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RESEARCH ARTICLE

Independent digit contributions to rotational manipulation in a three-digit pouring task requiring dynamic stability

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Abstract Many activities of daily living involve multi-digit, voluntary rotational manipulations of grasped objects. Yet, only a few studies have focused on coordination of individual fingertip forces during such tasks. The objective of this study was to investigate individual digit contributions to a three-digit task in which an object was rotationally manipulated against gravity. Center of mass was varied through the use of containers shaped like a water bottle, pint glass, and cocktail glass, from which subjects poured fluid carefully into a nearby receptacle. The center of mass of the grasped object changed continuously as fluid was poured out. Self-selected digit placement and contributions of fingertip forces to rotational manipulation were dependent upon anticipated center of mass location associated with container shape. The thumb resisted the rotation of the top-heavy, cocktail glass container until 79 % of the pouring phase had elapsed, but actively assisted the rotation of the less challenging containers. More directly opposing the thumb, the index finger contributed more to grasp stability. The middle finger contributed more to rotation of the container for pouring. It was found that the thumb, index, and middle fingers acted in unison temporally, but contributed independently to the grip forces and stabilizing moments throughout the dynamic, rotational manipulation task.

Keywords Fingertip forces · Independent digit control · Multi-digit manipulation · Pouring · Rotational manipulation · Three-digit grasp

Introduction

Many activities of daily living, such as pouring, involve multi-digit rotational manipulations of grasped objects. Only a few studies on human grasp and manipulation have focused on fingertip force coordination during voluntary, multi-digit rotational manipulations of objects. Some studies have reported on grip force responses to expected or unexpected torques applied to objects in a precision grip (Kinoshita et al. 1997; Goodwin et al. 1998; Johansson et al. 1999; De Gregorio and Santos 2013; Gorniak and Alberts 2013). In another two-digit study, subjects unscrewed a bottle cap, but the focus of the work was on postural synergies and time to task completion (Karnati et al. 2013). Five-digit grasps have been used to study rotations of objects grasped from the side (Pylatiuk et al. 2006; Shim et al. 2007; Zhang et al. 2009). In the Pylatiuk et al. 2006 study, subjects simulated a pouring task by lifting and tilting a container of constant mass with uniaxial force sensors along the lengths of the fingers. In another five-digit study on pouring, subjects were instructed to empty a quart of milk (Shiffman 1992). Although subjects could self-select their grasp type, fingertip forces were not recorded.

Studies on dynamic manipulation using three-digit grasps (thumb, index finger, and middle finger) are less common in the literature. Most three-digit studies have investigated fingertip forces during the lifting of objects grasped from above (Burstedt et al. 1999; Baud-Bovy and Soechting 2001, 2002; Brown and Valero-Cuevas 2006; Winges et al. 2007; Rácz et al. 2012). Independent control

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of individual fingertip forces was reported in response to variations in grip plate placement (Baud-Bovy and Soechting 2002) and friction conditions (Burstedt et al. 1999). Three-digit grasps have also been applied to objects comprised of three rigid links attached by a single hinge as subjects produced maximal isometric grip forces (Brown and Valero-Cuevas 2006) or voluntarily oscillated the thumb relative to the other digits (Rácz et al. 2012).

Studies on human grasp and manipulation have also focused on the effects of center of mass (COM) location. When subjects could self-select digit placement, their choices were affected by the known COM locations (Lukos et al. 2007; Fu et al. 2010; Crajé et al. 2011). When subjects were instructed to minimize the roll of a grasped object upon lift, and the change in the COM location was known, subjects changed their digit placement accordingly (Lukos et al. 2007). In a similar study, it was reported that subjects learned to adjust digit placement and fingertip forces after a few trials of interacting with an object having an undisclosed but consistent COM location (Fu et al. 2010). In a five-digit study by Crajé et al. (2011), subjects were asked to select digit placement to either lift a bottle or pour out its contents. It was found that subjects, aware of how much fluid was in the bottle, changed their fingertip locations as the initial COM changed. While this experiment involved actual pouring, the study focused on digit placement as opposed to grip forces. In another five-digit study, coordinated grip forces were reported in response to continuous changes in COM location (via filling or emptying a container with fluid), but the container was never rotationally manipulated (Sun et al. 2011).

The objectives of this work were to investigate the coordination of individual fingertip forces during a rotational manipulation task in which (i) an object is voluntarily rotated against gravity, (ii) placement of the three digits is self-selected, and (iii) center of mass location changes continuously during the task, as in the pouring task presented here. We hypothesized that multi-digit contributions would depend on anticipated COM location associated with container shape, and that the digits would not contribute identically to the task.

Materials and methods

Experiment

Thirteen subjects (seven males, six females; aged 23–29) gave their informed consent to participate in this study approved by the Arizona State University Institutional Review Board, in accordance with the ethical standards established in the 1964 Declaration of Helsinki. All subjects were right-hand dominant according to the Edinburgh Handedness Test and had no history of hand impairment or neurological or neuromuscular disorders.

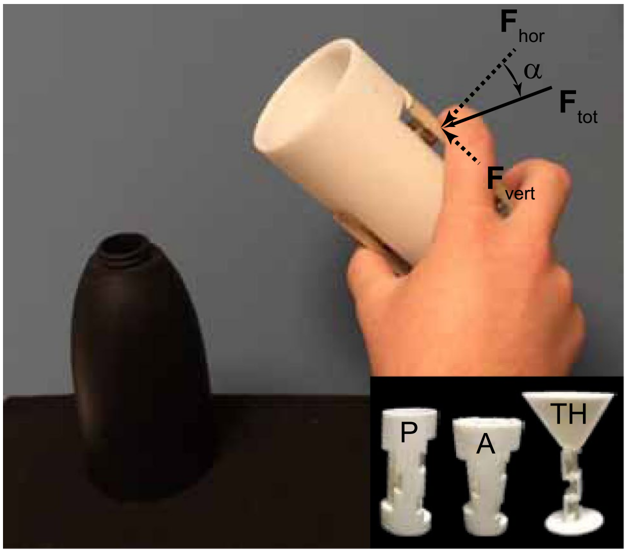

Fig. 1 Three containers with different COM locations (parallel *P*, angled *A*, and top-heavy *TH*) were used to pour fluid into a narrow-necked receptacle to the left of the container using a three-digit grasp. For all calculations, the axis of rotation was assumed to be perpendicular to the "grip plane" comprised of the three load cells. Individual fingertip forces F_{tot} were decomposed into horizontal F_{hor} and vertical F_{vert} components. The angle of the force vector α was positive when the force vector pointed toward the top of the container

Instrumented, 3D-printed containers were used in the pouring task that resembled a water bottle with parallel grip plates ("parallel," *P*), a pint glass that tapered downwards ("angled," *A*), and a top-heavy cocktail glass with a cone atop a narrow stem ("top-heavy," *TH*) (Fig. 1). The parallel and angled containers were inspired by a study that employed parallel and angled grip plates (Jenmalm and Johansson 1997). The top-heavy container was included to broaden the range of COM locations being investigated (Fig. 2).

Each container was instrumented with three 6-degree-of-freedom load cells (Nano-17, ATI Industrial Automation, Apex, NC) for the independent measurement of thumb, index finger, and middle finger forces and torques at 1 kHz. Slots in each container enabled the quick transfer of load cells between containers. The internal geometry of each container was carefully considered to ensure that the load cell accommodations would not hinder the fluid flow during container rotation. When instrumented but empty, the masses of the parallel, angled, and top-heavy containers were 321, 274, and 300 g, respectively. Each container was filled with 185 g (192 cc) of water at the start of each trial.

The aluminum grip plates were parallel for the parallel and top-heavy containers, but tapered downward at an angle of 6° for the angled container. To allow for a variety of self-selected digit placements, the thumb plate was 70 mm long and the index and middle finger plates were 50 mm long; all grip plates were 25 mm wide. The grip plates were 71 and 36 mm apart for the parallel and top-heavy containers, respectively. The distance between grip plates varied along the height of the angled container and was 75 mm at the height of the center of the thumb grip plate.

A six-camera infrared motion capture system (MX-T40 Cameras, Vicon, Centennial, CO) was used to track the rotation of each container at 200 Hz with triads of hemispherical reflective markers (3 mm diameter, Mocap Solutions, Huntington Beach, CA). The aluminum grip plates were covered in masking tape to minimize reflectivity during motion capture. A high-speed camera (Basler Pilot 640) was used to record videos.

Each subject sat upright with his dominant hand flat on a tabletop. At the start of each trial, a water-filled container was placed 30 cm in front of the subject with an empty receptacle 20 cm immediately to the left of the container such that a counterclockwise rotation of the container, as viewed by a right-hand dominant subject, was necessary to complete the task. The receptacle had a 21 mm diameter opening and sat on a platform atop a 6-degree-of-freedom load cell (Nano-25, ATI Industrial Automation, Apex, NC). The "grip plane," comprised of the three load cells, was parallel to the frontal plane of the subject, with the thumb grip plate on the left and the index and middle finger grip plates on the right. Using self-selected digit placement, subjects were instructed to grasp the container with the thumb, index, and middle fingers, and to curl the ring and little fingers into the palm, as if making a fist. Subjects were instructed to pick up the container, pour its contents into the receptacle as quickly as possible without spilling, and place the empty container back onto the table in its original location. No constraints were placed on arm or wrist motion. Subjects were notified that if they took longer than 15 s or spilled water, the trial would be considered unsuccessful and would be repeated.

The experiment was comprised of three blocks of ten trials: one block each for the parallel, angled, and top-heavy containers, in that order. Subjects received a minimum of 30 s of rest between each trial, while the experimenter refilled the container, and a minimum of 2 min of rest after each experimental block, while load cells were transferred to the next container. Subjects were instructed to notify the experimenter if more time was needed to avoid fatigue. No practice trials were permitted.

Data analysis

Vicon Nexus software was used to label the motion capture markers. MATLAB (Mathworks, Natick, MA) was used to post-process the motion capture and load cell data.

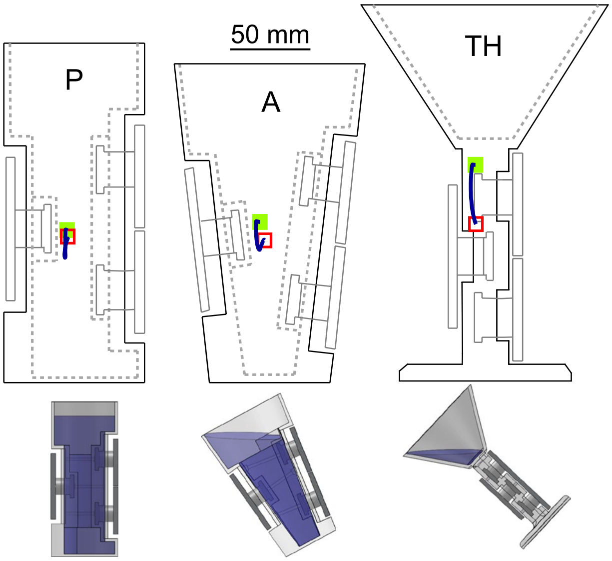

Fig. 2 *Top row Solid green* and *open red squares* indicate the COM location for the full and empty containers, respectively. *Blue lines* indicate the path of the COM location within the grip plane as the container was emptied. *Dotted lines* indicate boundaries of the internal cavity for the fluid. *Bottom row* SolidWorks was used to calculate the COM for the container-fluid system at any rotation angle (color figure online)

Using the container angle obtained from motion capture data, the 3D COM location of each container-fluid system was determined in SolidWorks (Dassault Systèmes SolidWorks Corp., Waltham, MA; Fig. 2). The water level was modeled for the entire pouring task, from 0° to the rotation angle at which each container became empty (90°, 84°, and 57° for the parallel, angled, and top-heavy containers, respectively). Considering movement of the COM along the long axis of the container, the COM remained within 10 mm of the center of the thumb grip plate for the parallel and angled containers. The top-heavy container acted more like an inverted pendulum, with its COM located at 46 mm above the center of the thumb grip plate at the start of each trial.

A low-pass Butterworth filter (fourth order, 30 Hz) was applied to the load cell force and torque data (Jordan and Newell 2004; De Gregorio and Santos 2013), which were used to determine individual fingertip force vectors and center of pressure locations on the grip plates. As shown in Fig. 1, the vertical axis was defined as pointing upwards toward the top of the container along the long axis of the container, while the horizontal axis was defined as being perpendicular to the vertical axis and pointing toward the grip plates, as in Jenmalm and Johansson 1997. The vertical and horizontal axes remained fixed with respect to the container throughout its rotation. The axis of rotation of the container was taken to be perpendicular to the grip plane.

The angle of each fingertip force vector α within the grip plane was calculated using the horizontal and vertical force components (Fig. 1).

Six major task events were identified in each trial: (1) initial contact, (2) container liftoff, (3) start of pouring, (4) end of pouring, (5) container replacement, and (6) final contact (Fig. 3). Additionally, three minor events were identified: (2a) start of container rotation, (3a) end of mass change, and (4a) end of container rotation. Initial and final contacts were defined as the timepoints at which the first digit made contact and the last digit broke contact with the container, respectively. Using high-speed videos, container liftoff and replacement were defined as the timepoints at which the container was first lifted from the tabletop and lowered onto the tabletop, respectively, and the start of pouring was defined as the timepoint at which water began flowing from the container. Motion capture data were used to determine the start and end of container rotation as well as the end of pouring. The end of pouring was defined as the timepoint at which the container reached its maximum angle of rotation with respect to a datum of 0° when the container sits flat on the tabletop. A SolidWorks model of the container-fluid system and the recorded angle of rotation were used to determine the timepoint at which the container became empty.

In order to normalize the data temporally for comparisons across trials and subjects, trials were subdivided into the five phases that occurred between adjacent pairs of the major task-specific events (Fig. 3): pre-liftoff contact, lifting, pouring, lowering, and post-replacement contact. The length of each trial-specific phase was normalized to the average phase length across all subjects and trials. Data are presented as a percentage of task completion.

Data were analyzed statistically using MANOVA (with the Wilk's lambda statistic) with independent variables for container shape (parallel, angled, and top-heavy) in order to test for differences across containers (Foster et al. 2006). MANOVA was also applied with independent variables for digit (index and middle fingers) in order to test for differences between digit contributions to the rotational task. Dependent variables ($n = 6$) for the test on the effect of container shape were (i) angular velocity of the container during pouring, (ii) thumb digit placement relative to the index and middle fingers, (iii) index and middle finger digit placement, and (iv) percent of task completion when the thumb vertical force and moment contributions crossed from positive to negative (indicating a transition from an antagonistic role to one of assistance). Dependent variables ($n = 12$) for the test on the effect of digit were (i) horizontal and vertical force components and (ii) contributions of the horizontal and vertical components to the total moment about the COM at events 3, 3a, and 4 (beginning to end of pouring). Post hoc ANOVA tests were used to identify which specific-dependent variables were significantly different for both MANOVA tests. Post hoc Bonferroni pairwise tests were used to compare pairs of containers. A significance level of $\alpha = 0.05$ was used for all tests. A Bonferroni correction ($\alpha = 0.05/\text{n}$, where n is the number of dependent variables) was additionally applied in order to avoid type I errors when performing the post hoc ANOVAs and pairwise comparisons. Results are reported as mean ± standard deviation, unless otherwise stated.

Results

Data from the 130 trials for each container were consistent within and across subjects. Approximately one failed trial per subject was repeated due to spilling or the trial lasting longer than 15 s. After all digits made first contact with the container (event 1), individual fingertip forces changed in unison temporally near key events throughout the task (Fig. 3). The only exception appeared to be a lack of fingertip force response when the container was empty (event 3a) and subjects continued to rotate the container to ensure its emptiness. All vertical fingertip forces increased together just prior to the liftoff (event 2). These anticipatory changes were consistent with other observations of preparatory adjustments of fingertip forces prior to the object liftoff or translation (Gordon et al. 1993; Winges et al. 2007; Fu et al. 2010).

The median duration of each phase as a percent of the entire trial was 2.8 % (0.3 s) for pre-liftoff contact, 14.0 % (1.6 s) for lifting, 70.4 % (8.0 s) for pouring, 9.9 % (1.1 s) for lowering, and 2.9 % (0.3 s) for post-replacement contact. The mean rotational velocities of the containers during the pouring phase were 8.7, 9.1, and 7.2°/s for the parallel, angled, and top-heavy containers, respectively. The study which inspired the use of the angled container shape showed that tapered shapes affected horizontal and vertical fingertip forces during lifting (Jenmalm and Johansson 1997). While the angled container and parallel container data were visually distinct (Figs. 3, 4, 5), none of the dependent variables were statistically different between the angled and parallel containers.

Fingertip center of pressure location

The center of pressure location for each digit varied along the long axis of the grip plates throughout the task due to roll of the fingertip (Fig. 4). Subjects could have easily chosen to oppose the thumb with either the index or middle finger. However, for all containers, the vertical distance between the index finger and thumb (12.0 ± 5.5 mm) at the onset of pouring was less than that for the middle finger and thumb (22.5 ± 5.9 mm) ($p < 0.05$). Data suggest that the index and middle fingers were placed higher along the

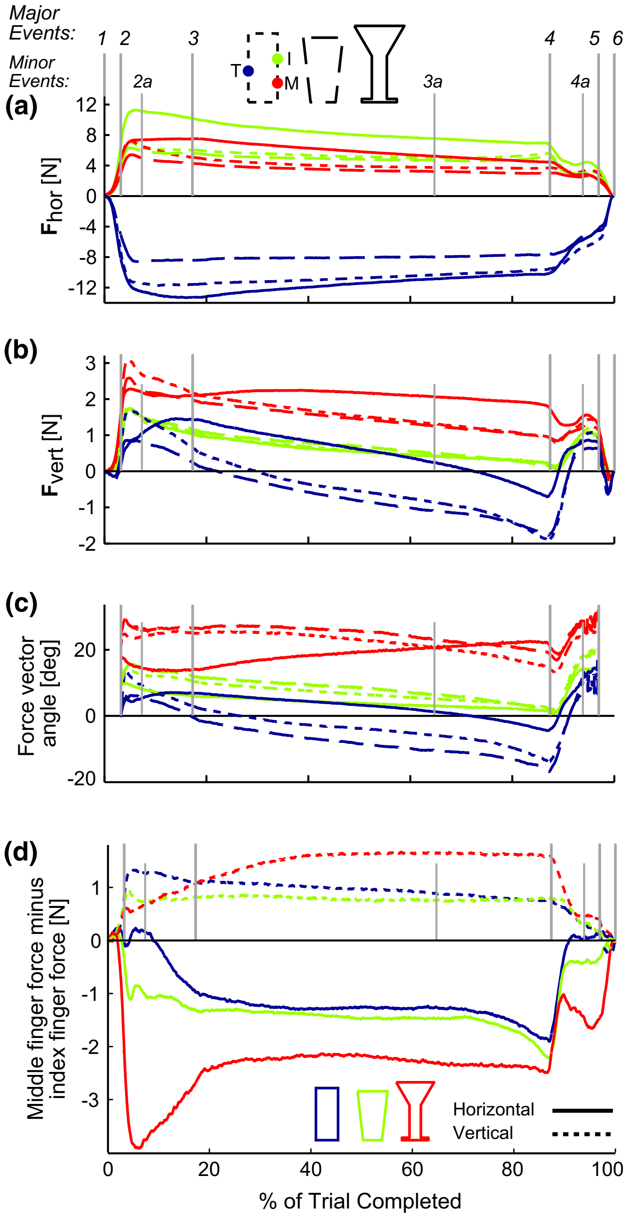

Fig. 3 **a** Horizontal fingertip force components, **b** vertical fingertip force components, and **c** fingertip force vector angles are shown for the thumb (*blue*), index finger (*green*), and middle finger (*red*) for the parallel (*dotted line*), angled (*dashed line*), and top-heavy (*solid line*) containers. *Vertical lines* mark events 1–6. Positive horizontal force components are directed toward the thumb. *Positive vertical force components* and *force vector angles* indicate fingertip forces pointed toward the top of the container. **d** The mean difference between middle and index finger force components is shown for the parallel (*blue*), angled (*green*), and top-heavy (*red*) containers. *Horizontal* and *vertical force components* are indicated with *solid* and *dotted lines*, respectively. *Positive values* indicate that the middle finger force component was larger than that of the index finger (color figure online)

grip plates when grasping the top-heavy container, although the only statistically significant finding was that the middle finger was placed higher along the grip plate when subjects

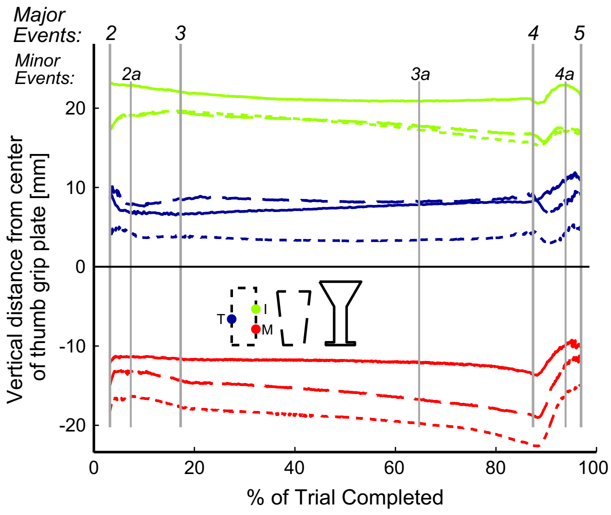

Fig. 4 Center of pressure locations along the height of the container is reported with respect to the center of the thumb grip plate for the thumb (*blue*), index finger (*green*), and middle finger (*red*) for the parallel (*dotted line*), angled (*dashed line*), and top-heavy (*solid line*) containers. Vertical lines mark events 2–5. Due to low magnitude fingertip forces during the pre-liftoff and post-replacement contact phases that reduced the accuracy of the center of pressure data (Fu et al. 2010), data are not reported between events 1–2 and 5–6 (color figure online)

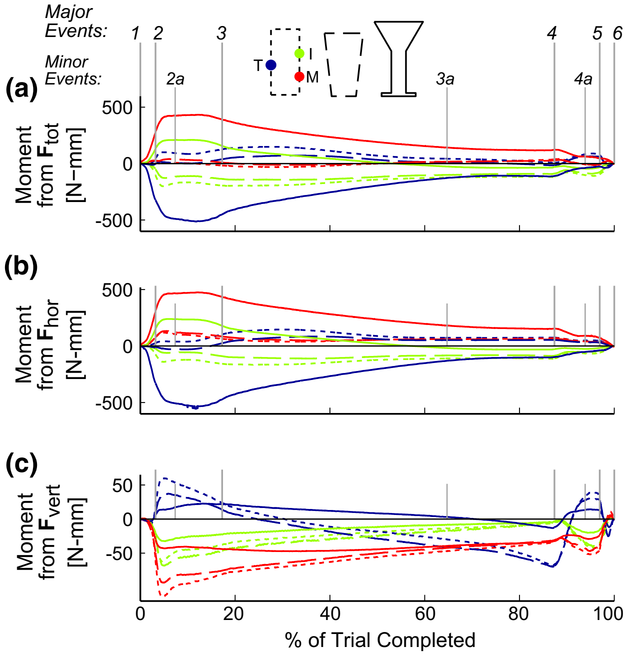

Fig. 5 Moments about the moving COM are shown for the thumb (*blue*), index finger (*green*), and middle finger (*red*) for the parallel (*dotted line*), angled (*dashed line*), and top-heavy (*solid line*) containers. The contributions to the total moment about the COM are shown for each digit for the **a** complete fingertip force vector, **b** horizontal fingertip force component, and **c** vertical fingertip force component. *Vertical lines* mark events 1–6. A negative moment magnitude indicates an assistive contribution to the counterclockwise rotation of the container for pouring (color figure online)

grasped the top-heavy container as opposed to the parallel container ($p < 0.05$).

Since we wanted to collect 3D fingertip force data while simultaneously allowing self-selected digit placement, the instrumented container was designed for a three-digit grasp. Future experiments could be designed to investigate the relative contributions of additional digits during this type of pouring task.

Fingertip forces

Fingertip forces were of particular interest for the pouring phase, during which the container was rotated and the COM of the container-fluid system changed. Horizontal fingertip force components could contribute to grasp stability and/or rotation of the container, depending upon digit placement. A negative vertical force component for the thumb (pointing toward the base of the container), or a positive vertical force component for the index or middle fingers (pointing toward the top of the container), would assist with counterclockwise rotation of the container for pouring.

Vertical fingertip force components did not appear to be affected by differences in mass of the plastic containers. The largest difference in mass (47 g) occurred between the parallel and angled containers. Minimal effects of this 0.46 N difference in weight were observed in the vertical lifting forces of the digits (Fig. 3b). Moreover, the digit responses for the parallel and angled containers were similar (Figs. 3, 4, 5). In contrast, the parallel and top-heavy containers only differed by 21 g in mass, but yielded markedly different digit responses.

For all containers during pouring, the horizontal fingertip force component was greater for the index finger than the middle finger ($p < 0.001$) (Fig. 3a, d). In contrast, the vertical fingertip force component was greater for the middle finger than the index finger ($p < 0.001$) (Fig. 3b, d). The vertical force component of the thumb assisted rotation for more of the pouring phase for the parallel (82 %) and angled (90 %) containers than for the top-heavy container (24 %; $p < 0.001$) (Fig. 3b).

Force vector angles were calculated using the horizontal and vertical forces as described in the Methods. It should be noted that the force vector angles are entirely dependent upon the horizontal and vertical force components and are included in Fig. 3c for visualization purposes only. As such, force vector angles were not included in the MANOVA tests, which are most accurate when the dependent variables being tested are not highly dependent on one another. During the pouring phase, the force vector angle was negative for the thumb for the parallel and angled containers, but positive for the first 79 % of pouring for the top-heavy container (Fig. 3c). The force vector angle for the middle finger was greater than that for the index finger for all containers.

Moments about the moving COM

To further investigate individual digit contributions to rotation of the container, the moment about the moving COM was calculated for each digit (Fig. 5). Negative moment values indicated contributions that assisted the counterclockwise rotation of the container for pouring. To gain insight into the specific contributions of each digit, it was necessary to evaluate the contributions of the horizontal (Fig. 5b) and vertical (Fig. 5c) fingertip force components separately. The horizontal force component contributions to the total moment about the COM were not a focus because the moment arms for horizontal force components varied drastically across digits (due to the fixed geometry of the containers themselves), which created artificial differences in the individual digit contributions to the rotational task. For example, since the middle finger was always placed below the COM, the moment from the middle finger horizontal force component was always antagonistic with regards to rotation of the container. In contrast, the moment arms for the index and middle finger vertical force components were identical for the parallel and top-heavy containers at any given timepoint, which enabled a fair comparison of index and middle finger vertical force component contributions to the rotational task. For the angled container, the moment arm for the middle finger vertical force component was nearly identical to that of the index finger; the middle finger moment arm was only 3.6 mm (9.0 %) less than that for the index finger. As such, we focused our analyses on the vertical force component contributions to the total moment about the COM.

When the thumb's vertical force component contribution to the total moment about the COM crossed from positive to negative, the thumb's contribution to container rotation changed from an antagonistic role to one of assistance. During the pouring phase, the thumb's antagonistic role lasted a median of 61 and 70 % longer for the top-heavy container than for the parallel and angled containers, respectively ($p < 0.001$). Both the index and middle fingers contributed negative moments from their vertical force components and, therefore, assisted with pouring for all containers ($p < 0.001$). Interestingly, the middle finger contributed more to the rotational moment about the COM with its vertical force component than the index finger ($p < 0.001$).

Discussion

Effect of container shape and COM location

Our hypothesis that fingertip force contributions would be affected by anticipated COM location associated with container shape was supported by a variety of output variables. Fingertip center of pressure locations differed across the containers. The top-heavy container had the highest initial COM location (Fig. 2). Digit placement of the index and middle fingers was observed to be higher for the top-heavy container than the parallel or angled containers, but only statistically higher for the middle finger when grasping the top-heavy container as opposed to the parallel container. This suggests that subjects initially tried to place their digits close to the COM prior to the liftoff (Fig. 4). This finding is consistent with other studies in which subjects altered their initial digit placement when an object's COM was knowingly changed between trials (Lukos et al. 2007; Fu et al. 2010; Crajé et al. 2011). Specifically, subjects grasped a bottle higher when it had a higher COM and subjects intended to pour out its contents (Crajé et al. 2011).

While the parallel and angled containers were rotated during the pouring phase at a mean rotational velocity of 8.7 and 9.1°/s, respectively, the top-heavy container was rotated statistically significantly slower at 7.2°/s (83 and 79 % of the parallel and angled container speeds, respectively). If the difficulty of a rotational manipulation can be assumed to be inversely proportional to the rotational velocity employed by subjects, the top-heavy container would be deemed most challenging because subjects used the smallest rotational velocities when pouring from this container. This could be due to the high COM and/or the relatively narrow grip width of the top-heavy container (Fig. 2). It has been reported, however, that small changes in grip width (up to 30 mm) did not affect vertical or horizontal fingertip forces in a whole hand grasp during a lift and hold task (Zatsiorsky et al. 2003). In the present study, the maximum change in grip width possible would be 42 mm since the top-heavy container had a grip width of 36 mm and the angled container had an average grip width of 78 mm. We hypothesize that the difficulty in rotational manipulation arises from COM location rather than differences in grip width, but future experiments could be conducted with containers having equal grip widths in order to assess the effects of grip width on our findings.

Thumb forces were also affected by container shape and COM location. The thumb force vector for all containers was initially directed toward the top of the container for lifting (Fig. 3c). By 18 and 7 % into the pouring phase for the parallel and angled containers, respectively, the thumb force vector pointed toward the bottom of the container in order to assist with counterclockwise rotation. In contrast, the thumb force vector pointed toward the top of the top-heavy container until 79 % of the pouring phase had elapsed (Fig. 3c), suggesting that the thumb primarily played an antagonistic role in that case. This delay of the thumb's assistive role was also evident in the contributions of the vertical force component to the total moment (Fig. 5c). The thumb's antagonistic moment for the top-heavy container lasted statistically significantly longer than for the parallel or angled containers ($p < 0.001$).

During the more challenging task of pouring from the top-heavy container, subjects used their thumbs to prevent rotation until late in the pouring phase. The conservative contribution of the thumb to container rotation could reflect subjects' care in rotationally manipulating an object with which they have less experience; a cocktail glass is less commonly used than a water bottle. The conservative thumb grip response could also be affected by subjects' prior knowledge of top-heavy objects, as internal models can influence anticipatory grip forces (Flanagan and Wing 1997).

Differences between index and middle finger contributions

Previous studies have used two main approaches for analyzing multi-digit manipulation. It is sometimes sufficient and appropriate to treat all digits opposing the thumb as a single "virtual finger," as done in a previous three-digit grasp study (Baud-Bovy and Soechting 2001). Other studies have treated each finger in a three-digit grasp independently (Burstedt et al. 1999; Baud-Bovy and Soechting 2002; Rácz et al. 2012) and reported that independent control of fingertip forces is necessary under specific task conditions. After lifting an object from above, subjects modulated individual fingertip forces independently when oscillating the thumb relative to the other digits (Rácz et al. 2012), when grip plate placements were changed (Baud-Bovy and Soechting 2002), and under different grip plate surface friction conditions (Burstedt et al. 1999). In another study, both virtual and independent fingertip approaches were used together to investigate high- and low-level synergies during a whole hand rotational task (Zhang et al. 2009).

As hypothesized, our data suggest that all digits contributed independently to the three-digit pouring task. In particular, rather than equally bearing half of the load borne by the thumb, the index finger and middle finger force components were unequal and each digit contributed to the total moment about the moving COM differently (Fig. 5). During the pouring phase, the index finger had a higher horizontal force for all containers than the middle finger (Fig. 3a, d), suggesting that the index finger contributed more to grasp stability than to container rotation. This was consistent with the fact that, upon self-selected digit placement, the index finger more directly opposed the thumb, while the middle finger was further from the thumb (Fig. 4). Similarly, when a five-digit grasp was used to shake an object in different directions, it was reported that the index finger grip force was the largest and, therefore, played a primary role in grip control (Kinoshita et al. 1996).

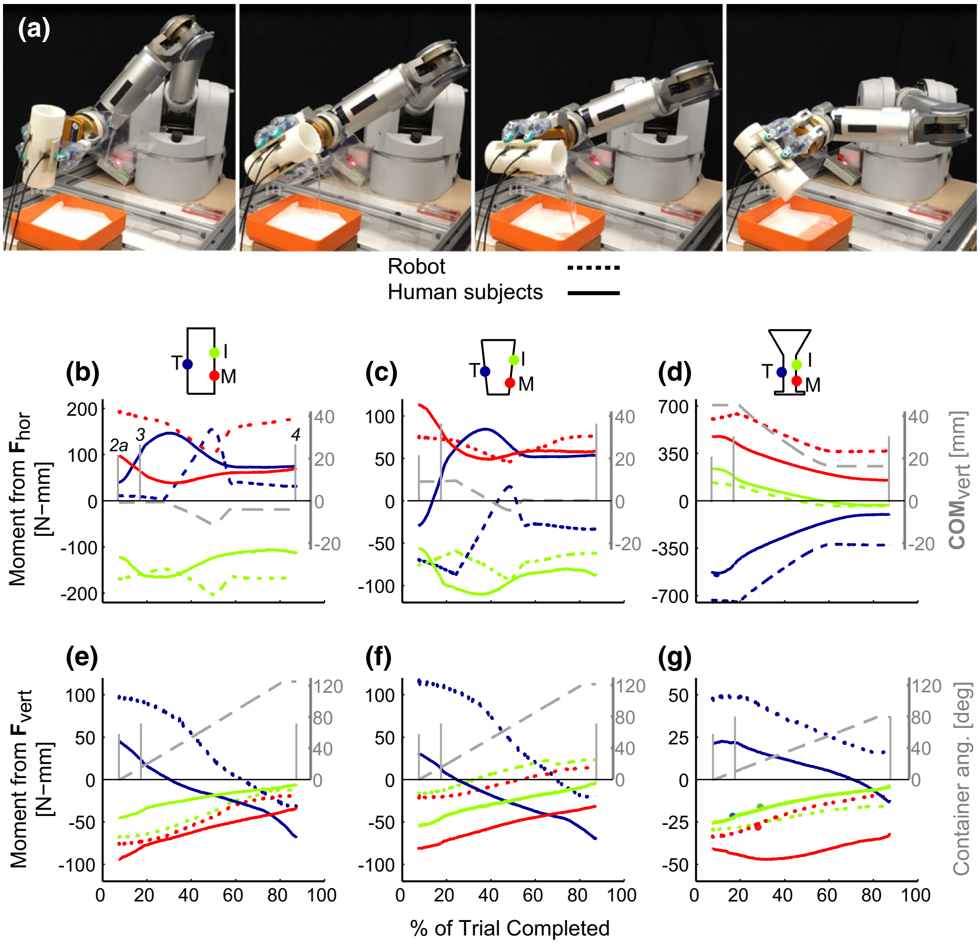

Fig. 6 **a** Robot arm and three-digit hand were used to replicate the pouring experiment with wrist rotation only. Data from the robot (*dotted line*) and human subjects (*solid line*) are shown for the thumb (*blue*), index finger (*green*), and middle finger (*red*) for **b–d** horizontal force component and **e–g** vertical force component contributions to the total moment about the COM for the parallel, angled, and top-heavy containers. The vertical component of the COM and the container rotation angle are also shown (*gray*, *dashed lines*) (color figure online)

As detailed in the Results, the moments due to the horizontal force components were affected by digit placement and container shape. The vertical force component contributions to the total rotational moment about the COM were significantly larger for the middle finger than those for the index finger (Fig. 5c), indicating that the middle finger contributed more to rotation of each container during pouring than the index finger.

Fingertip forces were not passive responses to wrist rotation

Since wrist and arm motions were not constrained, we sought to clarify whether fingertip forces were actively and independently controlled, or simply passive responses to the physics of the rotation of a grasped object in a gravitational field. In a post hoc mini-study, we replicated the pouring experiment using a robot arm and three-digit robot hand (Barrett WAM and BarrettHand, Barrett Technology, Inc., Newton, MA) (Fig. 6a). The robot hand has only four degrees of freedom. Each robot digit can flex and extend independently; the outer two digits (proxies for the index and middle fingers) can only adduct and abduct in unison. Due to these limitations, we elected to pose the robot hand in a tripod grasp such that pure flexion movements of each digit would produce normal forces on each of the parallel grip plates. The same grip posture was used for the angled container for consistency. The distal tips of the BarrettHand fingers were outfitted with soft fingertips to mimic the compliance of the human fingerpad.

A pure rotation of the container was achieved using the robot wrist and arm in order to simulate the pronation/supination of the human wrist. Container-specific wrist rotation speeds were set to the average speeds measured in the corresponding human trials. Since all human subjects rotated the container past the angle necessary to empty the container, the robot was programmed to achieve the same average maximum angle of rotation for each container

(Fig. 6e–g). As human and robot fingertip force data were compared for observational purposes only, no statistical analyses were performed.

The robot's horizontal force component contributions to the total moment changed abruptly along with the COM location (Fig. 6b–d). As expected, the robot index and middle finger vertical force component contributions to the total moment were nearly equal (Fig. 6e–g). In contrast, humans used their middle finger vertical force components to assist with rotation of the container for pouring more than their index finger vertical forces ($p < 0.001$).

In general, the digit-specific vertical force component contributions for the robot case increased or decreased as in the human case. However, there were three key differences between the robot and human datasets. First, the human index and middle finger vertical forces never resisted the counterclockwise rotation of any container for pouring. Second, the human thumb vertical forces assisted with the counterclockwise rotation of the container for pouring much sooner than the robot, which only "assisted" via physics once a container had been rotated past a horizontal orientation. In the case of the top-heavy container, the robot thumb's vertical force component never contributed to the counterclockwise rotation of the container. Finally, the trends in horizontal force component contributions to the total moment were quite different between the robot and human cases. Notably, the robot data featured sharp discontinuities that were not present in the smooth human data.

The robot experiment suggests that humans modulated fingertip forces prior to the key events demarcated by the passive responses of the robot digits. It has been reported that grip forces are modulated prior to the object liftoff (Gordon et al. 1993), advantageous digit placement can be selected prior to the object liftoff (Fu et al. 2010), and anticipated object properties influence object manipulation (Flanagan and Wing 1997). Winges et al. 2007 showed that digit stiffness was modulated in a feedforward manner for a three-digit task in which subjects transported a swinging pendulum whose COM changed throughout the task. Thus, it is possible that feedforward mechanisms contributed to the active and independent control of fingertip forces observed in the present study.

Conclusions

Rotational manipulations of objects are foundational to many activities of daily living. To our knowledge, this is the first study to investigate individual fingertip force contributions for a three-digit manipulation task in which subjects self-selected digit placement and rotationally manipulated an object against gravity. The pouring task is unique in that the COM of the grasped object changed continuously. Digit placement and contributions of fingertip forces to rotational manipulation were dependent on COM location.

The main findings of this study are that the contributions of the digits to a pouring task varied across the digits and were dependent upon COM location associated with container shape. 3D fingertip forces were actively modulated independently and were not simply passive responses to the physics of a pure wrist rotation of a grasped object in a gravitational field. The thumb assisted with pouring for the parallel and angled containers, but predominantly hindered rotation for the top-heavy container. More directly opposing the thumb, the index finger contributed more to grasp stability, while the middle finger contributed more to rotation of the container for pouring.

A multi-digit task involving rotational manipulations and continuously changing center of mass locations can be generalized to many activities of daily living in which mass is transferred from one container to another. Our results could be used to develop bio-inspired, low-level controllers for artificial hands that treat each digit as an independent agent with a task-specific role that is capable of coordinating with other agents according to functional task requirements. Such pre-programmed multi-digit coordination could reduce the cognitive burden on operators of teleoperated manipulators, such as upper-limb neuroprostheses or wheelchair-mounted robot hands.

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Conflict of interest The authors declare that they have no conflict of interest.

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