Multi-digit Position and Force Coordination in Three- and Four-Digit Grasping

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Abstract. In this paper, we investigate the redundancy problem by examining how humans control grasping of a hand-held object using three- and four-digits in response to external perturbations. Our results revealed a similar variability in digits' initial placements when grasping with three- and four-digits. Moreover, the distribution of digit normal forces were modulated depending on the number of digits used, their locations, and the type of the external perturbations. Our results suggest that the redundancy problem was addressed by the central nervous system in a similar fashion on a trial-to-trial basis in terms of digits' initial placements, but differently in terms of digits normal force distribution that was controlled online depending on the number of digits actively involved in the grasp.

Keywords: Redundancy problem · Unconstrained grasping · Three- and four-digits grasping

1 Introduction

Grasping tasks can be performed successfully in an infinite number of ways due to the large number of degrees of freedom (DOF) in the human hand, i.e., a larger number than required by the task. Successful grasping and manipulation require that the central nervous system (CNS) masters redundancy in DOF such as digit contact point selection, forces, and torques to be applied and to select an appropriate hand posture. This well-known issue is the so-called redundancy or Bernstein problem [1]. Accurate object grasping and manipulation are achieved by coordinating fingertip locations and forces. Force modulation to object properties can be implemented in an anticipatory fashion prior to the onset of manipulation [2] through sensorimotor memory normally cued by visual feedback of the object. However, the sensorimotor mechanisms underlying the

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coordination of digit positions on the object and the corresponding force distribution for dexterous manipulation are not fully understood. The modulation of digit normal and tangential forces during grasping objects depends crucially on digit locations as reported in two-digit precision grips [3], three-digit grasping [4,5] and five-digit grasping [6]. It should be noted that the studies where subjects could choose digit placement also reported a high trial-to-trial variability in digit positions (e.g., [3,6]). Therefore, we aim to provide insight into the mechanisms underlying the control of multi-digit prehension when digit locations are self-chosen. In the present study, we aim to address the redundancy problem when using different number of fingers during unconstrained grasping. Our first hypothesis is that with an increasing number of digits the trial-to-trial variability in digit locations will increase. The reasoning behind this hypothesis is that an increasing number of digits implies higher redundancy and thus more solutions which might lead to higher variability.

A stable grasp, after successfully selecting the digit locations on the grasped object, is defined as the ability of modulating digit forces in order to satisfy slip prevention, tilt prevention, and perturbation resistance [2,7]. It has been shown that the index and little fingers are more involved in torque (rotational) tasks, whereas middle fingers (middle and ring fingers) are more involved in load tasks to satisfy a stable grasp criterion during five-digits constrained grasping and pressing (finger specialization) [8,9]. At this level, we aim to investigate whether such a "finger specialization" would be flexible and if so, whether it depends on the number of digits used and their initial placement when grasping an object using three- and four-digits. An alternative strategy might consist of a proportional increase in the normal forces among all digits to compensate for the missing end effectors (using three- and four-digits instead of five-digits). Therefore, our second hypothesis is that when adding or removing a finger in the grasping task, the CNS might modulate digit forces based on the actual number of end effectors on the grasped object. In other words, the finger specialization will be flexible and will depend on the number of active end effectors on the grasped object and their locations. The present work was designed to test the above hypotheses on tasks involving object grasping with three- and four-digits at unconstrained contacts. To this end, we used the same experimental paradigm used in a previous study [6].

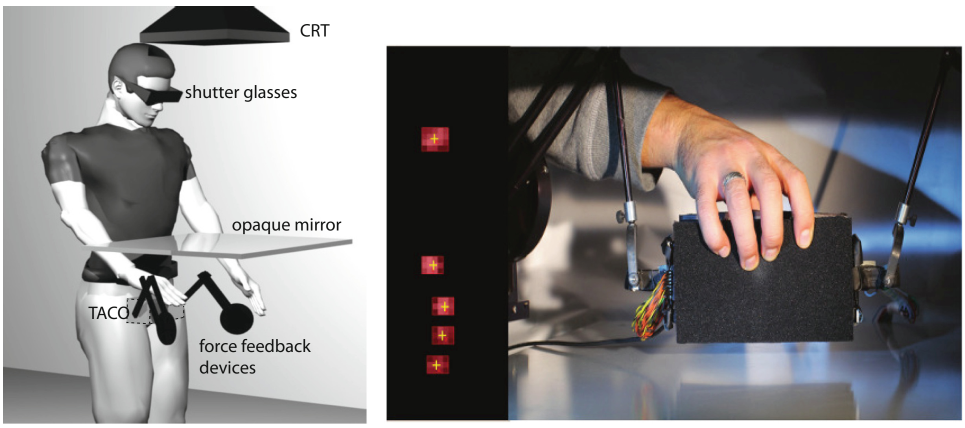
2 Methods

2.1 Participants

Ten right-handed participants (6 females), 24 ± 6 years of age, took part in the experiment. Five of them participated to the Three-digit Grasp Experiment and the other five participated to the Four-digit Grasp Experiment (between-subjects design). All participants had no history of neurological or motor deficits and they gave informed written consent in accordance with the Declaration of Helsinki.

2.2 Hardware

For our study, we built a Tactile Object (TACO) that is able to record the position and normal force exerted by each finger on the object, while allowing participants to choose digit placement and to grasp the object in an unconstrained fashion. The TACO is of rectangular, cuboid shape (length, l = 170 mm; height, h = 85 mm; width, w = 55 mm) and it is constructed using four modules with high-speed tactile sensors (up to 1.9 kHz) developed by Schurmann *et al.* [10]. Each module (area: $80 \times 80\,\text{mm}^2$) consists of a matrix of 16×16 of tactels with 5-mm spatial resolution. Thus, the output matrix of TACO is 64×16 tactels, with two of the modules mounted on the front and two on the back of the device. Thus, TACO allows us to simultaneously record the center of pressure and the normal force exerted by each digit. TACO is calibrated using a force gauge with a force ranging from 0 to 25 N. In our calibration we also varied the cross-sectional area of the gauge tip from 10 to $50\,\text{mm}^2$ with a step of $20\,\text{mm}^2$. By doing so, we aimed at the control of calibration precision since fingertips of participants are different in size. Participants viewed a virtual rectangular cuboid while they grasped the TACO and they had no visual feedback of their actual hand location or TACO in the scene. The visual scene was displayed on a 21" CRT-computer monitor (SONY® CPDG520) with a resolution of 1280×1024 pixels (refresh rate: 100 Hz). Participants viewed the mirror image of the visual scene via liquid-crystal shutter glasses (CrystalEyesTM) providing binocular disparity (Fig. 1a). The TACO was attached to two PHANToM$^{\text{TM}}$ Premium 1.5 (SensAble® Technologies) force-feedback devices (6 DOF) in order to track its position and apply force/torque perturbations while participants held the TACO with one hand (Fig. 1b). The sampling rate of the PHANToM$^{\text{TM}}$ was 1 kHz. The total mass of TACO attached to the PHANToM$^{\text{TM}}$ arms was 0.470 Kg. Constrained by the



(a) Setup (b) Tactile Object (TACO) with its output image

Fig. 1. Experimental materials. (a) Participants binocularly view the mirror image of the visual scene. (b) The TACO attached to the PHANToM$^{\text{TM}}$ force feedback devices. On the left, the TACO output image with yellow cross represents digit center of pressures (*CoP*s).

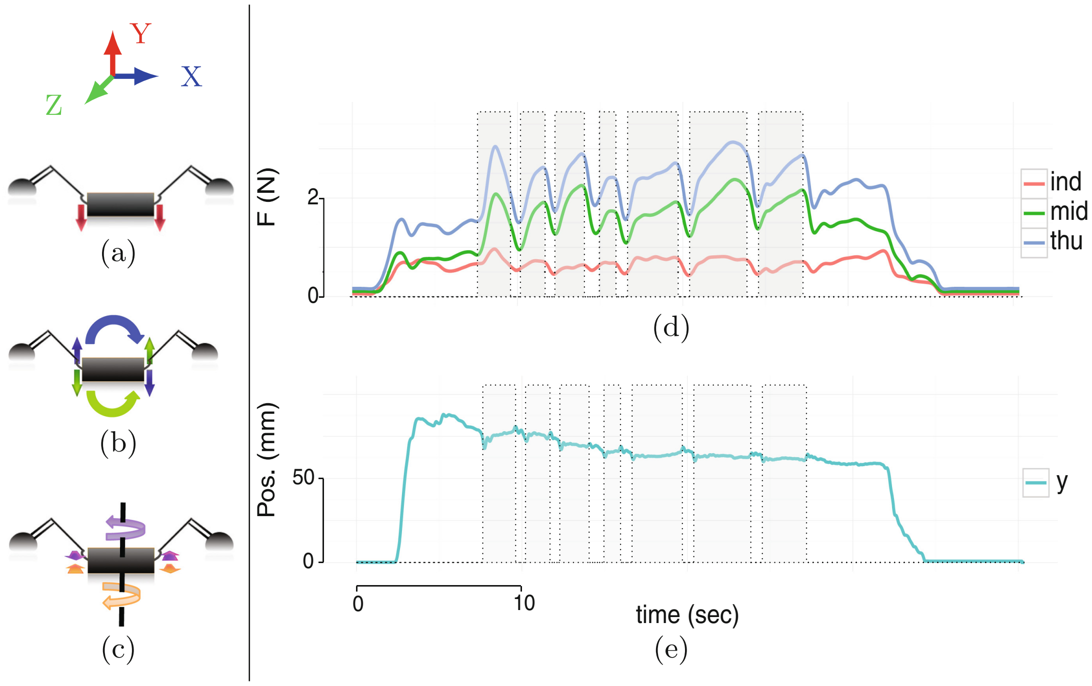


Fig. 2. Experimental protocol. (a) Perturbation force F_y. (b) Perturbation torque T_z CW and CCW. (c) Perturbation torque T_y CW and CCW. (d) and (e) Digits normal forces and TACO vertical coordinate respectively, of one trial for a representative subject during the condition T_y^{CCW} using three-digits (gray areas represents when force/torque perturbation is on).

arrangement of the PHANToM^{TM} force feedback devices, TACO has five DOF of unconstrained motion $(x, y, z, 0 : \text{no pitch rotation}, \alpha : yaw, \beta : roll)$.

2.3 Procedure

Participants sat on a chair of adjustable height. Before the start of the grasping movement, participants forearm rested on a plank with the palm of the hand facing downward. Participants received an auditory "GO" signal instructing them to start grasping the TACO with the tip of either the thumb, index and middle fingers, or thumb, index, middle and ring fingers of the right hand, and lift the TACO 100–150 mm. The non-involved fingers (ring and little fingers, or little finger only) were extended and taped to hard paper in order to prevent them from contacting the TACO. To cue subjects about the desired height at which they were required to stabilize the TACO, the color of the virtual rectangular cuboid changed when they reached the desired height. At that height, participants were asked to hold the TACO as still as possible for 20 s irrespective of any disturbance forces acting on the object. The finger locations on the TACO were self-chosen (grasping without constraints). After having stabilized the TACO for approximately 20 s, participants received another auditory signal cueing them to replace the TACO on the table. During the object hold phase, perturbation forces and torques where applied using the PHANToM^{TM} force feedback devices.

We studied 3 conditions of force/torque perturbations: force of $Fy = 2.4$ N (Fig. 2a) was applied in vertical direction, or torques of 25 N·cm were applied around the y- or z-axis (Fig. 2b, c respectively) causing yaw and roll rotations around TACO's center of mass (T_y and T_z). The perturbations were turned on with a duration ranged between 1 to 3.5 s and off with durations ranged between 0.6 to 1 s; both randomly presented. Both perturbation torques (T_z and T_y) were applied in clock-wise (CW) and counter-clock-wise (CCW) directions. Thus, there were in total 5 conditions: (F_y, T_y^{CCW}, T_y^{CW}, T_z^{CCW}, T_z^{CW}). The order of conditions was randomly presented to the participants. Twenty trials were conducted for each condition. Each trial lasted approximately 25 s from grasp onset to the end. Before starting the experiments, subjects performed four trials with Fy perturbation in order to familiarize them with the task. Participants could rest as much as they wanted between two consecutive trials. The total duration of the experiment was approximately two hours per subject with a break of one hour in half-way through the experiment.

2.4 Data Processing and Analysis

The normal forces F of the fingers and the center of pressures CoP_x and CoP_y were directly read from the force modules of the TACO with the origin $(0, 0)$ cm being the center of the TACO. The CoP_x and CoP_y were defined as the location of the global maximum of the activated region of tactels for each fingers' region in the output matrix. The output matrix was converted to force in Newtons using the lookup table generated during calibration. The calibration table was obtained with a resolution of ± 0.2 N. Digit locations (CoPs) and normal forces were recorded and ran through a second order Butterworth low pass filter with 1 Hz cutoff frequency (Fig. 2d and e). Digit peak forces were extracted and averaged across perturbations. Linear mixed model (LMM); the model accounts for both the variability between participants and the variability within participant due to trial repetitions, was used to analyze the data.

3 Results

3.1 Center of Pressure for Individual Participants

We first investigated the locations of the digits on the TACO during the holding phase in both the Three- and Four-Digits Experiments to quantify digit CoP variability. Figure 3 show CoP data for individual participants. We found a high variability between participants' digit initial locations for both three- and four-digits experiment respectively (Table 1) indicating that participants differed in their digit placement on the TACO (initial locations). We also found high variability in fingertip placement within subjects in both the three- and four-digit grasps. The high variability in digit placement was found mostly in the horizontal coordinates. Bartlett's test was used to test homogeneity of variances of CoPs in the conditions three- and four-digits and revealed that they are similar

Table 1. Digit CoP results

	Three-digits		Four-digits	
Finger	$CoP_x : M \pm SD$ (cm)	$CoP_y : M \pm SD$	$CoP_x : M \pm SD$ (cm)	$CoP_y : M \pm SD$
Thumb	0.62 ± 1.58	1.69 ± 0.53	0.39 ± 1.33	0.73 ± 0.99
Index	0.40 ± 1.59	1.20 ± 0.99	-1.34 ± 1.54	0.17 ± 0.99
Middle	2.41 ± 1.37	0.26 ± 1.31	1.58 ± 1.52	-1.27 ± 1.18
Ring	-	-	3.14 ± 1.43	0.13 ± 1.52

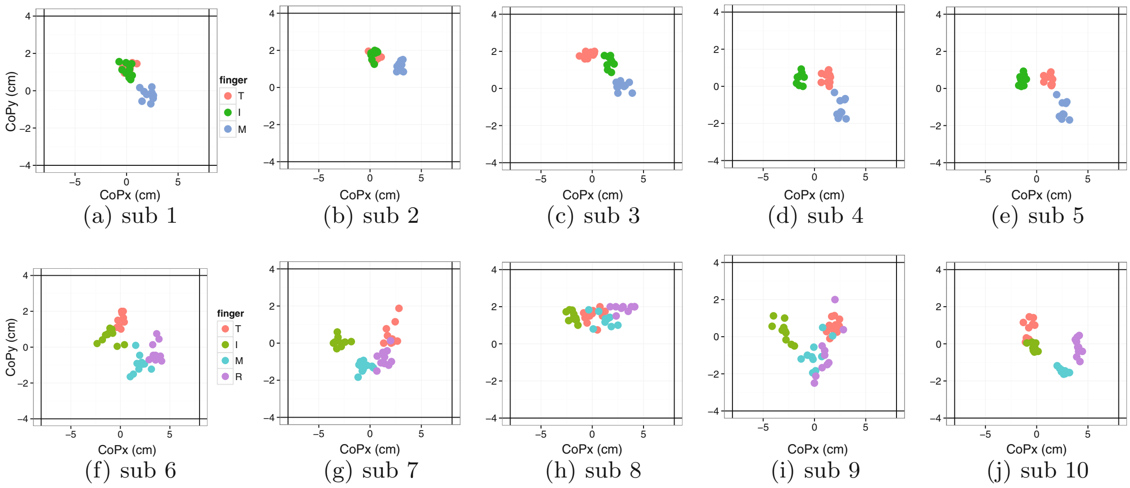
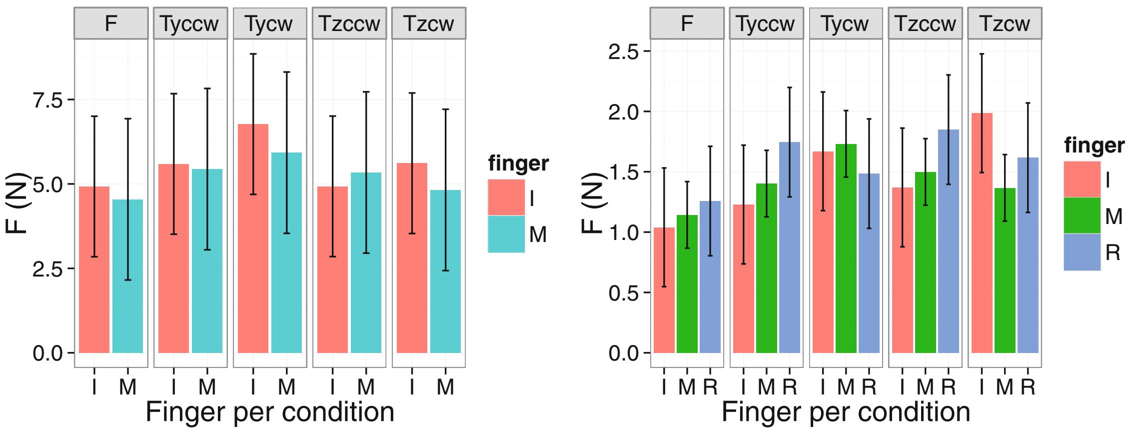


Fig. 3. Digit CoP results for individual participants averaged across trials for each condition for three- and four-digits experiment. The thumb CoPs were plotted at the same plane with other fingers (T: thumb, I: index, M: middle, R: ring, sub: subject). Upper row (sub 1..5) data for three-digits experiment, bottom row (sub 6..10) data for four-digits experiment.

($p = 0.99$). Thus, we reject our first hypothesis and this result indicates that adding or removing one finger in the grasping task did not affect the variability in initial digit placement.

3.2 Digit Forces

Secondly, we sought to evaluate the modulation of digit forces for each perturbation to test the "finger specialization" hypothesis. In this analysis, we averaged data from each participant across: perturbations, and trials. In the LMM model used for each digit, we included "digit" as a fixed effect and "participants" as random effect. Figure 4 show the mean and standard errors of normal forces estimated by LMM for each finger (fingers opposing the thumb digit) for different perturbation types (F_y, T_y^{CCW}, T_y^{CW}, T_z^{CCW}, T_z^{CW}). In the Three-digit Grasps Experiment, the index finger applied a slightly higher normal force than the middle finger for F_y, T_y^{CW}, T_z^{CW} conditions, whereas the middle finger applied slightly higher normal force in T_y^{CCW}, T_z^{CCW} to counterbalance the TACO against the external torque perturbations (T_y^{CCW} closer mean to the index finger but with higher variability; Figs. 2d and 4). In the Four-digit Grasp Experiment, the index finger applied more normal force in the condition T_y^{CW}, T_z^{CW} (with higher variability than the middle finger in F_y), whereas the ring finger applied more normal forces in the conditions F_y, T_y^{CCW}, T_y^{CCW} (Fig. 4). In addition, the middle finger applied a considerable amount of normal force in the rotational task as well as in the load task. In other words, the normal forces increased gradually among the fingers opposed to thumb in order to generate a net torque against the external torque to counterbalance the TACO for the rotational perturbation (T_y^{CCW}, T_y^{CW}, T_z^{CCW}, T_z^{CW}). These results indicate that the outer fingers were involved in the rotational task (torques clockwise and counter clockwise) depending mainly on the active end effectors on the grasped TACO and their initial placement. Therefore, the "finger specialization" for the grasping task was established based on the active end effectors on the TACO, indicating that this is a configuration problem depending on number of digit used, fingers locations on the grasped object, and the external torque rather than reflecting a specialization for each digit as reported previously in [8,9].



(a) Three-digits (b) Four-digits

Fig. 4. Mean normal forces for each finger in different perturbation conditions for three- and four-digits experiments. Error bars represent standard error (I: index, M: middle, R: ring).

4 Discussion

In this study we investigated the redundancy problem during unconstrained grasping task using three- and four-digits in response to force perturbations. The high variability in digit CoPs was observed at both levels: within and between participants in both coordinates. In addition, digit normal force responses were modulated depending on their location and the number of digit used in the grasping task. It has been shown that the CNS independently learned grasping and manipulation tasks such that they could transfer the learned task regardless of the number of digit used during learning [5]. In other words, this finding extends previous findings claiming the flexibility and independence of high-level motor processing from low-level motor execution at the end effector used in the task. These considerations indicate that the "redundancy problem" is addressed by the CNS in a similar way when adding or removing one finger in the grasping task. Overall, participants differed in their initial digit placement similarly in both three- and four-digit grasps, whereas digit normal forces were modulated differently among digits as to adapt to the number of digits used in the task. Thus, it appears that the CNS addresses the redundancy problem similarly when adding or removing one finger in the grasping task by modulating grip force sharing among the active digits based on their actual locations on the grasped object and as a function of an expected external perturbation.

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