

The independent controls of grasping stability (normal forces) and rotational equilibrium (moment of force) are not affected by the mechanical constraints within tasks. The data support the validity of principle of superposition in human hand static grasping tasks.

REFERENCES

1. Zatsiorsky VM, et al. *Robotica* **22**,231-234, 2004.
2. Shim, JK. and J. Park, *Exp Brain Res* **180**, 541-556, 2007
3. Shim, JK, et al. *J Neurophysiol* **93**(6), 3649-3658, 2005.