PREHENSION SYNERGIES: TRIAL-TO-TRIAL VARIABILITY AND PRINCIPLE OF SUPERPOSITION DURING STATIC PREHENSION IN THREE DIMENSIONS

[1,2]Jae Kun Shim, [1]Mark Latash and [1]Vladimir Zatsiorsky
[1]The Pennsylvania State University and [2]University of Maryland
Email: shimjaekun@hotmail.com

INTRODUCTION

Multi-digit prehension is performed by a redundant system (the hand) which exerts numerous combinations of digit forces and moments to produce a required output of a hand-held object. The human central nervous system (CNS), confronts a choice of selecting a solution of digit forces and moments from an apparently infinite set (Bernstein 1967).

According to the principle of superposition suggested in robotics (Arimoto et al. 2001), some actions can be split in several subtasks that can be controlled by independent control processes. In two dimensions, both simulations of a two-digit robot grasping and experiments with multi-digit human grasping (Shim et al. 2003a; Zatsiorsky et al. 2004) have confirmed the principle of superposition showing the existence of two decoupled subgroups of elemental variables (digit forces and moments): one related to adjustments of the grasping forces, '*grasp control*' and the other associated with control of rotational equilibrium of the hand-held object, '*torque control*'. In the current study, we tested the principle of superposition during multi-digit human prehension in three dimensions (3D).

METHODS

Subjects held a customized handle statically twenty-five times under each of seven external torques (ranged from -0.7 to 0.7 Nm) about a horizontal axis (*X*-axis) in a plane passing through the centers of all five digit force sensors (the grasp plane; Shim et al 2004). *Y*- and *Z*-axes were respectively defined as a vertical axis and an axis perpendicular to *X*- and *Y*-axes. Three force and moment components in 3D were recorded from each sensor.

Regression analysis and principal component analysis (PCA) with varimax rotation and Kaiser criterion were performed on elemental variables (forces and moments) of the thumb and virtual finger (VF: an imagined finger producing a wrench equal to wrenches generated by individual fingers; McKenzie and Iberall 1994; Shim et al. 2004).

RESULTS

PCA performed on all thumb and VF forces and moments under each external torque condition generated three PCs (PC1 to PC3) which accounted for 94.80±0.65 % of the total variance (average ± SD across external torque conditions after the results were averaged across the subjects for each external torque condition). Among the three PCs, one PC had large loadings of thumb and VF grasping forces (F_Z^{vf} and F_Z^{th}), Table 1. The rest two PCs had large loadings on the moments about *X*- and *Y*-axes, respectively. Therefore, the '*grasp control*' variables (F_Z^{vf} and F_Z^{th}) were decoupled from the '*torque control*' variables (all of moment variables). These findings were true for all external torque conditions in each subject.

Table 1. Loadings of principal components (PC1, PC2, and PC3) in all elemental variables under -0.70 Nm external torque condition of a representative subject.

Variable	PC1	PC2	PC3
$M_X^{vf(Y)}$	***0.89***	0.00	-0.27
$M_X^{vf(Z)}$	***-0.92***	0.02	0.26
$M_X^{th(Y)}$	***0.90***	0.03	-0.27
$M_Y^{vf(Z)}$	0.01	***-0.99***	0.07
$M_Y^{vf(X)}$	0.00	***0.97***	-0.04
$M_Y^{th(Z)}$	-0.02	***-0.99***	0.06
F_Z^{vf}	-0.25	-0.10	***0.97***
F_Z^{th}	0.26	0.07	***-0.96***

F_Z^{vf} and F_Z^{th} are VF and thumb forces along Z-axis (grasping forces). $M_X^{vf(Y)}$ is a moment of F_Y^{vf} about X-axis and similar nomenclatures are applied to the other moment variables. The loadings with large magnitudes are shown in ***italics.*** Variables without significant loadings according to the Kaiser criterion are not included in the table.

CONCLUSIONS AND DISCUSSION

The grasping control (the slipping prevention) is realized separately from other subtasks (e.g. maintaining the rotational equilibrium of the object about each axis in 3D) that have to be solved by the CNS during multi-digit prehension. The changes of the grasping forces (F_Z^{vf} and F_Z^{th}) being perfectly matched to each other do not immediately affect the other variables. Therefore, we conclude that the principle of superposition is supported in a 3D static prehension.

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