EFFECTS OF GRAVITY ON MULTI-DIGIT TORQUE PRODUCTION TASK IN HUMANS

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In this study we investigated the effect of gravity on multi-digit prehension to know how the digits' force and moment are organized in the imposed static constraints according to the gravity. Specifically, we tested if decoupling of grasping and rotational equilibrium control is even valid during grasping in the microgravity condition. There were two experimental conditions: gravity-induced (GI), and microgravity conditions (MG). For the MG condition, the handle was attached to the end of the robot-arm, which produced a count-balanced force for the weight of the handle and hand. The results showed that the selected experimental variables were separated into two sub-sets in both GI and MG conditions. Thus, we can conclude that the grasping stability is independent from the rotational equilibrium control regardless of the gravity acting on the hand-held object.

KEY WORDS: gravity, torque production, static constraints

INTRODUCTION: Astronauts are required to perform tasks under microgravity conditions that require considerable dexterity of the hands and fingers. In this project, we systematically investigated how human prehensile actions are affected by the microgravity condition such as outer space. 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 (Zatsiorsky, Latash Gao, & Shim, 2004). It has been known that the microgravity environment of space flight induces adaptive modification in the brain's central processing to produce appropriate motor response (Bloomberg & Mulavara, 2003; Clement, Gurfinkel & Lestienne, 1984). Great attention has been given to questions of adaptive in-flight posture control in humans, but little is known about the adaptive control strategies of human grasping action in microgravity condition. Holding or moving an object is one of the basic functions of the hand and is core to the dexterous actions of hand and fingers required to execute various tasks. The microgravity environment induces modified mechanical constraints of hand-held object system during prehensile actions. One of the mechanical constraints in the static grasping task is that the sum of digit contact forces in vertical direction (i.e., tangential forces) should be equal in their magnitude and opposite direction to the weight of the hand-held object (i.e., vertical translational constraint). While satisfying vertical translational constraints by the digit tangential forces, the digit tangential forces also contribute to produce the moment of force about the axis of rotation. In the microgravity condition, the vertical translational constraint is modified (i.e., sum of digit tangential force should be equal to zero) in the static grasping, and the modification of the vertical translational constraint in the microgravity condition would affect the contribution of digit tangential forces toward the rotational action. Therefore, adaptive control strategies are necessary to satisfy the modified mechanical constraints in the microgravity condition. In this study we investigate the effect of gravity on multi-digit prehension to know how the central nervous system (CNS) controls digits' force and moment against the imposed static constraints according to the gravity. Specifically, it is unknown whether the principle of superposition (i.e., decoupling of grasping force control and rotational equilibrium control) is even valid during prehensile tasks in the microgravity condition. If the grasping stabilization, which has been proved to have a significantly high correlation between the normal forces of thumb and sum of normal forces of fingers in trial-to-trial changes, is still maintained, and the other elemental variables are grouped into independent subset, then we may expect to support the claim that the principle of superposition in static human hand prehension is valid regardless of gravity acting on the mass of the hand-held object. Understanding these adaptive control strategies could provide underlying mechanisms for improving space-glove design and rehabilitation interventions for hand/digit motor coordination impairment that may result from extended stays in micro-gravity.

METHODS

Subjects: Eight male subjects with no previous history of serious upper extremity or hand injuries participated in this experiment. All subjects were right-handed.

Equipment: For digit force data acquisition, five six-component (three force and three moment components) transducers (Nano-17s, ATI Industrial Automation, Garner, NC, USA) were attached to an aluminum handle shown in Fig. 2. A horizontal aluminum beam (45cm in length) was affixed to the bottom of the handle in order to hang a load. In addition, a 24V DC/5,500 rpm Globe Motor was fixed at the center of beam. The motor moved a 0.2-kg load smoothly with a speed of about 0.02 m/s. The load moved over 0.24m from one end of the beam (supination effort) to the other end (pronation effort), and the magnitude of maximal external torque at the extreme load positions was about 0.5 Nm. The robot-arm (HapticMaster) was used to generate anti-gravity force of the weight of the handle and the load (Fig. 1B). The hand-held object was attached to the end of robot-arm, and the robot-arm provided a constant level of force in vertical direction, which was equal and opposite in force to the weight of the handle and hand.

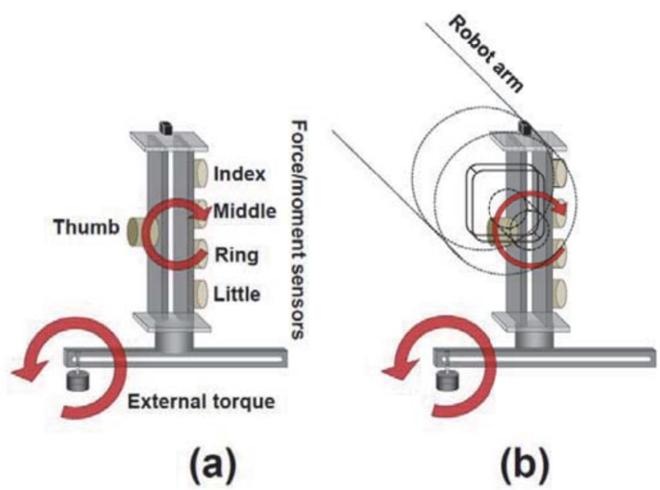

Figure 1. Schematic illustration of experimental setup for **(a)** Gravity-induced condition (GI) and **(b)** microgravity conditions (MG) with 'inverted-T' handle/beam apparatus and robot arm. The force-moment sensors, shown as cylinders, were attached to two vertical aluminum bars. A Linear motor was fixed at the center of the beam. The motor will move a 0.2-kg load smoothly with a speed of about 0.02 m/s along the beam.

Experimental procedures: The experiment consisted of two conditions: gravity-induced (GI), and microgravity conditions (MG). For the MG condition, the handle was attached to the end of the robot-arm (Fig. 1B). Note the force by the robot-arm compensated for the weight of the handle and hand, while the load created external torques for both GI and MG conditions (Fig. 1). The task for the subjects was to hold the handle while maintaining the constant linear and angular positions (i.e., maintaining static grasping) of the handle against external torques until the load was moved over from one end of the beam to the other end. For each condition, fifteen consecutive trials were performed. Thus, each subject performed a total of 30 trials (2 conditions × 15 trials = 30).

Model: The following three task constraints (i.e., mechanical constraints) existed for a static prehension regarding digits forces and moments in a two-dimensional grasping plane.

$$-F_n^{th} = F_n^i + F_n^m + F_n^r + F_n^l \quad (1)$$

$$F_t^{th} + F_t^i + F_t^m + F_t^r + F_t^l = -w \quad (2a)$$

$$F_t^{th} + F_t^i + F_t^m + F_t^r + F_t^l = 0 \quad (2b)$$

$$\sum_k (M_n^k + M_t^k) = -Tq, k = \{th, i, m, r, l\} \qquad (3)$$

F and *M* represent the force and moment; *n* and *t* refer to the normal and tangential force component; *w* and *Tq* represent the weight of the object and external torques; superscripts *th, i, m, r,* and *l* indicate the thumb, index, middle, ring and little finger, respectively. For the GI condition, Eq. 2a should be satisfied while Eq. 2b needed to be satisfied for the MG condition. *Data analysis:* Virtual finger (VF) forces and moments were calculated as the vector sum of all four finger forces and moments. These variables were used to test the validity of the principle of superposition. For the 15 trials in each condition, Pearson coefficient correlations between selected experimental variables, which presumably construct simultaneous sequences of local cause-effect adjustment predicted by the task mechanics [so called "chain effect"], were calculated (Fig. 2). The analysis was performed at the virtual finger (VF) level. Note that the action of the VF can be the same as mechanical effects produced by individual fingers. The variables include $F_n^{th}, F_n^{vf}, F_t^{th}, F_t^{vf}, F_t, M_n^{vf}, D_n^{vf}$,and M_t. *D* stands for moment arm. The 1st local chain (i.e., correlation between normal forces of the thumb and VF, $F_n^{th}\ vs\ F_n^{vf}$) was necessitated by the task mechanics of the horizontal translation constraint (i.e., equal and opposite normal forces by the thumb and VF), and the 9th local chain (i.e., correlation between tangential forces of the thumb and VF, $F_t^{th}\ vs\ F_t^{vf}$) was predicted by the task mechanics of the vertical translation constraint (i.e., sum of tangential forces is equal to the weight of object or zero). The validity of the Principle of Superposition was decided by the existence of two independent groups of variables which form cause-effect (significant correlation) chains.

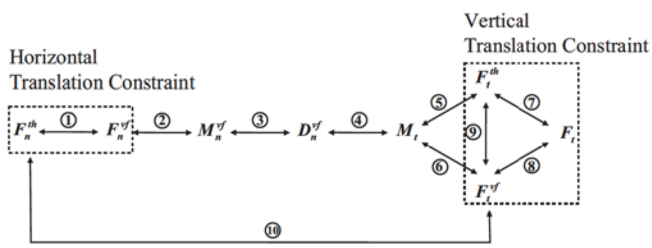

Figure 2. Schematic illustration of overall chains among VF level variables during multi-finger torque production tasks. The 1st and 9th local chains represent the constraints of horizontal and vertical translation, respectively.

RESULTS: For both GI and MG conditions, the thumb normal force was highly correlated with the VF normal force across the 15 trials for each conditions (r > .8, pairs of variables $F_n^{th} vs F_n^{vf}$) , while the VF normal force was not significantly correlated with the moment of VF normal force (r < .3, pair of variables $F_n^{vf} vs M_n^{vf}$) in both GI and MG conditions (Fig. 3). For both conditions, the 1st and 9th local chains showed significant correlations as expected by the constraints of linear translations (i.e., the constraints of horizontal and vertical translation) (Fig. 3). The correlations of the 3rd, 4th, 5th and 6th chains, which were serially linked, were all statically significant for both conditions. However, the 7th and 8th chains were not significantly correlated due to the constant value of resultant tangential force as the task mechanics prescribed ($F_t^{th} + F_t^{vf} = F_t = -w$ or $F_t^{th} + F_t^{vf} = 0$).

DISCUSSION & CONCLUSION: It has been experimentally (Shim, Latash & Zatsiorsky, 2005) and mathematically (Arimoto & Nguyen, 2001) suggested that the grasping force control and rotational equilibrium control are linearly superposed, and, therefore, independently controlled in a multi-digit static prehension. This decoupled controls of grasping stability and rotational equilibrium in human hand static prehension has been supported by the principle of superposition. There are two important aspects of the inter-relations among experimental variables in the virtual finger level regarding principle of superposition in the human hand static torque production tasks: The first is that the experimental variables are separated and grouped into two sub sets, and the second is that the correlations among variables in each sub-set are significantly high. This is also knows as a chain-effect (Zatsiorsky, Latash, Gao & Shim, 2004). The ‘chain effect’ explains coupled relations among elemental variables within each subset, and these significant correlations among variables, which forms “cause-effect” chain, where mechanically necessitated relations among elemental variables are prescribed by the given task mechanics. In the current study, the vertical translational constraint was modified (i.e., sum of digit tangential force should be equal to zero) in the MG condition, and the modification of the vertical translational constraint in the microgravity condition affects the contribution of digit tangential forces toward the rotational action. However, the decoupled control of grasping stability and rotational equilibrium was maintained during the MG condition. Therefore, we can conclude that the independent controls of grasping stability and rotational equilibrium are not affected by the existence of the gravity in human hand prehension, thus supporting the validity of the principle of superposition. We have to admit that the current study was not directly related to sports. However, we have a need to prepare the Space Age, thus the result outcomes of the study may help to understand the adaptive control strategies and underlying mechanisms for improving space-equipment design (e.g., space glove) and rehabilitation interventions for hand/digit motor coordination impairment that may result from extended stays in micro-gravity environment such as space. Further, we hope the follow-up study will extend to more dynamic sports activities in micro-gravity environment.

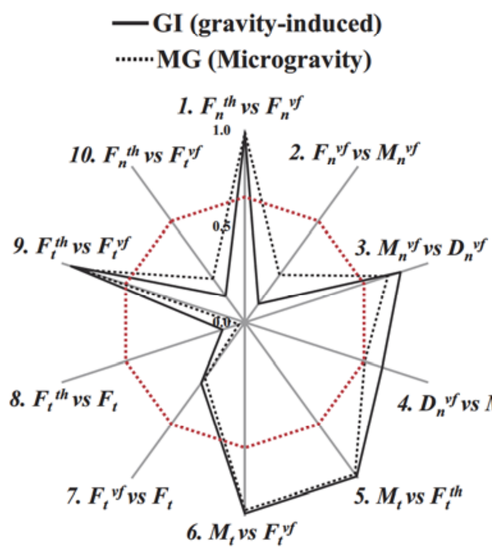

Figure 3: The correlation coefficients between ten pairs of elemental variables at the VF level for the GI (solid line) and the MG condition (dotted line). Averaged data across subjects are presented. Red dotted line indicates the significant level of correlation coefficients (r = .5) with 15 sample size.

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