Published in final edited form as:

J Mot Behav. 2012 May ; 44(3): 169–178. doi:10.1080/00222895.2012.665101.

Stability Control of Grasping Objects with Different Locations of Center of Mass and Rotational Inertia

Gregory P. Slota, Moon Suk Suh, Mark L. Latash, and Vladimir M. Zatsiorsky
Pennsylvania State University

Abstract

The objective of this study was to observe how the digits of the hand adjust to varying location of the center of mass (CoM) above/below the grasp and rotational inertia (RI) of a hand held object. Such manipulations do not immediately affect the equilibrium equations while stability control is affected. Participants were instructed to hold a handle, instrumented with five force/torque transducers and a 3-D rotational tilt sensor, while either the location of the CoM or the RI values were adjusted. On the whole, people use two mechanisms to adjust to the changed stability requirements; they increase the grip force and redistribute the total moment between the normal and tangential forces offsetting internal torques. The increase in grip force, an internal force, and offsetting internal torques allows for increases in joint and hand rotational apparent stiffness while not creating external forces/torques which would unbalance the equations of equilibrium.

Keywords

Grasping; Stability; Center of mass; Motor control

Introduction

Controlling the position and orientation of a free grasped object is accomplished by the forces and moments applied by the digits. The system is mechanically redundant: the object in space has 6 kinematic degrees of freedom (DoF) while the forces and moments at the digit-object contacts have 30 DoFs (6 force and moment components at each contact $\times$ 5 digits=30). The motor control mechanisms utilized to solve the redundancy problem is a continuing area of research (Goodman & Latash, 2006; Gorniak, Zatsiorsky, & Latash, 2009; Li, Latash, Newell, & Zatsiorsky, 1998; Yang, Scholz, & Latash, 2007). Grasping an object and maintaining equilibrium is an everyday task that is accomplished with minimal conscious thought and effort. Solving the six equations, with overlapping variable sets, with numerous possible solutions, comes naturally. Understanding how this control is performed will further our understanding of how the human body works and how it can be replicated in the design of artificial limbs and robotics.

It should be noted that the problem of motor redundancy, firstly formulated by N.A. Bernstein (1967), is a general problem of motor control that is explored on various movement tasks and from different perspectives, see e.g. (Todorov, 2004) and (Guigon, Baraduc, & Desmurget, 2007). We expect that solving this problem for the specific case of multi-finger prehension could contribute to the understanding of the problem in general.

The control of the digits of the hand follows a 2-tier hierarchy, the lower level being the individual fingers (Index, Middle, Ring, Little), and the higher level consisting of the thumb (Th) and virtual finger (Vf: the four fingers combined) (Arbib, Iberall, & Lyons, 1985; MacKenzie & Iberall, 1994). At the Th-Vf level of control, the sum of the forces and moments must counteract all external forces and moments. At the individual finger level, the efforts of the Vf are distributed amongst the fingers and include potential internal forces and moments (Gao, Latash, & Zatsiorsky, 2005; Gorniak, Zatsiorsky, & Latash, 2008; Kerr & Roth, 1986; Murray, Li, & Sastry, 1994; Yoshikawa & Nagai, 1991).

To maintain a hand-held object at rest the mechanical equations of equilibrium should be satisfied. For the five-digit grasp and a planar case, where the “grasp plane” contains all the centers of digit forces application, the five equations of equilibrium are presented below (see also Figure 1). The equations are based around the forces (F_n : normal force, F_t : vertical tangential force) generated by the four fingers (Index, Middle, Ring, Little) and the Th. The moments generated are results of the geometry of the handle and the point of force application. The horizontal positions (moment arms) of the digits (R) are fixed while the vertical positions are affected by finger roll on the sensor surface (Zatsiorsky, Gao, & Latash, 2003a) and can change the moment arms (D). Equilibrium is achieved in the planar case if the sum of the horizontal digit forces is zero (equation 1), the sum of the vertical digit forces is equal and opposite to the weight of the object (equation 2), and the generated moments (equations 3 & 4) are equal to and opposite of external moments (M_{ex} , equation 5).

$$F_{n_{vf}} = F_{n_i} + F_{n_m} + F_{n_r} + F_{n_l} = -F_{n_{th}} \quad (1)$$

$$F_{t_i} + F_{t_m} + F_{t_r} + F_{t_l} + F_{t_{th}} = -W \quad (2)$$

$$M_n = (F_{n_i} \times D_i) + (F_{n_m} \times D_m) + (F_{n_r} \times D_r) + (F_{n_l} \times D_l) \quad (3)$$

$$M_t = (F_{t_i} \times R_i) + (F_{t_m} \times R_m) + (F_{t_r} \times R_r) + (F_{t_l} \times R_l) + (F_{t_{th}} \times R_{th}) \quad (4)$$

$$M_n + M_t = -M_{ex} \quad (5)$$

where W is the weight of the object (a load force), M is the moment of force, and n and t refer to the normal and tangential forces, respectively.

The control of the equilibrium of hand-held objects has been tested under various conditions of changing the parameters of the object. This includes increased vertical load forces (Kinoshita, Kawai, & Ikuta, 1995), changes in handle geometry (Zatsiorsky, Gao, & Latash, 2003b), and changes in the external moment of force (Kinoshita, Backstrom, Flanagan, & Johansson, 1997). The measured patterns of F_n , F_t , and the moments generated have been shown to change to match the new conditions. Note however that these different conditions have a direct effect on the parameters in the equilibrium equations (load force: W in equation 2, moment arms: R and D in equations 3 and 4, and external moment: M_{ex} in equation 5).

Some changes to the hand-held object properties result in force/moment adjustments that are not required by the equations of equilibrium. Case in point is different friction conditions of the object's surface. The reduction in surface friction is matched with an increase in grip force (Aoki, Niu, Latash, & Zatsiorsky, 2006; Johansson & Westling, 1984). While surface friction is not a part of the base equations, it is a mechanical constraint for the production of

Ft. In a similar fashion, this study was designed to test changes that do not affect the equilibrium equations directly, but affect the stability control. By keeping the object mass constant, and not applying any external forces or moments, the object's equilibrium is not immediately affected. But, by adjusting the location of the center of mass (CoM), above or below the hand, or the rotational inertia (RI), the stability control [requirements for quick and properly scaled moment of force production] of holding a handle upright is changed. The changes in CoM and RI can be achieved by the relocation of external masses along the vertical axis of the object. (A comment on the terminology: We will call the task changes that directly affect the variables of the equilibrium equations, i.e. the changes in the supported load, external moment and the grasp width, the *equilibrium requirements*. The task variations, such as the object moment of inertia and vertical location of the CoM, which are not immediately represented in the equilibrium equations, will be called *stability requirements*.)

There has been a similar study of stability control dealing with the control of the human spine (Granata & Orishimo, 2001). In this study a subject would hold a barbell at a fixed distance (fixed moment arm) in front of their body. Electrical activity of the trunk muscles was recorded while the bar was held at various heights. With the mass and external torque held constant, equilibrium was not changed during the tasks while the stability of the "inverted pendulum" condition was changed. As the barbell was held in higher and higher positions, the muscles of the trunk increased in co-contraction (activation of muscles which apply forces against each other). This muscle activity resulted in no net forces/moments and resulted in increasing the stiffness of the spine (Lee, Rogers, & Granata, 2006).

The purpose of this study was to investigate the digit force patterns with changes: (1) in the vertical location of the object's CoM and (2) in the RI of the handle. While both of these conditions do not immediately affect the static equilibrium equations we expected that people react to these changes by varying the internal forces and moments, i.e. the forces and moments that offset each other (Gao, et al., 2005). The internal forces and moments will not affect the equations of equilibrium but will increase the resistance to perturbation (the apparent stiffness) of the joints. Increased apparent stiffness will help stabilize the object when the CoM location or RI are changed.

It was hypothesized that:

1. Elevating the location of the CoM (H1, H2) with respect to a neutral handle configuration (Baseline: BL) will result in increased co-contraction. Here the term co-contraction is used in the meaning "parallel increase in the forces produced by digits that generate moments of force acting against each other".
2. Lowering the location of the CoM (L1, L2) will not significantly affect the level of co-contraction with respect to the BL configuration. The inherently stable handle configurations (L1,L2) will result in force patterns similar to that of the neutrally stable handle configuration (BL) since increased co-contraction is not required in these instances.
3. Increasing the RI of the handle with respect to the BL condition will result in increased co-contraction. (This hypothesis is not self-evident: it may be argued—as it was done by one of the anonymous reviewers (we thank him/her for this idea)—that higher rotational inertia by itself stabilizes the equilibrium and hence increased co-contraction is not necessary. Such a controversy in opinions can be sorted out only by an experiment.)

4. Changes in co-contraction (measured as Grip Force) will be matched by changes in other variables of the equations of equilibrium, namely the equations related to torque control (Equations 3-5).

Note that the hypothesized force adjustments, besides their expected positive effect on the balance control, may have also some negative consequences. In particular, while co-contraction helps stabilizing an object orientation by increasing the object's apparent rotational stiffness, it comes at the costs of increased energy consumption and increased muscle fatigue. Hence, the central controller has to balance the pros and cons of different solutions.

Methods

Subjects

Ten male participants took part in the experiment. The group data (mean $\pm$ SD) were: age 24.4 $\pm$ 5.0 years, height 178.0 $\pm$ 4.4 cm, weight 77.7 $\pm$ 9.0 kg, hand length from the proximal palmar crease to the tip of the middle finger 18.5 $\pm$ 0.8 cm, width at the level of metacarpal heads 9.0 $\pm$ 0.4 cm. Every subject was right-handed and none of them reported to have any neurological or upper extremity pathology. None of the subjects were involved in any professional activity, such as professional violin or piano playing or professional typing, which may affect their hand dexterity. Each subject provided informed consent according to The Pennsylvania State University Institutional Review Board.

Apparatus

The task involved holding onto an instrumented handle (Figure 1) that measured applied forces, linear accelerations, and rotational orientation. The basic handle (aluminum block, screws, and sensors) was designed such that the CoM would be in the geometric center. The weight of the handle was 460 grams. The coordinate frames of each system are also depicted in Figure 1. Four Nano-17 and one Nano-25 force/torque transducers (ATI Industrial Automation, Apex, NC, USA) for the four fingers and the thumb, respectively, were implemented to record the forces and moments (6 DoF) of each digit. The Nano-17s were vertically spaced apart 30 mm. The Nano-25 was centered vertically and horizontally spaced for a 60 mm grip span. These sensors were connected to individual Net-F/T cards (ATI) which were connected to a wireless router and transmitted to a laptop computer. Data from the sensors were sampled at 1000 Hz and then processed and calibrated into forces and moments at the Net-F/T cards. Each sensor was covered with 320 grit sand paper so that the fingertip-surface interface had a coefficient of static friction of 0.94 ± 0.11 (Cole & Johansson, 1993; Savescu, Latash, & Zatsiorsky, 2008).

Handle linear acceleration (3 DoF) and orientation (3 DoF) were recorded from a 3DM-GX2 (Microstrain Inc., Williston, VT, USA) sensor cluster (weight 50 g) consisting of tri-axial sensors: linear accelerometer, gyroscope, and magnetometer. Information from the sensor cluster was wirelessly broadcasted to a USB Base Station (Microstrain) connected to the laptop computer. Data was initially processed and calibrated in the sensor cluster and were sampled at the laptop computer at 100 Hz. Both data streams, ATI and Microstrain, were collected on a single laptop computer using a custom written LabVIEW program (National Instruments, Austin, TX, USA). The program handled data stream initializations, synchronization, and terminations. Post processing was handled with custom written code in Matlab (Mathworks INC., Natick, MA, USA).

Protocol

Subjects stood with their forearm supported with their hand located within the testing area. The forearm rest ensured that the arm was steady and all movement was limited to the fingers and wrist. Subjects were instructed to grasp the instrumented handle with the tips of each digit (one per sensor), apply normal effort, and to rest their forearm on the support. For each trial, subjects were instructed to hold the handle steady with an upright orientation. Subjects were provided feedback from the sensor cluster about the orientation of the handle on a computer screen. The handle, when not in use, rested on a rack that maintained an upright handle orientation with no contact of the force sensors, allowing for re-zeroing of all the sensors. The initial position of the handle (on the rack) was just outside the reach of the subject when their arm was on the forearm rest. The start of each trial required some arm movement to grasp the handle and then rest the arm on the forearm rest. This small dynamic motion introduced some rotational disturbances that the subjects had to correct for. This portion of the data was not investigated as we were interested in the steady state time period when the subjects were in control of the object.

Test conditions included five levels of CoM location and three levels of RI (Figure 2) which were controlled by adjusting the location of two external masses. The CoM conditions consisted of a baseline normal condition (BL) with the two external masses directly on either side of the handle (see figures 1 & 2); each mass being 235 grams for a total of 470 grams. The total weight of the handle with the attachments was $460+470=930$ grams. There were two conditions of an elevated CoM location with the two external masses centered 353 mm (H1) and 643 mm (H2) above the CoM of the basic handle. There were also two conditions of reduced CoM location with the two external masses located at -353 mm (L1) and -643 mm (L2) below the CoM of the basic handle. The RI conditions consisted of three levels: the baseline condition (BL), middle level RI (Mid), and high RI (High). The middle RI condition had the two external masses split up and located at ± 360.5 mm from the CoM of the basic handle while the high RI condition had the external masses at ± 650.5 mm. Each test condition was visually recognizable to the subject.

The seven CoM and RI conditions were presented in random order (the BL conditions of CoM and RI were identical). There were three repetitions of each trial per test condition and subjects were provided ample time to rest between each data collection. Subjects were given practice trials before any data were collected to adjust the equipment and tasks. Each trial was recorded for 30 seconds, with the beginning and ending trimmed for the initial adjustment period (<5 seconds) and final 1 second. Practice trials (usually one-three) were provided so that the subjects could familiarize themselves with the handle, sensor feedback display, and the task of controlling the handle orientation. If required additional practice was permitted for subjects when more difficult tasks were performed (RI:High and CoM:H2).

Data Processing

Signals from each force/torque sensor were passed through a conditioning box (Net-F/T, ATI Industrial Automation, Apex, NC, USA) where each signal was processed and calibrated. Customized Labview programs (National Instruments, Austin, TX, USA) were used to display and capture the data. Data samples were collected for a 30-second period at 1000 Hz. Signal conditioning included conversion from signal voltages to forces (N) and moments (Nm) using calibration matrices per sensor. According to Newton's laws in the present tasks the normal forces of the Th and Vf are expected to be equal. Small differences in these forces (<0.6 N) have been recorded in some trials and were neglected. The differences can be due to the slight handle tilts and temperature effects. Grasp force (the average magnitude of the Th and Vf normal force) was computed and used in further analysis. Additionally, the moment arm for the moment generated by the F_{nVf} was

computed from the ratio of the total moment of normal forces generated by the four individual fingers divided by the $F_{n_{Vf}}$. This measurement is relative to the point of application of the $F_{n_{Th}}$.

The signals from the sensor cluster were also collected wirelessly via a USB Base Station (Microstrain) and sampled in Labview at 100 Hz. Data from the sensor cluster were analyzed in terms of the average angular position during the entire trial and the angular error (the range of “wiggle” measured as the root mean squared error about the average angular position during the entire trial) along the two directions of forward/backward and left/right tilt. These directions are with respect to the local coordinate system of the sensor cluster on the handle. Subjects grasped the handle in a comfortable position which was roughly at 45° flexion of the wrist.

Post collection processing was handled with customized code in Matlab. Each data file was inspected for potential trimming of any anomalies that could be recorded (e.g. if subject's fingers slipped or rapid handle orientation adjustment) or those that were seen post processing. However no anomalies were seen for this experiment. Processing included data reduction to average values per trial for each force and moment for each sensor per handle configuration. The three repeated trials of each test configuration were then averaged together.

Statistical analysis

The statistical analysis consisted of within-subject repeated measures ANOVA tests for each of the measured forces (F_n , F_t) as well as two sets of tests for the angular control (Front-Back: $\alpha_{F/B}$, Left-Right: $\alpha_{L/R}$). The CoM and RI conditions were each analyzed at the two hierarchy levels of control. For the F_n analysis at the Th-Vf level, there were one-factor repeated measures ANOVAs for the grasp force across each set of conditions of CoM [L2, L1, BL, H1, H2] and RI [BL, Mid, High]. For the F_t analysis, two-way repeated measures ANOVAs were used for $[Th, Vf] \times CoM$ and $[Th, Vf] \times RI$. For the individual finger level, for both the F_n and F_t , two-way repeated measures ANOVAs were used. The studied factors were FINGER [i, m, r, l] $\times$ CoM as well as FINGER $\times$ RI. In such ANOVA designs, the FINGER and $[Th, Vf]$ are non-repeated factors and the factors of CoM and RI are repeated factors for which subjects participate at each level of the factor.

All statistical analysis was performed with Statistica (StatSoft, Tulsa, OK, USA) with $\alpha=0.05$. Mauchly's sphericity tests were performed to verify the validity of using repeated measures, and sphericity was not violated. The data presented below are the group means and standard deviation.

Results

Task performance

All subjects were able to hold the handle in an upright position. The average angles for the CoM trials were $\alpha_{F/B}$: $0.03 \pm 0.46^\circ$ and $\alpha_{L/R}$: $-0.08 \pm 0.31^\circ$ and for the RI trials were $\alpha_{F/B}$: $0.03 \pm 0.34^\circ$ and $\alpha_{L/R}$: $-0.01 \pm 0.42^\circ$. These measures were considered negligible and statistical tests resulted in no noticeable trends. This suggests that the CoM and RI conditions did not result in the subjects' holding the handle in different postures per condition.

Results of the analysis of angular error (“wiggle” in terms of the root mean squared error about the local point of equilibrium) showed that: (1) level of RI had no effect for either front/back ($F_{2,18}=0.228, p<0.799$) or left/right angular variability ($F_{2,18}=0.707, p<0.506$), (2) the location of the CoM had a significant effect for both front/back ($F_{4,36}=18.7, p<0.001$)

and left/right angular variability ($F_{4,36}=10.1, p<0.001$). Post-hoc analysis showed that the angular variability for the L2-L1-BL CoM locations were not significantly different from each other. The angular variability of the elevated CoM locations (H1, H2) were significantly larger for both tilt directions as compared to the BL condition (Figure 3) with increasing angular deviations as the CoM height increased. However, in all cases the average standard deviation was less than one angular degree and hence in our opinion the subjects maintained the vertical orientation of the device rather well with small angular deviations.

The finger force analysis is presented below, arranged in order of task (CoM, RI), with sections for normal forces and tangential forces, first at the Th-Vf level and then the individual finger level.

Center of Mass Location: Normal Forces

At the level of the Th-Vf, there was significant effect of CoM location on the grasp force ($F_{4,369}=32.16, p<0.001$). The Post-Hoc analysis across the five CoM locations showed significant increases of the grasp force for the H1 and H2 locations (Figure 4) as compared to BL. The force increase at the H1 location (16.21 ± 3.18 N) was significant with respect to the grasp force at the BL (12.51 ± 2.49 N, $p<0.016$) and L1 (12.49 ± 2.89 N, $p<0.018$) locations while the force level (23.45 ± 4.03 N) at the H2 location was significantly larger with respect to the other four locations ($p<0.001$).

At the level of the individual fingers, there were significant differences of the F_n between the four fingers ($F_{3,27}=9.60, p<0.001$), between the five CoM locations ($F_{4,36}=32.7, p<0.001$) and also significant interaction of the two factors ($F_{12,108}=6.7, p<0.001$). Among the four fingers, Post-Hoc analysis indicated a significant lower F_n applied by the little finger (3.01 ± 1.32 N) as compared to the index (4.88 ± 1.80 N, $p<0.001$) and middle fingers (4.48 ± 1.59 N, $p<0.001$, Figure 4). The overall effect across the individual fingers of changes to the CoM location matched the same trend as reported above for the Vf: forces at H2 (5.96 ± 1.62 N, $p<0.001$) were larger than at all other locations and forces at H1 (4.13 ± 1.34 N) were greater than at BL (3.20 ± 1.11 N, $p<0.017$) and L1 (3.19 ± 1.11 N, $p<0.015$). The H2 increase was significant for each finger, while the H1 increase was significant for all fingers except the little finger.

Center of Mass Location: Tangential Forces

At the Th-Vf level the differences between F_{tTh} and F_{tVf} were significant ($F_{1,9}=14.2, p<0.005$) and while there were no significant differences in the tangential forces across the CoM locations ($F_{4,36}=0.844, p=0.863$) there was a significant interaction [Th,Vf] $\times$ CoM ($F_{4,36}=3.14, p<0.026$). Between F_{tTh} (5.60 ± 0.83 N) and F_{tVf} (4.01 ± 0.82 N), the Th force was on average 39.7% higher than the Vf force (Figure 5). It is also important to see that the total F_t remained constant: as seen in the CoM location averages in top right of Figure 5 and in the top line graph where the Th force increase was matched by a decrease of the Vf force of identical magnitude and vice versa. The post hoc analysis of the interaction showed significant differences between the Th and Vf forces for all locations of CoM except the BL.

At the individual finger level, there were significant differences in F_t across the four fingers ($F_{3,27}=6.64, p<0.002$), among the five CoM locations ($F_{4,36}=3.36, p<0.02$), and also a significant interaction of the two main factors ($F_{12,108}=3.19, p<0.001$). Post hoc analysis showed that the index finger force (0.35 ± 0.60 N) was significantly less than the ring finger (1.50 ± 0.55 N, $p<0.002$) and little finger forces (1.16 ± 0.68 N, $p<0.024$). The same trend was also observed for the middle finger (1.00 ± 0.51 N, $p<0.089$, Figure 5). Among the five CoM locations, there was a significant decrease of forces at H2 (0.89 ± 0.90 N) from BL

(1.08 ± 0.63 N, $p < 0.020$). Post hoc analysis of the interactions between the two main factors showed that the index finger was the only finger with significant differences between CoM locations with the force at the H2 location less than both at the BL ($p < 0.003$) and L1 ($p < 0.001$) CoM locations.

Rotational Inertia: Normal Forces

At the Th-Vf level, there was a significant difference across the three RIs for the grasp force ($F_{2,18} = 9.10$, $p < 0.002$). Post hoc analysis across the RI conditions showed a significant increase of the grasp force at High RI (16.18 ± 3.37 N) with respect to both BL RI (12.51 ± 2.49 N, $p < 0.002$) and Mid RI (13.85 ± 3.40 N, $p < 0.039$).

At the individual finger level, there were significant differences among the F_n of the four fingers ($F_{3,27} = 7.10$, $p < 0.002$) and significant differences among the forces at different RIs ($F_{2,18} = 9.62$, $p < 0.002$) while there was no significant interaction between the main factors ($F_{6,54} = 2.18$, $p = 0.059$). Post hoc analysis shows a significantly lower F_n of the little finger force (2.68 ± 1.11 N) with respect to the index finger (4.32 ± 1.41 N, $p < 0.002$) and middle finger forces (3.99 ± 1.23 N, $p < 0.01$, Figure 6). For the RI conditions, the overall effect across the four fingers' tangential forces at the High RI (4.13 ± 1.34 N) was significantly different with respect to the other two RI conditions: BL RI (3.20 ± 1.11 N, $p < 0.002$) and Mid RI (3.54 ± 1.26 N, $p < 0.034$).

Rotational Inertia: Tangential Forces

At the Th-Vf level, there was a significant difference between the F_{tTh} and F_{tVf} ($F_{1,9} = 38.8$, $p < 0.001$) while there was no significant difference across the RIs ($F_{2,18} = 0.536$, $p = 0.594$) or the interaction between the two main factors ($F_{2,18} = 0.724$, $p = 0.498$). The F_{tTh} (5.60 ± 1.02 N) was 40% greater than the F_{tVf} (4.00 ± 1.03 N, Figure 7). Though not significant, there appears to be a trend for the F_t of the Th to increase, while the F_{tVf} decreased, as the RI increased.

At the individual finger level, there were significant differences across the four finger forces ($F_{3,27} = 5.66$, $p < 0.004$), among the RIs ($F_{2,18} = 4.39$, $p < 0.028$), and the interaction between the two main factors ($F_{6,54} = 2.67$, $p < 0.024$). Post hoc analysis showed that the F_t of the index finger (0.36 ± 0.67 N) was significantly lower than the ring (1.49 ± 0.54 N, $p < 0.003$) and the little finger (1.16 ± 0.74 N, $p < 0.040$, Figure 7) forces. There was also an overall significant decrease in F_t across the four individual fingers from BL RI (1.08 ± 0.63 N) to High RI (0.90 ± 0.90 N, $p < 0.023$), where the follow-up post hoc of the interaction of FINGER $\times$ RI turns out to only be significant within the index finger tangential forces.

Rotational equilibrium of the object

Moments of force generated by the normal forces (M_n) and tangential forces (M_t) can be seen in Figure 8. The positive, i.e. in pronation, M_n was counter balanced by the negative, i.e. in supination, M_t , such that the total moment equaled zero and the rotational equilibrium was preserved. The absolute values of the M_n and M_t increased with (a) displacement of the CoM of the system up or down from the BL location, and (b) increase of the RI. The displacement of the CoM in the upward directions (H1 and H2) resulted in the larger M_n and M_t changes than its displacement downwards (L1 and L2). The moment arm of the normal Vf forces (computed with respect to the point of application of the thumb normal force) was on average 8.24 ± 3.88 mm for the CoM conditions, and 8.04 ± 4.10 mm for the RI conditions. Neither set of test conditions significantly affected the Vf moment arm: CoM $F_{4,36} = 0.654$, $p = 0.628$; RI $F_{2,18} = 3.55$, $p = 0.051$. Additionally, the sharing pattern (measured in terms of each individual finger F_n as a percentage of the Vf F_n) was not significant for CoM location ($F_{4,36} = 2.38$, $p = 0.070$), FINGER $\times$ CoM ($F_{12,108} = 1.40$, $p = 0.175$), RI level

($F_{2,18}=1.15$, $p=0.338$), or FINGER $\times$ RI ($F_{6,54}=0.70$, $p=0.635$). Changes in the Mn are therefore primarily a result of overall increase in F_n across all four fingers: performers grasp the handle stronger or weaker without changes in finger force sharing.

Discussion

Moving the external masses to different locations, to modify either the location of the handles' CoM or RI, changed the difficulty in holding the handle upright. While the equilibrium requirements were still the same, the stability requirements were changed. With the increase in stability requirements, i.e. an increase of the CoM height above the grasp or the RI value, the small angular deviations require larger restoration efforts to return the handle to the vertical orientation and stabilize it. In all tested conditions, the subjects were able to hold the handle in an upright posture with angular deviations of less than one degree throughout a trial. This shows that the measured changes in force/torque patterns of the digits provided the necessary means to control the stability of the handle orientation.

Several previous studies examined the equilibrium control at different positions of the object CoM and various RI values (Cluff & Balasubramaniam, 2009; Foo, Kelso, & de Guzman, 2000; Gawthrop, Loram, & Lakie, 2009; Lakie & Loram, 2006; Loram, Gawthrop, & Lakie, 2006; Milton, et al., 2009). In these studies, however, inverted pendulum models similar to balancing a stick on a finger were examined. Maintaining object equilibrium required translations of the end point, essentially turning the CoM of the object into a pivot point. In such movements, higher CoM locations and larger moments of inertia made the tasks more simple resulting in greater correction times and smaller angular deviations in the object orientation.

The current study differs in that the object's orientation was controlled by rotational efforts of the hand. The orientation of the handle was maintained by the moment of force applied to the object; in this regard it was similar to the Sun et al. (2011) study that investigated the digit coordination during filling/emptying a drink glass. In contrast to 'balancing' studies cited in the previous paragraph, an elevated CoM location (above handle) makes the task more difficult: it generates larger disturbance torques for a given angular deviation. Also, a larger RI requires larger torques to restore orientation during angular deviations.

When the CoM of the handle was raised above center (H1, H2 vs. BL condition) or when the RI was increased (High vs. BL, Mid), the response for the subjects was to grip the handle tighter (see Figure 4). The grasp force, i.e. the normal forces at the Th-Vf level, as well as across all the individual fingers increased with the task. These data are in good agreement with the findings by Milner (2002) who investigated the subjects' reaction to different perturbations induced by a torque motor. A significant increase in co-contraction of wrist flexor and extensor muscles was observed. The increase in grasp force is analogous to the co-contraction as seen in studies of trunk stability (Granata & Orishimo, 2001). The increase in finger muscle activity will increase the finger stiffness [or quasi-stiffness, see (Latash & Zatsiorsky, 1993)] and thus increase rotational stiffness of the system to provide more stability to control the handle orientation. The decrease in the CoM location (L2, L1 vs. BL) did not have an overall significant effect on the normal forces. There appears to be a small trend for an elevated normal force, which was significant only within the index and middle fingers.

The effects of changing the CoM or RI on the tangential forces are related to the equilibrium requirements of the system due to chain effects. With the digits increasing their normal forces generated and maintaining their sharing pattern, the net moment generated also increased. This increase in Mn was then matched by the equilibrium requirement of

offsetting increased magnitude of M_t (see matched magnitude changes in M_n and M_t in Figure 8). This change in M_t was achieved by imbalanced force contributions at the Th-Vf level: with the CoM moving from the central position either up or down the Vf tangential forces decreased while the Th tangential forces increased (see Figure 5).

With the digit locations for this experiment, there are two sets of internal forces. At the Th-Vf level, the normal forces are an internal force, the grasp force. Squeezing the object harder does not affect object equilibrium. The natural tendency for holding an object, and not dropping it, is to grasp it harder (Kinoshita, et al., 1995). In all cases, people operate within a safety margin to prevent slipping (Westling & Johansson, 1984). When static load forces increase, surface friction decreases, or the object is manipulated in vertical direction (increased dynamic load forces), the grasp force increases (Slota, Latash, & Zatsiorsky, 2011). This effect is present even when the original safety margin would have been sufficient to maintain grip of the object without slipping (Flanagan & Wing, 1993).

The control of grasp force is utilized to maintain the stability of the object's orientation. As seen in this study, the grasp force increased and the sharing pattern of the fingers was not changed. This suggested that the higher tier of digit control, the Th-Vf level, was utilized for orientation stabilization.

The other internal force that allows for flexibility in force distributions patterns is at the individual finger level (index, middle, ring, little) with the vertical tangential forces. With four fingers having the same moment arm length, the distribution of the net Vf F_t across the four fingers will not affect the torque generated. As can be seen in Figures 5 and 7, the index finger tangential force can be either positive or negative. The flexible behavior of the index finger can balance out the variations from the other three fingers. This effect however is only able to stabilize the Vf tangential force and does not account completely for the orientation stability control.

We would like to discuss possible control mechanisms behind the increased grasp force values not only at the high COM positions but also —albeit to a much smaller degree— at L2 location (see Figure 4).

It has been reported in the literature (McIntyre, Mussa-Ivaldi, & Bizzi, 1996; Woollacott, Inglis, & Manchester, 1988) that to ensure rotational control and resist spontaneous angular deviations, people increase 'passive' resistance to stabilize the joints through control of joint stiffness/impedance. This is achieved by muscle antagonist co-contraction (Latash & Zatsiorsky, 1993) and "moment co-contraction" (Sun, Zatsiorsky, & Latash, 2011). The latter can be seen in Figure 8 where the moments of force magnitudes increased with the elevated CoM locations and increased RI. Similar mechanisms are used when the central controller stabilizes objects against high impact loads (White, et al., 2011). Selen et al. (2005) in a simulation study arrived at the conclusion that muscular co-activation is an effective strategy to meet accuracy demands. It is interesting that—as follows from the whole-brain fMRI recordings— when people manipulate stable (rigid) and unstable (flexible) handheld objects different brain structures are involved in the control (Milner, Franklin, Imamizu, & Kawato, 2006).

While the increased grasp forces observed in this study increase the 'passive' resistance of the system, it is also well documented that higher force magnitudes are also associated with higher force variances (Newell & Carlton, 1985; Sosnoff, Valentine, & Newell, 2006). This signal-dependent noise can be seen as self induced destabilizing forces (Harris & Wolpert, 1998). However, exploring the noise-stability relation Selen et al. (2009) arrived at the conclusion that an increase in stiffness relative to the increase in noise reduces kinematic variability, thereby allowing stiffness control to improve stability in natural tasks.

These two effects of increased grasp force—increased passive resistance but also increased force variance—have counter acting effects. A subject can apply higher forces to a very stable object (which is not going to suffer much from the increased force variance as in L2) but not to a marginally stable one (as in H2). Considering the passive resistance alone, one can expect the lowest forces at L2 and highest at H2. If the goal is to decrease the self induced force errors, one can expect the highest forces at L2 and lowest at H2. These two effects act together with unknown (arbitrary and not linear) coefficients, yielding the non-monotonic curves like the ones seen in the current data on the effects of the CoM location on the grasping forces (Figure 4).

On the whole, people use two mechanisms to adjust to the changed stability requirements, i.e. to the higher position of the COM above the grasp and to the increased RI of the object: they increase the grasp force and redistribute the total moment between the normal and tangential forces. Strangely, they show the similar trends, but to a smaller extent, when the COM is lowered below the hand level.

Acknowledgments

This work was in part supported by National Institutes of Health grants AG-018751, NS-035032, and AR-048563. The authors would like to thank Denny Ripka for mechanical assistance. They also appreciate the technical assistance provided by Jim Metzler. We thank the anonymous journal reviewers for valuable comments.

References

- Aoki T, Niu X, Latash ML, Zatsiorsky VM. Effects of friction at the digit-object interface on the digit forces in multi-finger prehension. *Exp Brain Res*. 2006; 172(4):425–438. [PubMed: 16496136]
- Arbib M, Iberall T, Lyons D. Coordinated control programs for movements of the hand. *Experimental Brain Research Supplemental*. 1985; 10:111–129.
- Bernstein, NA. *The Co-ordination and Regulation of Movement*. Pergamon Press; Oxford: 1967.
- Cluff T, Balasubramaniam R. Motor learning characterized by changing Levy distributions. *PLoS One*. 2009; 4(6):e5998. [PubMed: 19543399]
- Cole KJ, Johansson RS. Friction at the digit-object interface scales the sensorimotor transformation for grip responses to pulling loads. *Exp Brain Res*. 1993; 95(3):523–532. [PubMed: 8224079]
- Flanagan JR, Wing AM. Modulation of grip force with load force during point-to-point arm movements. *Experimental Brain Research*. 1993; 95(1):131–143.
- Foo P, Kelso JA, de Guzman GC. Functional stabilization of unstable fixed points: human pole balancing using time-to-balance information. *J Exp Psychol Hum Percept Perform*. 2000; 26(4): 1281–1297. [PubMed: 10946715]
- Gao F, Latash ML, Zatsiorsky VM. Internal forces during object manipulation. *Exp Brain Res*. 2005; 165(1):69–83. [PubMed: 15912369]
- Gawthrop P, Loram I, Lakie M. Predictive feedback in human simulated pendulum balancing. *Biological Cybernetics*. 2009; 101(2):131–146. [PubMed: 19588160]
- Goodman SR, Latash ML. Feed-forward control of a redundant motor system. *Biol Cybern*. 2006
- Gorniak SL, Zatsiorsky VM, Latash ML. Hierarchical control of static prehension: II. Multidigit synergies. *Exp Brain Res*. 2008
- Gorniak SL, Zatsiorsky VM, Latash ML. Hierarchical control of static prehension: I. Biomechanics. *Exp Brain Res*. 2009; 193(4):615–631. [PubMed: 19066870]
- Granata KP, Orishimo KF. Response of trunk muscle coactivation to changes in spinal stability. *J Biomech*. 2001; 34(9):1117–1123. [PubMed: 11506782]
- Guigon E, Baraduc P, Desmurget M. Computational motor control: redundancy and invariance. *Journal of Neurophysiology*. 2007; 97(1):331–347. [PubMed: 17005621]
- Harris CM, Wolpert DM. Signal-dependent noise determines motor planning. *Nature*. 1998; 394(6695):780–784. [PubMed: 9723616]

- Johansson RS, Westling G. Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental Brain Research*. 1984; 56(3):550–564.
- Kerr J, Roth B. Analysis of multifingered hands. *International Journal of Robotics Research*. 1986; 4(4):3–17.
- Kinoshita H, Backstrom L, Flanagan JR, Johansson RS. Tangential torque effects on the control of grip forces when holding objects with a precision grip. *Journal of Neurophysiology*. 1997; 78(3):1619–1630. [PubMed: 9310447]
- Kinoshita H, Kawai S, Ikuta K. Contributions and co-ordination of individual fingers in multiple finger prehension. *Ergonomics*. 1995; 38(6):1212–1230. [PubMed: 7758447]
- Lakie M, Loram ID. Manually controlled human balancing using visual, vestibular and proprioceptive senses involves a common, low frequency neural process. *J Physiol*. 2006; 577(Pt 1):403–416. [PubMed: 16959857]
- Latash ML, Zatsiorsky VM. Joint stiffness: Myth or reality? *Human Movement Science*. 1993; 12(6):653–692.
- Lee PJ, Rogers EL, Granata KP. Active trunk stiffness increases with co-contraction. *J Electromyogr Kinesiol*. 2006; 16(1):51–57. [PubMed: 16099678]
- Li ZM, Latash ML, Newell KM, Zatsiorsky VM. Motor redundancy during maximal voluntary contraction in four-finger tasks. *Exp Brain Res*. 1998; 122(1):71–78. [PubMed: 9772113]
- Loram ID, Gawthrop PJ, Lakie M. The frequency of human, manual adjustments in balancing an inverted pendulum is constrained by intrinsic physiological factors. *J Physiol*. 2006; 577(Pt 1):417–432. [PubMed: 16973712]
- MacKenzie CL, Iberall T. The grasping hand. 1994 Artist.
- McIntyre J, Mussa-Ivaldi FA, Bizzi E. The control of stable postures in the multijoint arm. *Experimental Brain Research*. 1996; 110(2):248–264.
- Milner TE. Adaptation to destabilizing dynamics by means of muscle cocontraction. *Experimental Brain Research*. 2002; 143(4):406–416.
- Milner TE, Franklin DW, Imamizu H, Kawato M. Central representation of dynamics when manipulating handheld objects. *Journal of Neurophysiology*. 2006; 95(2):893–901. [PubMed: 16251266]
- Milton JG, Ohira T, Cabrera JL, Fraiser RM, Gyroffy JB, Ruiz FK, et al. Balancing with vibration: a prelude for “drift and act” balance control. *PLoS One*. 2009; 4(10):e7427. [PubMed: 19841741]
- Murray, R.; Li, Z.; Sastry, S. A mathematical introduction to robotic manipulation. CRC Press; Boca Raton: 1994.
- Newell KM, Carlton LG. On the relationship between peak force and peak force variability in isometric tasks. *J Mot Behav*. 1985; 17(2):230–241. [PubMed: 15140693]
- Savescu AV, Latash ML, Zatsiorsky VM. A technique to determine friction at the fingertips. *J Appl Biomech*. 2008; 24(1):43–50. [PubMed: 18309182]
- Selen LP, Beek PJ, van Dieën JH. Can co-activation reduce kinematic variability? A simulation study. *Biological Cybernetics*. 2005; 93(5):373–381. [PubMed: 16249892]
- Selen LP, Franklin DW, Wolpert DM. Impedance control reduces instability that arises from motor noise. *J Neurosci*. 2009; 29(40):12606–12616. [PubMed: 19812335]
- Slota GP, Latash ML, Zatsiorsky VM. Grip forces during object manipulation: experiment, mathematical model, and validation. *Experimental Brain Research*. 2011; 213(1):125–139.
- Sosnoff JJ, Valantine AD, Newell KM. Independence between the amount and structure of variability at low force levels. *Neurosci Lett*. 2006; 392(3):165–169. [PubMed: 16188384]
- Sun Y, Zatsiorsky VM, Latash ML. Prehension of half-full and half-empty glasses: time and history effects on multi-digit coordination. *Exp Brain Res*. 2011; 209:571–585. [PubMed: 21331525]
- Todorov E. Optimality principles in sensorimotor control. *Nat Neurosci*. 2004; 7(9):907–915. [PubMed: 15332089]
- Westling G, Johansson RS. Factors Influencing the Force Control during Precision Grip. *Experimental Brain Research*. 1984; 53(2):277–284.

- White O, Thonnard JL, Wing AM, Bracewell RM, Diedrichsen J, Lefevre P. Grip force regulates hand impedance to optimize object stability in high impact loads. *Neuroscience*. 2011; 189:269–276. [PubMed: 21640167]
- Woollacott M, Inglis B, Manchester D. Response preparation and posture control. Neuromuscular changes in the older adult. *Ann N Y Acad Sci*. 1988; 515:42–53. [PubMed: 3364898]
- Yang JF, Scholz JP, Latash ML. The role of kinematic redundancy in adaptation of reaching. *Exp Brain Res*. 2007; 176(1):54–69. [PubMed: 16874517]
- Yoshikawa T, Nagai K. Manipulating and grasping forces in manipulation by multifingered robot hands. *IEEE Transactions on Robotics and Automation*. 1991; 7(1):67–77.
- Zatsiorsky VM, Gao F, Latash ML. Finger force vectors in multi-finger prehension. *J Biomech*. 2003a; 36(11):1745–1749. [PubMed: 14522218]
- Zatsiorsky VM, Gao F, Latash ML. Prehension synergies: effects of object geometry and prescribed torques. *Exp Brain Res*. 2003b; 148(1):77–87. [PubMed: 12478398]

Figure 1.

Handle design consists of four Nano-17 sensors for the fingers and a Nano-25 for the thumb. Shown attached at the top and bottom of the handle are two movable external masses. Not shown in the figure is the sensor cluster, located on the backside of the handle about the handle center of mass. Sensor locations are marked (D: horizontal Th-Finger spacing; R: vertical finger spacing about the Th)

Figure 2.

Handle setup for experimental conditions. A) CoM locations with the two external masses located at H2 or L2 (black), H1 or L1 (white), and the baseline (BL, grey). B) Rotational Inertia test conditions where the two external masses are split above and below the handle: BL (grey), Mid (white), and High (black)

Figure 3.

Angular standard deviations from the average position. Measured in degrees, with significance (* $p < 0.05$) of H1 or H2 with respect to BL.

Figure 4.

Normal forces (N) at the Th-Vf level (Grasp Force, top) and the individual finger level (bottom) for the five locations of the CoM (L2,L1,BL,H1,H2). Results (from left to right) are depicted for: FINGER averages, FINGER $\times$ CoM interaction, and averages across CoM. * $p < 0.05$ with respect to arrows. Significance within the individual fingers for the FINGER $\times$ CoM interaction (bottom line graph) is not marked. Values plotted are mean $\pm$ SD.

Figure 5.

Tangential forces (N) at the Th-Vf level (top) and the individual finger level (bottom) for the five locations of the CoM (L2,L1,BL,H1,H2). Results (from left to right) are depicted for: FINGER averages, FINGER $\times$ CoM interaction, and averages across CoM. * $p < 0.05$ with respect to arrows. Significance within the individual fingers for the FINGER $\times$ CoM interaction (bottom line graph) is not marked. Values plotted are mean $\pm$ SD.

Figure 6.

Normal forces (N) at the Th-Vf level (Grasp Force, top) and the individual finger level (bottom) for the three rotational inertia conditions (BL, Mid, High). Results (from left to right) are depicted for: FINGER averages, FINGER $\times$ RI interaction, and averages across RI. * $p < 0.05$ with respect to arrows. Values plotted are mean $\pm$ SD.

Figure 7.

Tangential forces (N) at the Th-Vf level (top) and the individual finger level (bottom) for the three rotational inertia conditions (BL, Mid, High). Results (from left to right) are depicted for: FINGER averages, FINGER $\times$ RI interaction, and averages across RI. * $p < 0.05$ with respect to arrows. Significance within the individual fingers for the FINGER $\times$ RI interaction (bottom line graph) is not marked. Values plotted are mean $\pm$ SD.

Figure 8.

Total moment of normal forces (*Mn*) and total moment of tangential forces (*Mt*) for the five CoM locations (L2, L1, BL, H1, H2) and the three rotational inertia conditions (BL, Mid, High). Post-Hoc results marked (* $p < 0.05$) of CoM H2 vs. BL, and RI High vs. BL for both *Mn* and *Mt*. Values plotted are mean $\pm$ SD.