# Multi-digit positions and forces coordination for grasping

Abdeldjallil Naceri[1,2], Alessandro Moscatelli[1,2], Robert Haschke[2], Marco Santello[3] and Marc O. Ernst[1,2]

[1]*Department of Cognitive Neuroscience ofExcellence (CITEC)*

*33615 Bielefeld*

[2]*Center of Excellence Cognitive Interaction Technology (CITEC), Bielefeld University*

*33619 Bielefeld*

[3]*School of Biological and Health Systems Engineering**,** Arizona State University Tempe, Arizona 85287*

## Abstract

It has been shown that digit placement on objects prior to exerting forces and torque for manipulation varies across trials. This phenomenon limits the extent to which subjects can use the same digit forces used for previous manipulations, as using the same forces at different positions would generate a different dynamic on the object. Because of the high dimensionality in the number of grasp control variables, purposeful hand-object interactions rely on highly unconstrained control mechanisms as an infinite number of digit position and force combinations can be used to attain stable grasps. Although the phenomenon of digit force-to-position coordination has been addressed for the two-digit grasping case, how subjects coordinate multiple digit forces to position remains to be established. **Our hypothesis is variability in initial digit placements and individual digit normal forces would be altered when varying the number of digits involved in the grasping task**. In this study, we investigated digit position and force coordination exhibited by humans while a hand-held object was perturbed by external forces and torques. Our results revealed a similar across-trial variability in digits' initial placement when adding or removing fingers in the grasping task. Moreover, digit normal forces were controlled in a feed-forward manner within single perturbations, but in a closed-loop fashion across perturbations occurring within individual trials. Furthermore, the distribution of normal digit forces in response to mechanical perturbations reflected the external perturbation. Interestingly, a similar pattern was observed in a control experiment that was conducted using the same experimental paradigm performed by a five-digit robot hand using a joint position and stiffness controller. Our results suggest that participant adopted a whole-hand stiffening strategy to compensate for the task uncertainty associated with external perturbations at unpredictable directions and natural trial-to-trial variability in digit placement.

{Formatting Citation}

# Introduction

Grasping is a complex task due to the fact that the sensorimotor system has to coordinate a large set of control variables. Specifically, object grasping and dexterous manipulation are achieved by modulating digit positions and forces through the integration of multiple sensory modalities, i.e., vision, proprioception, and touch. Such modulation takes into account object geometry, the planned action, and prior knowledge about object properties, e.g., mass or center of mass (Fu, Zhang, & Santello, 2010; J. Lukos, Ansuini, & Santello, 2007; J. R. Lukos, Ansuini, & Santello, 2008). Moreover, digit force control is achieved in an anticipatory fashion during constrained pinch grasping tasks (Johansson & Westling, 1984; Westling & Johansson, 1984). For unconstrained pinch grasping task, it has been shown that participants anticipated the properties of the grasped object (e.g. its center of mass (CoM) in different locations) in terms of where to place the fingers and how much force to apply (Fu et al., 2010). The large number of degrees of freedom in the human hand (more than the number required by the task) allows an infinite number of digit force-to-position coordination patterns. Thus, successful grasping and manipulation rely on central nervous system's (CNS) ability to effectively master the redundancy in the available degrees of freedom, (Bernstein 1967; Friedman & Flash, 2007)

Digit normal and tangential forces during grasping objects are modulated as a function of digit locations as reported for two-digit precision grips (Fu et al., 2010), three-digit grasping (Baud-Bovy & Soechting, 2002) and five-digit grasping (Naceri, Moscatelli, Santello, & Ernst, 2014).

(Fu et al., 2010) showed that digit normal forces were optimal during unconstrained pinch grasping task compare to the constrained one. It should be noted that the studies where subjects could choose digit placement also reported a large trial-to-trial variability in digit positions (Friedman & Flash, 2007; Naceri et al., 2014). All studies discussed above investigated either constrained grasping task using two, three and five digits or unconstrained grasping tasks using two and five digits grasp. In other words, to the best of our knowledge there was no study that compared grasping task using various numbers of digits. Thus, we aimed to compare in the current study variability in digit initial location and digit normal force modulation when grasping using two, three, four and five digits unconstrained grasping task. For this purpose, we developed a tactile object that track digit normal forces and allows participants to freely choose their digit locations on the grasped object as well as use different number of digits, e.g., from two to five digits. Our first question is whether increasing the number of digits involved in the grasp would increase the trial-to-trial variability in digit locations. The rationale for this expected finding is that increasing the number of digits would lead to an increase in the number of force coordination patterns that would satisfy the grasp task requirements, and this may lead to larger digit position variability.

After successfully selecting and establishing contact points on the grasped object, a stable grasp is defined based on whether it satisfies slip prevention, tilt prevention, and perturbation resistance constraints (Zatsiorsky & Latash, 2008). Slip prevention is attained by force modulation that satisfies the "safety margin", that is, the digits have to apply grasp forces above the required minimum that is necessary to hold the object against gravity (Johansson & Westling, 1984). For tilt prevention and to accurately maintain the orientation of the object, digit forces have to be distributed such as to compensate the external torque acting on the object, or to avoid generating a net torque on the object in absence of an external torque (Zatsiorsky & Latash, 2008). Resistance to perturbations is defined as the forces that the digits have to produce to ensure a stable grasp when mechanical perturbations are present (Hasan, 2005).

In the current study, we designed an experimental task where participants experienced repetitive mechanical perturbations during the holding phase. By doing so, we aimed to answer our second question concerning how the CNS implements multi-digit corrective force responses to single and multiple perturbations within a trial as a function of the number of digits involved in the grasp. Specifically, we sought to determine whether force responses across multiple digits would be synchronous, thus supporting a generalized stiffening of the hand regardless of the grasp configuration, or asynchronous, and therefore dependent on the grasp type.

With regard to the control of individual digit normal force, studies of five-digit grasping and pressing tasks have reported that 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, i.e., the concept of 'finger specialization' (Park, Zatsiorsky, & Latash, 2010; Zatsiorsky, Gregory, & Latash, 2002). Our third question was whether such a finger specialization ~~is flexible~~would still hold when grasping with a number of digits less than five and if so, whether it depends on the number of digits used and their moment arm when grasping an object using different number of digits. An alternative strategy might consist of a proportional increase or decrease in stiffness among all digits to compensate for the missing or additional end effectors, i.e., when decreasing or increasing the number of digits involved in the grasp. Based on previous work (Winges, Soechting, & Flanders, 2008) we expected multi-digit force responses to be organized based on a stiffening strategy.

The present work was designed to answer the above three questions. ~~on tasks involving object grasping with two, three, four and five digits at unconstrained contacts.~~ Specifically, we used a tactile force-sensing device of rectangular cuboid shape and implemented an experimental protocol in order to generate force and torque perturbations within time intervals that were either predictable (periodic) or unpredictable (aperiodic) while subjects were instructed to hold the object stationary.

**Methods**

*Participants*

Twenty-one right-handed participants (8 females), 24±6 years of age, took part in the experiment. Five participants participated to the two-digits condition, five participated to the three-digits condition, five participated to the four-digits condition, and six participated to the five-digits condition. All participants had no history of neurological or motor deficits and they gave informed written consent in accordance with the Declaration of Helsinki.

The Shadow Dexterous Hand™ mounted on KUKA-lwr took part in the control experiment using five-digit grasp.

*Hardware*

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 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 consists of four modules with high-speed tactile sensors (up to 1.9 kHz) developed by Schürmann et al. (Schurmann, Koiva, Haschke, & Ritter, 2011). Each module (area: 80x80 $mm^2$) 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. To quantify the accuracy of the sensing modules, in our calibration we also varied the cross-sectional area of the gauge tip from 10 to 50 $mm^2$ with a step of 20 $mm^2$ to account for across-subjects differences in fingertip size.

Participants viewed a virtual rectangular cuboid while they grasped the TACO but 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 (CrystalEyes™) providing binocular disparity (Figure 1a). The TACO was attached to two PHANToM™ (SensAble® Technologies) force-feedback devices to track its position and apply force/torque perturbations while participants held the TACO with one hand (Figure 1b). The sampling rate of the PHANToM™ was 1 kHz. The total mass of TACO attached to the PHANToM™ arms was 0.470 Kg. Constrained by the arrangement of the PHANToM™ force feedback devices, TACO has five degrees of freedom of unconstrained motion (x,y,z, 0: no pitch rotation, α: yaw, β :roll).

For the control experiment, The Shadow Dexterous Hand™ is human-like sized hand and has the same kinematics and number degrees of freedom as human hand (Figure 2). The Shadow Dexterous Hand™ was attached to KUKA® lightweight robot (lwr) end effector (Figure 2d) to allow lifting movements of the TACO as achieved by human participants. The finger joints allow almost human-like movements (Rothling, Haschke, Steil, & Ritter, 2007). The hand has 20 degrees of freedom (DoF) plus 4 DoF of the wrist (abduction/adduction and flexion/extension). An antagonistic pair of McKibben style pneumatic muscle actuates each joint.

*Procedures*

Participants sat on a chair with 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 the thumb and one to four fingers (thumb-index finger, thumb-index-middle fingers, thumb-index-middle-ring fingers, or whole hand), and lift the TACO to a height of100-150 mm. The non-involved fingers (middle, ring and little, or 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™ force feedback devices. We studied 3 conditions of force/torque perturbations: force of $F_y$ = 2.4 N (Figure 3a) was applied in vertical direction, or torques of 0.25 N·m were applied around the y- or z-axis (Figures 3b, 3c respectively) causing yaw and roll rotations around TACO's center of mass. The applied force and torques ($F_y$, $T_y$ and $T_z$) were turned "on" and "off" periodically (perturbation frequency) in one condition and were thus "predictable" in terms of frequency (Figure 3d). In the other condition, the applied force and torques were turned on aperiodically (i.e., the duration of the perturbations "on" ranged between 1 to 3.5 s and perturbations "off" ranged between 0.6 to 1 s; both randomly presented) and were thus "unpredictable" (Figure 3e). The rationale of this experimental design was to test whether the grasping forces of the fingers would depend on the predictability of the perturbations and therefore adapt differently to the two temporal patterns of the perturbations. 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 × 2 = 10 conditions, ($F_y$, $T_y^{CCW}$, $T_y^{CW}$, $T_z^{CCW}$ , $T_z^{CW}$) with both periodic and aperiodic (P/Ap). The order of conditions was randomly presented to the participants. Subjects performed ten trials per condition. Each trial lasted approximately 25 s from grasp onset to release. Before starting the experiments, subjects performed four trials with $F_y$ perturbation in order to familiarize with the task. Participants could rest as much as needed between trials. The total duration of the experiment was approximately two hours per subject with a few minutes break after the first half of the experiment.

In control experiment, The Shadow Dexterous Hand™ grasped the TACO using 5 fingers and achieved the experimental task as human participants did in the main experiment (explained above). After "GO" signal, the Shadow Dexterous Hand™ grasp state was changed from "no grasp" to "yes grasp". After, the hand successfully grasped the TACO, the experimenter controlled the TACO height using KUKA-lwr, and once the arm reached the suitable height the KUKA-lwr was grounded to avoid any oscillations of the KUKA-lwr end effector that could alter the hand performance. During the object hold phase, the PHANToM™ applied only $T_y^{CCW}$, $T_y^{CW}$ perturbation in periodic and aperiodic fashion. We used only these two perturbations, because of the absence of the low friction force in the Shadow Dexterous Hand™.

At the end of the trial, the KUKA-lwr replaced the TACO and the hand grasp state was set to "no grasp" in order to release the TACO and wait for "GO" signal of the next trial to re-grasp it again. Each perturbation was repeated 16 times giving a total of 64 trials.

## Data processing and analysis

The normal forces F of the fingers and the digit horizontal and vertical center of pressures ($CoP_x$ and $CoP_y$, respectively) were read from the force modules of the TACO with the origin (0, 0 mm) 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, normal forces, and TACO position were recorded and ran through a second order Butterworth low pass filter with 1 Hz cutoff frequency (Figure 4). $CoP_x$ and $CoP_y$ were extracted during the holding phase.

The positions and rotations of TACO were tracked using PHANToM™ devices and used to compute the net torques generated by the subject ($HT_{y,z}$) using Newton's second law for rotation:

$$\begin{cases} HT_y + T_y = \dfrac{d^2\alpha}{dt^2} I_y \\ HT_z + T_z = \dfrac{d^2\beta}{dt^2} I_z \end{cases} \quad (1)$$

where $T_y$ and $T_z$ are external torques, $\frac{d^2\alpha}{dt^2}$ and $\frac{d^2\beta}{dt^2}$ are the angular accelerations, and $I_y$ and $I_z$ are approximated to a rectangular cuboid moments of inertia:

$$\begin{cases} I_y = \dfrac{1}{12} m(l^2 + w^2) \\ I_z = \dfrac{1}{12} m(l^2 + h^2) \end{cases} \quad (2)$$

The parameters *m*, *l*, *w*, and *h* correspond to TACO's mass when attached to the phantoms' arms, length, width, and height, respectively. The moments of inertia of the PHANToM™ arms were not considered due to the complexity of the design of the PHANToM™ device.

Digit peak forces and torques were extracted and analyzed only for the first five perturbations in order to have an equal number of periodic and aperiodic perturbations. A linear mixed model (LMM; Baayen, Davidson, & Bates, 2008) with a repeated measure-structure was used to analyze the data and its general formulation is as follows:

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{Z}\mathbf{b} + \varepsilon \qquad (3)$$

where $y$ denotes digits normal forces, $X$ is model matrix for the vector of fixed effects $\beta$ , $Z$ is the model matrix for the random effects vector $b$, and $\varepsilon$ is a residual vector for random effects. . In digit normal force analysis, we use here LMM where the dependent variable "normal force" was modeled with including trials, conditions, perturbations frequency and types as fixed effect and subjects as random effect. Moreover, Tukey's test was conducted between two successive perturbations for digits normal forces on the same LMM for digit normal forces. LMM was used as well to analyze the error of participants' hand torque using participants as random effects while the fixed effects were: perturbation frequency (periodic, aperiodic), perturbation number (p1, p2, p3, p4, p5), and number of trials. Levene's test was used to test equality of standard deviations (variances) in digit initial placements across number of digits conditions. We used specifically this test because of its robustness under non-normality. Finally, for the control experiment, we conducted ANOVA test with repeated measures of error in the Shadow Dexterous Hand™ net torque with factors frequency type (two levels: Ap, P), condition type (two levels: $T_y^{CCW}$ and $T_y^{CW}$) and perturbations types (five levels: $F_y$, $T_y^{CCW}$, $T_y^{CW}$, $T_z^{CCW}$ , $T_z^{CW}$).

## Results

*Center of pressure for individual participants*

We first investigated the locations of the digits on the TACO during the holding phase in all fingers conditions. to quantify digit CoPx,y across-trial variability. Figure 5 shows CoP data for individual participants. Although the grasping task is stereotyped due to the TACO's fixed shape, participants differed in their digit placement on the TACO (initial locations). Figure 6a,b shows mean standard deviations in digits horizontal and vertical placements for each condition. Data shown in Figure 6 reveals that there was a high variability among participants' digit initial locations for all digits conditions. We used Levene's test to determine whether the variances of thumb and index finger position were similar across digit conditions, e.g. variability of index finger position in the 2-digit condition vs. variability of index finger position in the 3-digit condition). The rationale for this analysis was quantify variances using a balanced design since both digits are used across all digits conditions.

Levene's test revealed that digits variances were statistically indistinguishable across digit conditions for both CoPx: ($F(7,34) = 0.93$, $p = 0.50$) and CoPy: ($F(7,34) = 0.57$, $p = 0.78$). Therefore, adding or removing digits in the grasping task did not significantly affect the variability in digits' initial locations.

*Digit normal force adaptation and time to peak synchronization:*

We sought to investigate digit normal force adaptations across perturbations within each trial. LMM revealed that the difference in normal force in response to the first perturbation vs. all the subsequent perturbations was positive (i.e., normal force was smallest for the first perturbation) for all digits and did not exceed 2N across all digit conditions. Table 1 summarizes all p-values of Tukey's test between digit normal forces recorded in the first perturbation versus those recorded in the rest of the perturbations. For the two-digit condition, significant differences were found when comparing perturbation 1 (P1) versus perturbation 4 (P4) (e.g. see Figures 7a for the index finger). For the three-digit condition, the comparison between forces from P1 versus the rest of perturbations revealed significant force differences (e.g. see Figures 7b for index finger). For the four-digit condition, significant differences were found when comparing P1 versus P2 except for the ring finger, where a significant force difference was found only when comparing P1 versus P5. For the five-digit condition, only the middle finger exhibited significant force differences when comparing P1 versus the rest of perturbations. Starting form the second perturbation, the multiple pair comparisons did not reach the level of significance (e.g. P2 versus P3, P3 vs. P4, P4 vs. P5) for any of the digit conditions. The results of the latter comparisons indicate that for most grasp configurations, reactive force responses triggered by the first perturbation differed from subsequent ones, and suggest a transition from a feedback-driven response (P1) to more feed-forward-based force control to counter the perturbations delivered to the TACO. The only exception to this scenario was the five-digit condition where the overall increase in the grip force from P1 to P2 (as revealed by LMM) but this increase did not reach statistical significance except for the middle finger (Table 2).

To address the question of whether multi-digit normal forces were adjusted and modulated in a closed-loop or feed-forward fashion, we examined the patterns of multi-digit force responses within each perturbation. We first estimated the mean time to peak in each perturbation of each digit in all digit conditions using the same LMM model used for the above across-perturbation analysis. As shown in Table 2, the difference in time to peak normal force between digits in each digit condition did not exceed 100 ms. Figure 8 shows different distributions of time to peak normal force in each perturbation for both frequency conditions (Periodic and Aperiodic) across trials, torques conditions and participants. We recorded a similar distribution of time to peak of different digit within a single perturbation. It was shown that control loops engaged for the correction of load and normal forces during manipulation tasks takes about 100 ms (Johansson & Flanagan, 2010). This result indicates lag magnitude between individual digit peak forces were synchronized. Thus, our results suggest that the CNS modulated digit normal force in feed-forward fashion within a single perturbation then it corrects the digit normal force for the next perturbation using closed-loop control (across perturbations).

*Compensatory external torque*

In this subsection, we explored the question of how the learning pattern observed in digit forces responses affected the stabilization of the TACO in order to compensate the external torque within the first five perturbations averaged across trials, participants, and perturbation type for each digit condition. This approach is justified by the fact that the perturbations were delivered in a consecutive fashion within a single trial. Figure 9 shows the error of hand compensatory torque for the periodic and aperiodic (P and Ap) conditions during the five perturbations per trial when grasping for each digits number condition.

As expected, LMM revealed that the mean error in hand torque was higher for the aperiodic than periodic condition in all digit conditions (2 digits: 2.18±0.24, 3 digits: 2.22±0.27, 4 digits: 2.02±0.26, 5 digits: 1.05±0.18 Ncm). Posthoc analysis on the comparison between two successive perturbations revealed a significant effect between the P1 and the rest of perturbations in all digits experiments (all $p < 0.001$) and between p2 versus p3, p4, p5 perturbations in two, three, and four digits conditions (2d, 3d, 4d: $p<0.001$). For five digits conditions error in hand ~~net hand~~net torque at p2 was significant versus p4 and p5. After perturbation 2 there was no significant difference between hand net torques in the pairs (p3 vs. p4, p3 vs. p5 and p4 vs. p5). This result is consistent with the results described in the above section and with the interpretation that learning to compensate the external torque was faster and easier in the periodic than aperiodic condition especially when using a five-digits grasp (Figure 9).

*Digit normal forces*

We sought to evaluate the modulation of finger forces for each perturbation when adding or removing digits from the grasp. To address this question, our analysis focused on the fingers opposing the thumb since it shares half of the grip force with the rest of the fingers. Moreover, we averaged data from each participant across perturbations (five) as well as periodic and aperiodic trials. For this analysis we did not include the 2-digit condition because the thumb and the index digits shares equally the total grip force.

Figure 10 (a, b, c) shows the normalized mean and standard errors of normal forces estimated by LMM for each finger (fingers opposing the thumb digit) for different perturbation types. The normalization was achieved by subtracting the index finger mean normal force from each finger normal force in each number of digit conditions. In the three-digit condition, the index finger applied a slightly higher normal force than the middle finger for F, $T_y^{CW}$, $T_z^{CW}$ perturbations, whereas the middle finger applied slightly higher normal force in $T_y^{CCW}$ and $T_z^{CCW}$ to counterbalance the external torque perturbations ($T_y^{CCW}$ closer mean to the index finger but with higher variability; Figures 4 and 10b). In the four-digit condition, the index finger applied more normal force in the torque perturbations $T_y^{CW}$, $T_z^{CW}$ (with higher variability than the middle finger in F), whereas the ring finger applied more normal forces in the perturbations F, $T_y^{CCW}$, $T_z^{CCW}$ (Figure 10). In addition, the middle finger applied a considerable amount of normal force in the rotational task as well as the load task. In the five-digit grasp condition, similarly to four digits condition, the index finger applied higher forces than the rest of the fingers in the torque perturbations $T_y^{CW}$, $T_z^{CW}$ and the little finger played similar role as the ring finger in four digits condition by applying higher forces than the rest of the fingers in the torque perturbations $T_y^{CCW}$, $T_z^{CCW}$ (Figure 10). These results indicate that the outer fingers produced higher force in the rotational task (torques clockwise and counter clockwise) depending mainly on the active end effectors on the grasped TACO and their initial placement. Thus, the further the fingers from the TACO's center, the higher the force exerted by the subjects in the direction opposite to the direction of the external torque perturbation. Therefore, this result does not support the framework of “finger specialization” (see Introduction). To further test the validity of our interpretation, we conducted a control experiment using a robotic hand.

## Control experiment

In this part we aim to investigate the force control strategy achieved by participants. In other words we aim to investigate whether participants control the hand grasp stiffness (all fingers together) regardless the external perturbation or individual finger force were controlled and modulated independently for each finger depending on the external perturbation. To do so, we repeated the same experimental paradigm for a robot hand: Shadow Dexterous Hand™. The hand controller developed by (Rothling et al., 2007) is based on two variables: joint positions and joint stiffness since the difference in pressure correlates with the joint position while the pressure sum correlates stiffness joints. In this experiment we set the hand stiffness constant and the hand posture as well that allows to successfully grasp and lift the TACO. In other words, all digit end effectors were positioned on the TACO similarly as representative participant (s16) in Figure 4 using joint position controller. The resulted posture was defined the “yes grasp” of the hand maintained for the whole experiment. Thus, the hand has two states: release state or fully opened “no grasp” and grasp posture for the TACO “yes grasp”. Once the “yes grasp” posture was set, the joints positions were controlled to maintain the same posture during the whole trial. Similarly, the stiffness of the resulted posture was controlled and was maintained constant using the controller based sum in pressure of hand muscles (Rothling et al., 2007)

## Results

*Digit normal force*

Here, we sought to compare digit normal force across perturbations within each trial in order to compare with human participants data. Figure 11 show a single trial of the Shadow Dexterous Hand™ when externally perturbed with $T_y^{CCW}$. As shown this figure, the little and ring finger are mainly involved in this condition. This latter effect is due to the fact that the external perturbation applies forces against the fingers that are maintaining its stiffness and joint positions at the steady state using the joint position controller. Figure 12 shows the mean finger normal forces of each finger for both conditions $T_y^{CW}$, $T_y^{CCW}$ averaged across trials and frequency condition (no significant difference between periodic and Aperiodic conditions). Similarly to human participants performance (Figure 12), the index finger was the mainly involved in the condition $T_y^{CW}$ and the ring and little finger were mainly involved $T_y^{CCW}$. This latter result is due to the fingers locations on the TACO: the further is the moments arm the higher the force in opposite direction of the external perturbation. Recall, the hand posture and stiffness were set to a steady state, the only control that can be achieved by the hand is to converge to steady state for both stiffness and joints positions.

*Compensatory external torque*

Next we aim to evaluate the hand net torque. Figure 13 shows the error of hand compensatory torque for the perturbation $T_y^{CCW}$ and $T_y^{CW}$ periodic and aperiodic (P and Ap) for the Shadow Dexterous Hand™. ANOVA test revealed no significant effect of the perturbation type ($F(1,13) = 2.41$, $p =0. 14$), perturbation frequency ($F(1,13) = 0.05$, $p = 0.83$) and between perturbation ($F(4,13) = 1.92$, $p = 0.13$). The hand successfully compensated the external torque by just simply stiffening on the object regardless the frequency and the external perturbation. The only difference between the human participants is the learning trend observed between the P1 versus the rest of the perturbations and also the perturbation frequency where periodic condition was easier than aperiodic one. Obviously, no learning is expected here since no learning algorithm was implemented and fed to the grasping control, the only control was used by the hand is joint position and stiffness that were kept constant.

## Discussion

The results of the current study revealed that adding or removing fingers in the grasping task did not alter variability between participants in initial digit placements. In addition, participants adopted a hand stiffening strategy regardless to the external perturbation and number of digits used in the task in order to counterbalance the TACO as confirmed in the control experiment using the Shadow Dexterous Hand™ controlled by joints positions and stiffness controller.

*Choice of digit locations*

In our first question, we expected that trail to trial variability would increase by increasing the number of digits but this was not the case. An important feature of our experimental design was that subjects could freely choose their digit placement across trials regardless the number of digits used. Interestingly, adding or removing one finger (substantial amount of degrees of freedom) did not alter variability in digits' initial placement although the task could be considered as more challenging when using less digits than five for instance in terms of magnitude of digit normal forces and compensatory external torque required to perform our experimental task. Specifically, we found slightly higher variability in all digit conditions in the horizontal CoPs than the vertical one. In contrast, it has been reported that the largest variability was recorded for thumb digit in vertical CoPs (CoPy) and both coordinates (CoPx, CoPy) for index and middle fingers during tripod grasping (Baud-Bovy & Soechting, 2002). Our results revealed that the variability was large and nearly the same for both coordinates (slightly larger in CoPx). In (Friedman & Flash, 2007) also observed a large amount of variation in finger placement on daily life object using five digits grasp. Between participants variability can be explained by idiosyncratic grasping strategies.

*Grip force control*

Our second question regarding the nature of digit normal force control within and across perturbations, we observed that time to peak of digit normal forces were synchronous with in a single perturbation (Figure 8 and Table 1) indicating that they are controlled in feed-forward manner within a single perturbation. This results confirm what was found previously that CNS avoids long time delays that lead to instability during grasping and manipulation tasks (Budgeon, Latash, & Zatsiorsky, 2008; Johansson & Flanagan, 2010). Similar synchronous forces changes was found when adding or removing the fifth finger during the hold phase of the grasping task (Budgeon et al., 2008). In contrast, digit normal force increased from the first perturbation to the next ones that consequently reduced the error in net hand torque (Figure 9). This result indicates that digit normal forces are controlled in closed-loop manner from one perturbation to another during the holding phase. This regulation process did not reach the level of significance only for five digits condition, although we recorded an overall increase as well in digit normal force from the first perturbation to the next ones.  One possible explanation of a such motor behavior is that participants used simple strategy of force control by increasing the grip force (stiffening the full hand) in the following perturbations compare to the first one that was suitable to successfully counterbalance the TACO. Similar strategy was observed during arm movements that was perturbed using mechanical manipulandum where participant learned arm stiffness that was independent from the external perturbations but successfully compensate them (Burdet, Osu, Franklin, Milner, & Kawato, 2001). The adopted a strategy led to stable grasp that optimized the error in the hand net torque across perturbations, indicating that the hand grasp control resisted rather than assisted the external perturbations in contrast of many common situations in motor control (Hasan, 2005) where it has been shown the opposite.

Concerning the third question concerning individual digit normal forces would verify finger specialization. We observed that the higher force response is in the outer fingers. This latter effect is mechanical one that was a consequence of the full hand stiffening and the finger moment arm: the further the finger from the center of the TACO is the higher the normal force. This result was confirmed when using the Shadow Dexterous Hand™ controlled by joints positions and stiffness controller (Figures 10, 12). The stiffening strategy was achieved regardless to the external perturbations and number of digits used in the task. Therefore, based on our results, the modulation of digit normal forces is a 'configuration' problem rather than a 'finger specialization' problem as reported in (Park et al., 2010; Wu, Zatsiorsky, & Latash, 2012;

Zatsiorsky et al., 2002).

Although variability in digits initial placement and the number of digit used in task, the hand stiffening strategy persisted that was compatible with our experimental task. Hard-wired muscle synergy at hand and arm level that serve all fingers (Santello, Baud-Bovy, & Jörntell, 2013) can also explain the adopted strategy by participants. Different hand postures lead to different grasp stiffness (Friedman & Flash, 2007) and different grip force (Naceri et al., 2014) but satisfied a stable grasp because of the canceling out of the applied forces (equilibrium). It has been shown that arbitrary net force and/or torques produced by force closure of a robotic hand (SoftHand) satisfy a stable grasp in the absence of friction forces (Bicchi, Gabiccini, & Santello, 2011). This finding might underscores the flexibility and independence of high-level motor processing from low-level motor execution at the end effector used in the task (Fu, Hasan, & Santello, 2011).

In summary, participants substantially varied in their initial placements on the TACO, once they grasped and lifts the object using the required grip force that was not enough to counterbalance the TACO against the first perturbation during the holding phase. Digit normal forces were controlled in feed-forward manner within a single perturbation. Hand net torque was optimized across perturbations by increase the grip force in the next perturbations compare to the first one, which indicates that it was controlled in closed-loop fashion. The synchronous increase of digit normal forces was achieved by all digits regardless to the external perturbation.

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Figure and table Captions

*Table 1*. Multiple comparisons of normal force means using Tukey's test between the first perturbation and the rest of perturbations across trials in different digit conditions (P: perturbation)

*Table 2*. LMM estimates for the mean time in milliseconds to peak of each digit in both periodic and aperiodic perturbation frequency conditions for all digit conditions.

*Figure 1*. Experimental materials. (a) Participants binocularly view the mirror image of the visual scene. (b) The TACO attached to the PHANToM™ force feedback devices. On the left, the TACO output image with red cross represents digit center of pressures (CoPs).

*Figure 2*. The Shadow Dexterous Hand™ . (a): Kinematics and degrees of freedom. (b,c): The Shadow Dexterous Hand™ grasping the TACO. (d): The Shadow Dexterous Hand™ attached to the KUKA® light weight robot end effector.

*Figure 3*. Experimental protocol. (a) Perturbation force $F_y$. (b) Perturbation torque $T_z$ clockwise "CW" and counter clockwise "CCW". (c) Perturbation torque $T_y$ CW and CCW. (d) periodic "P"(e) aperiodic "Ap" with gray areas represents when force/torque perturbation is on.

*Figure 4*. Trial of representative subject in $T_y^{CCW}$ (gray areas represent intervals when external perturbations are active "on").

*Figure 5*. Digit CoP results for individual participants in all conditions for all finger number conditions. The thumb CoPs were plotted at the same plane with other fingers. (a): 2 digits, (b): 3 digits, (c): 4 digits, (d): 5 digits.

*Figure 6*. Mean variability of digits CoPs across participants. (a): horizontal digits placements (CoPx). (b): vertical digits placements (CoPy). Error bars represents standard deviation of the mean standard deviations. "d" in legends refers to digits (e.g., 2d: 2 digits).

*Figure 7*. Distribution of index normal force in two and three digits condition during both periodic and aperidic frequency across all participants and perturbation types. Horizontal blue lines represents the mean estimated by LMM in each perturbation. Dashed black line at 5N was used as line of reference. (a): 2 digits, (b): 3 digits. (c) and (d) detailed data for digit normal force: mean and standard deviation  across subjects in 5 perturbations for all perturbation types.

*Figure 8*. Distribution of time to peak for digit normal forces. Gray rectangles represent the perturbation on (pi: perturbation for i =1 to 5). Red area represents distribution. Vertical lines represents the mean estimated by LMM in each perturbation. (a): 2 digits, (b): 3 digits, (c): 4 digits, (d): 5 digits

*Figure 9*. Average error in hand net torque for all digit experiments (id) in five perturbations (pi) averaged across all participants and perturbation types. Left panel (Ap): aperiodic and right panel (P): periodic frequency. Error bars represent the standard error.

*Figure 10.* Mean normal forces for each finger normalized by subtracting the index normal force in each digit number condition. Error bars represent standard error. (a): Data for the perturbation F, (b): Data for Perturbation torque $T_{y,z}$ clockwise "CW (c): Data for Perturbation torque $T_{y,z}$ counter clockwise "CCW.

*Figure 11.* Trial of the Shadow Dexterous Hand™ in $T_y^{CCW}$ (gray areas represent intervals when perturbations are set "on").

*Figure 12.* Mean normal forces for each finger averaged across trials and frequency condition (P and Ap). Error bars represent standard error. Right panel represents data for $T_y^{CW}$ left panel represents data for $T_y^{CCW}$.

*Figure 13*. Average net torque of the Shadow Dexterous Hand™. Left panel (Ap): aperiodic and right panel (P): periodic frequency. Error bars represent the standard error.

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

| | | *P2-P1* | *P3-P1* | *P4-P1* | *P5-P1* |
|---|---|---|---|---|---|
| 2 digits | Thumb | 0.31 | 0.08 . | 0.01* | <0.001*** |
| | Index | 0.32 | 0.08 . | 0.01* | <0.001*** |
| 3 digits | Thumb | 0.005** | <0.001*** | <0.001*** | <0.001*** |
| | Index | 0.04* | 0.002** | <0.001*** | <0.001*** |
| | Middle | 0.04* | 0.005** | 0.01* | 0.002** |
| 4 digits | Thumb | 0.05 . | 0.005** | 0.01* | 0.003** |
| | Index | 0.05 . | 0.005** | 0.01* | 0.002** |
| | Middle | 0.05 . | 0.005** | 0.01* | 0.002** |
| | Ring | 0.78 | 0.37 | 0.14 | 0.03* |
| 5 digits | Thumb | 0.64 | 0.46 | 0.47 | 0.23 |
| | Index | 0.8 | 0.9 | 0.9 | 0.78 |
| | Middle | 0.02* | 0.002** | <0.001*** | <0.001*** |
| | Ring | 0.83 | 0.62 | 0.77 | 0.59 |
| | Little | 0.9 | 0.9 | 0.9 | 0.9 |

| | | *Thumb* | *Index* | *Middle* | *Ring* | *Little* |
|---|---|---|---|---|---|---|
| 2 digits | Periodic | 221 | 221 | *NA* | *NA* | *NA* |
| | Aperiodic | 1229 | 1229 | *NA* | *NA* | *NA* |
| 3 digits | Periodic | 216 | 222 | 232 | *NA* | *NA* |
| | Aperiodic | 1120 | 1100 | 1100 | *NA* | *NA* |
| 4 digits | Periodic | 465 | 497 | 456 | 462 | *NA* |
| | Aperiodic | 1230 | 1170 | 1180 | 1185 | *NA* |
| 5 digits | Periodic | 476 | 443 | 448 | 449 | 487 |
| | Aperiodic | 1254 | 1247 | 1257 | 1207 | 1206 |