On preparatory object rotation to adjust handle orientation for grasping

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Abstract

This study investigates preparatory rotation as a manipulation strategy for grasping objects from different presented orientations. Participants lifted heavy, handled objects from eight initial orientations under two task constraints. When object motion was permitted, participants used preparatory rotation to first adjust the object handle to a desired orientation before lifting. The amount of rotation increased for handle orientations further from the central orientation. When object motion was not permitted, increased upper body joint torque was required for the direct grasping strategy compared to that for the preparatory rotation strategy. Grasp configuration and ratings for comfort and naturalness also exhibited similar trends, leading to the conjecture that both energetic considerations and grasp kinematic considerations may drive the selection of preparatory rotation.

Contents

1 Introduction

The activities of daily living require manipulating a wide variety of differently-shaped objects. To successfully complete many goal-oriented tasks in unstructured environments, humans must be able to adapt basic manipulation skills in response to novel conditions such as changes in the object shape, weight, and placement in the environment. Several studies have focused on finding underlying invariant characteristics of human reaching and grasping motor control, such as the timing coordination of hand transport with hand pre-shaping during reaching (Jeannerod, 1981) or the existence of motor synergies in hand force regulation (Li et al., 1998; Latash et al., 1998). Another aspect of interest is how humans adjust manipulation strategies in response to different parameters for a given class of tasks. For example, Johansson (1996) investigated how finger grip forces are adjusted in response to surface friction.

One body of previous research has investigated how body posture and hand orientation in reaching movements are related to manipulation task parameters. Bongers et al. (2004) reported that the stopping distance in a reaching manipulation task was dependent on the tool-use posture, tool length, and tool weight. Work by Stelmach et al. (1994) and Desmurget et al. (1996) showed that wrist angle and trajectory changed according to the orientation of the cylindrical object placed in the same position. Similarly, Rand & Stelmach (2005) studied how arm transport duration and distance in reach-to-grasp movements differed for starting forearm positions with supination or pronation.

In addition, Rosenbaum and colleagues have investigated the selection of hand grips for a variety of handle transport and handle rotation tasks where a cylinder is grasped and placed at several different goal configurations (Rosenbaum et al., 1990, 1992, 1993). This has led to several inquiries testing how perceived end-state comfort of a task affects the choice of initial hand grasps in object transport tasks (Rosenbaum et al., 1992; Short & Cauraugh, 1997; Zhang & Rosenbaum, 2008). In recent work, Rosenbaum & Gaydos (2008) present a relative cost approach for evaluating the movement costs for tasks such as object-positioning and object-rotation.

Our experiments are the first, to our knowledge, to explore what we refer to as preparatory manipulation strategies. Preparatory manipulation occurs whenever the interaction first adjusts the object configuration in the workspace prior to grasping (Fig. 1). This approach takes advantage of the object's movability on the surface to effectively change the intermediate task parameters. In such cases, the action in anticipation of a grasping task not only consists of changes in the manipulator's posture such as arm reaching movement and hand pre-shaping, but it also includes changes in the object configuration in the environment prior to grasping. This study specifically examines object rotation as a preparatory manipulation strategy for lifting heavy objects from different presented object orientations. Departing from the previous studies (Rand & Stelmach, 2005; Rosenbaum et al., 1992) on manipulation of lightweight objects, we chose to investigate lifting of heavy objects since we believe preparatory manipulation is most relevant to more demanding tasks.

The aims of this study are to quantify the consistency of object rotation as a preparatory strategy and to examine possible criteria that the strategy may optimize. The preparatory adjustment may allow a novel or difficult task to be transformed to a familiar, easier one. In the case of lifting heavy objects, pre-rotating the object prior to lifting may move the handle to a familiar canonical configuration. The canonical orientation

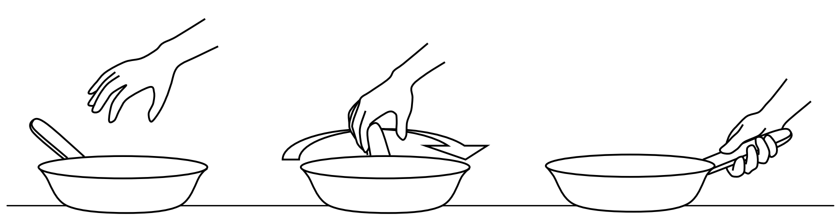

Figure 1: Preparatory manipulation adjusts the object configuration in the workspace prior to grasping. One example of preparatory manipulation is preparatory object rotation, shown here for a handled pan, where the object orientation is adjusted before grasping.

may be preferable to the orientation initially presented because it requires less exertion in the lifting posture, allows more stable grasps of the handle, or is perceived to be more comfortable.

Previous studies have examined similar qualities as possible optimization criteria for motor control. Exertion or energy as measured by the magnitude of joint torques has been used for simulating walking behavior (Chow & Jacobson, 1971), predicting postures for sagittal plane lifting (Dysart & Woldstad, 1996; Chang et al., 2001), and modeling upper extremity postures for reaching tasks (Engelbrecht, 1997). Several studies (Fischman, 1998; Short & Cauraugh, 1997; Rosenbaum et al., 1992) have investigated end-state comfort for hand grasps of elongated objects. It is possible the perceived grasp comfort may be related to the grasp location on the object, as work by Turvey et al. (1999) found that object inertia asymmetry was a factor in weight perception.

In our study, we investigate how the amount of preparatory object rotation changed in response to eight different object orientations on a horizontal surface. Other metrics computed from the body posture at time of object liftoff included the joint torques at the torso, shoulder, elbow, and wrist, and the grasp configuration with respect to the object handle. In addition, participants rated the lifting task trials for comfort and naturalness. All of the response variables were compared between different task constraints where preparatory object rotation was permitted or not permitted in the verbal task instructions.

2 Method

2.1 Participants

Ten right-handed adults (5 male, 5 female) volunteered for the study (age = 26.7 ± 3.5 years [mean ± standard deviation], height = 167.1 ± 9.1 cm, weight = 58.7 ± 10.9 kg). All participants signed informed consent forms approved by the Institutional Review Board.

2.2 Procedure

Participants performed the object lifting tasks in a kitchen counter top setting (Fig. 2). The object start position was located on the right side counter area. The object goal area was located 77 cm to the left of the start position and was marked by a circular cover over the bottom left stove burner. At the start position, the object was presented in one of eight possible orientations, indicated by the direction of the object handle. In the baseline orientation, the handle directly faces the participant, and the remaining 7 orientations spanned a full 360 degrees in 45 degree increments. The two handled objects tested for all ten participants were a large plastic water jug and a cast iron frying pan, both without lids (Fig. 3). The objects were filled with water for a total mass of 3.4 kg for the jug and 1.5 kg for the pan.

Kinematic data for the participant and objects were recorded at 120 Hz using a Vicon camera system (Vicon Motion Systems, Los Angeles, California, USA). Motion of the full body, including hands and fingers, was tracked by 80 reflective markers attached to the participant. The marker set included 4 markers on the hips, 8 markers on the torso, 7 markers on the arm, 6 markers on the hand dorsum, and 10 markers on the fingers. Prior to the lifting tasks, a calibration trial was recorded where the participant exercised the range of motion for all joints. In the following experiments, each object was tracked by 5 attached markers.

In each lifting task trial, the participant started facing the counter with toes at a distance of 78 cm from the counter edge, such that the object was outside of arm's reach. The participants arms were held out to the side with the hands resting prone at table height, which improved the tracking of the hand markers by the camera system. For all trials, the task goal was to move the object to the goal position without spilling any water. No specific object orientation was required at the goal. Participants were instructed to perform the transport task at a self-selected speed with no time constraints. We investigated the performance of the transport task for the

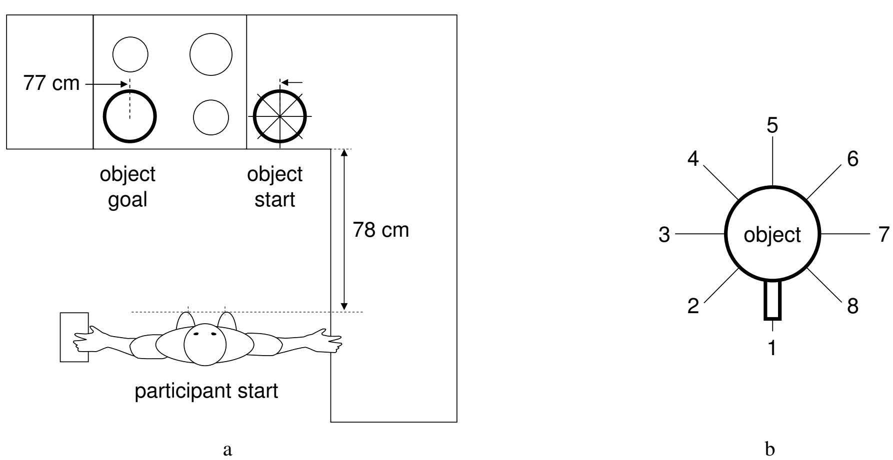

Figure 2: General layout of the experimental setting. (a) Participants started in a standing position facing the countertop setting. Participants transported the handled objects from the start position to the goal position with their right hand. (b) In each trial, the handled object started in one of eight orientations defined by the handle direction. In the figure, the handled object is in orientation 1, the baseline orientation.

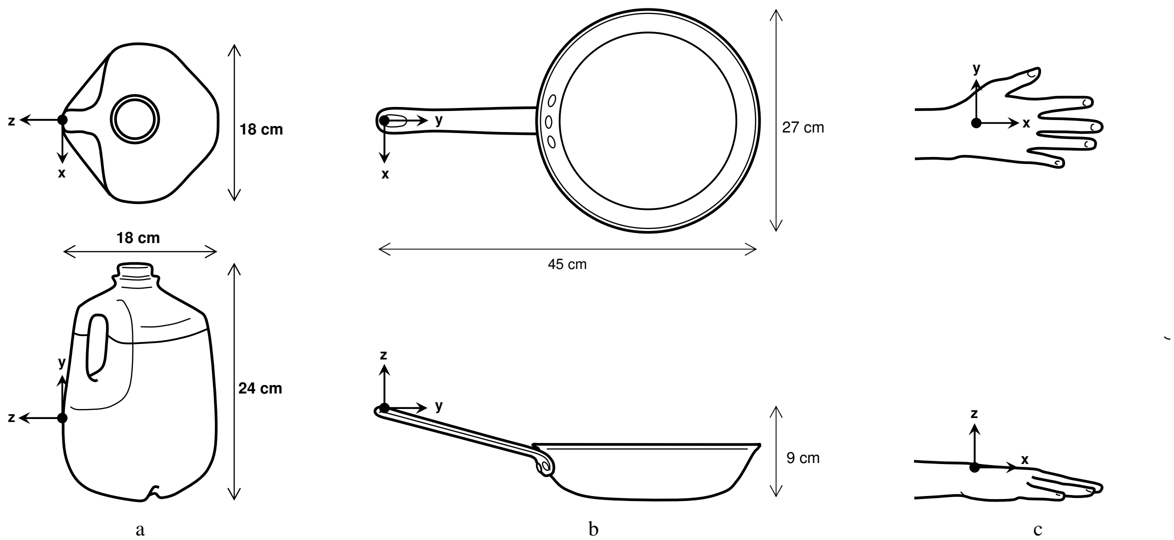

Figure 3: Participants transported two different handled objects filled with water, (a) an uncapped water jug and (b) a cast iron cooking pan. The coordinate systems located at the object handles provide a reference frame for measuring the (c) hand dorsum configuration during the object grasp.

two objects over the 8 possible object starting orientations. Each set of 8 trials started with the object handle in the baseline handle orientation, and subsequent 7 trials progressed clockwise in the handle orientation.

The experiment consisted of three phases to examine three types of task scenarios. The first phase served as practice trials to familiarize the participants with the task setting. Participants were instructed to complete the transport task with no restrictions, using either or both hands as desired. In the first set of 8 trials, participants transported the filled water jug from the 8 initial handle orientations. Then, in the second set of 8 trials, the filled frying pan was transported from the 8 initial handle orientations. At the end of the practice phase, participants rated the 16 different lifting tasks for comfort and naturalness on a scale of 1 to 9.

The second phase investigated unimanual lifting performance in response to the different object handle orientations. The purpose of this phase, as the main portion of the experiment, was to observe to what extent object preparatory adjustment would be used as a strategy to compensate for changes in object orientation. Participants were instructed to complete the transport task using only their right hand to contact the object. Besides this unimanual constraint, there were no restrictions on the task performance. The verbal instructions did not suggest preparatory object motion as a strategy, as it was our intent to observe what strategies the participants would naturally select. Two sets of 8 trials were completed for the jug to obtain a measure of performance repeatability. Next, two sets of 8 trials were completed for the pan. As before, participants rated the 16 unimanual task conditions for comfort and naturalness.

The final phase tested how participants would respond to different object handle orientations in the absence of preparatory object adjustment on the counter surface. The task performances from this third phase provide a reference measurement for analyzing the object adjustment motion in the second phase. Participants were instructed to transport the object using only right hand contact and without any lateral sliding on the surface prior to lifting the object from the start position. Participants were given the option of aborting a trial at any time during the task if they could not complete the task under the given constraints. The first set of 8 trials was completed for the jug, and the second set of 8 trials was completed for the pan. The 16 tasks were rated for comfort and naturalness at the end of the phase.

The experiment required approximately 90 minutes for a single participant.

3 Data analysis

Kinematic skeletal models for each participant were fit to the recorded marker trajectories as follows. The generic skeletal template modeled the lower back, shoulder, elbow, and wrist as spherical joints with three rotational degrees of freedom. An individual skeleton was automatically fit to the manually-labeled range of motion data using the Vicon IQ software's subject calibration function (Vicon Motion Systems, Los Angeles, California, USA). For the lifting task trials, the joint center locations of the individual skeletal model were fitted to the labeled marker trajectories automatically using the Vicon IQ software's kinematic fit function. Gaps in the marker trajectories due to occlusions, which occurred frequently for the lower body markers and hand dorsum markers, were not manually reconstructed. Due to the frequent occlusions, reliable joint center locations were obtained only for the torso, shoulder, elbow, wrist, and finger knuckle joints.

In each trial, four time points represent key events in the task performance. The key time points were determined by the following events: (1) initial body movement, (2) initial object contact, (3) object liftoff from the surface, and (4) object arrival at the goal. These mark the start and end points of three segments of the motion (Table 1). First, reaching and approach to the object start with the initial body movement from the participant's start position and ends when the object is first contacted ($T1$). Then, object manipulation and grasping occur between the initial object contact and the object liftoff from the surface ($T2$). Finally, object transport starts after the object liftoff and ends on object arrival at the goal position ($T3$). The four key time points were estimated automatically from the trial marker trajectories based on manually-selected thresholds. Initiation of body movement was estimated as the first frame where the average body marker distance from the starting pose exceeded 1 cm. In the absence of tactile sensor data for either the participant's hand or the object surface, we estimated initial object contact from the initial object movement. As with body movement, initiation of object movement was detected when the average object marker distance from

Table 1: Response metrics observed for each trial where the participant lifted and transported a handled object from the presented object start orientation. The linear mixed-effects models tested the differences in each of the metrics between the unimanual constraint trials and object motion constraint trials.

Response metric	Computation notes
Timing	
Approach and reaching, $T1$	Initiation of body movement to initiation of object movement
Manipulation and grasping, $T2$	Initiation of object movement to object lift off from surface
Object transport, $T3$	Object lift off surface to object arrival at goal position
Total time, $T1 + T2 + T3$	Initiation of body movement to object arrival at goal position
Object liftoff posture	
Object rotation	Angle change at liftoff from initial orientation, on surface plane
Joint torque load	Sum of squared torques over torso, shoulder, elbow, and wrist
Grasp orientation	Angle of single rotation between hand frame and object frame
Grasp location	Distance between origins of hand frame and object frame
Perceptual rating	
Comfort	Self-reported on scale of 1 to 9 after trial set
Naturalness	Self-reported on scale of 1 to 9 after trial set

the starting configuration exceeded 1 cm. Object liftoff from the surface was marked when the vertical coordinate of one object marker exceeded 1 cm change from the starting vertical position. Object arrival at the goal position was marked when the vertical coordinate of one object marker fell within 1 cm of the ending vertical position. The time durations for the reaching, object manipulation, and object transport segments of the task are determined from the differences between the four key time points. Total task duration is the sum of the three segment durations.

The third key time point, object liftoff from the surface, is the focus of our data analysis. Four metrics were computed from the participant's body pose at the liftoff time frame: object rotation, joint torque load, grasp orientation, and grasp location (Table 1). Object rotation was measured as the change in angular orientation with respect to the horizontal plane between the object's starting orientation and the object orientation in the liftoff frame. We computed the absolute amount of rotation so that there was no distinction between clockwise or counterclockwise rotation. Upper body joint torques were estimated from the liftoff body pose as follows. The segment mass of the torso, right upper arm, right forearm, and right hand were estimated as a fraction of total body mass according to the anthropomorphic data reported in Clauser et al. (1969) (Table 2). Locations of the segment center of mass were also estimated as a fraction of segment length according to the results of Clauser et al. (1969) (Table 2). Given the fitted joint center locations for the lower back, shoulder, elbow, and wrist, joint torques were calculated from the loads due to distal limb segment weight and the object weight. The four joint torques were combined into a single metric of the sum of squared joint torques. The configuration of the hand dorsum coordinate system was then computed with respect to the reference coordinate system attached to the object handle (Fig. 3). The grasp orientation is measured as the angle magnitude of the single axis-angle rotation which would align the hand dorsum coordinate system to the object handle coordinate system. The grasp location is measured as the distance between the hand coordinate system origin at the proximal end of the third metacarpal and the object coordinate system origin at the base of the handle (Fig. 3).

The overall set of dependent variables examined in this study were difference in metrics (Table 1) between the tasks with the unimanual constraint (second phase) and the tasks with the additional object motion constraint (third phase). The difference in metrics were computed between matched pairs of trials performed by the same participant on the same object for the same initial handle configuration, with only a difference in the task constraint. The differences were computed for the two sets (repetitions) of 8 trials per object in the unimanual constraint phase with respect to the single set of 8 trials per object in the motion constraint phase. In addition to the metrics for the liftoff pose, the differences in time duration, comfort rating, and naturalness ratings were computed between the unimanual and motion constraint phases.

We analyzed the difference metrics with linear mixed-effect (LME) models (Verbeke & Molenberghs, 2000) using the NLME package (Pinheiro & Bates, 2000) for R 2.6.2 (R Development Core Team, 2008). Our study contains repeated measures because each participant performs the lifting task for both objects and

Table 2: Parameters used for joint torque load estimation, based on results reported by Clauser et al. (1969). The location of the center of mass of each segment is estimated from the fraction of the segment length defined by joints at the segment ends. The joint locations were obtained from the kinematic skeleton fitted to the marker position data at the object liftoff time frame.

Body segment	Segment mass (percent body mass)	Joints defining segment length		Center of mass, C (percent length, $\overline{AC}/\overline{AB}$)
		Endpoint A	Endpoint B	
Torso	50.7	sternoclavicular	lower back	38.0
Right upper arm	2.6	shoulder	elbow	51.3
Right forearm	1.6	elbow	wrist	39.0
Right hand	0.7	middle knuckle	wrist	18.0

all 8 orientations. Thus the observations are not independent, and we cannot use a standard linear analysis of variance (ANOVA) to correctly test the significance of the explanatory variables. LME models address the correlated errors from dependent observations by including random effects in addition to the mean fixed effects. In our study, the data is grouped by participant such that the LME model accounts for the correlation between the repeated observations for each participant. LME models can also handle missing observations without discarding all observations for one participant. This allowed us to include data from participants even if the lifting task was not completed for all handle orientations.

The explanatory variables available as fixed effects for the LME models included the object, the initial handle orientation, the square of the initial handle orientation, and the task repetition (either the first or second observation) of the unimanual constraint trials. Model selection was used to determine an appropriate combination of available explanatory variables for modeling each dependent variable. In the model selection process for a given dependent variable, multiple LME models were fitted for different combinations of possible explanatory variables. Using a standard statistical method to favor better data fits without using too many model parameters, we selected the model with the lowest Bayesian Information Criterion (BIC) score (Pinheiro & Bates, 2000) as the final LME model for that dependent variable. The t-test results for the final LME model indicate which explanatory variables were statistically significant as fixed effects. In addition, the significance of each random effect in the final LME model was checked using a likelihood L ratio test comparing the selected LME to a linear model without the random effect (Pinheiro & Bates, 2000).

Separate LME models were selected for each of the four dependent variables computed from the liftoff pose: difference in object rotation, difference in sum of squared joint torques, difference in hand grasp orientation, and difference in hand grasp position. Model selection was also performed to select LME models for the differences in comfort rating and differences in naturalness rating.

4 Results

When participants were only restricted by the unimanual constraint, they often rotated the object on the countertop surface to a new orientation before lifting and transporting the object to the goal. The resulting body poses at object liftoff (Fig. 4) were similar in terms of the upright torso orientation and object handle directed toward the participant. In contrast, when the object rotation strategy was precluded by the object motion constraint, the resulting body poses at object liftoff were more varied in the torso orientation and arm configuration. For trials where the object handle faced away from the participant, the torso was often tilted over the countertop surface with the elbow extended away from body to achieve the grasp of the object handle. One participant chose to abort one lifting trial in the object motion constraint phase after grasping

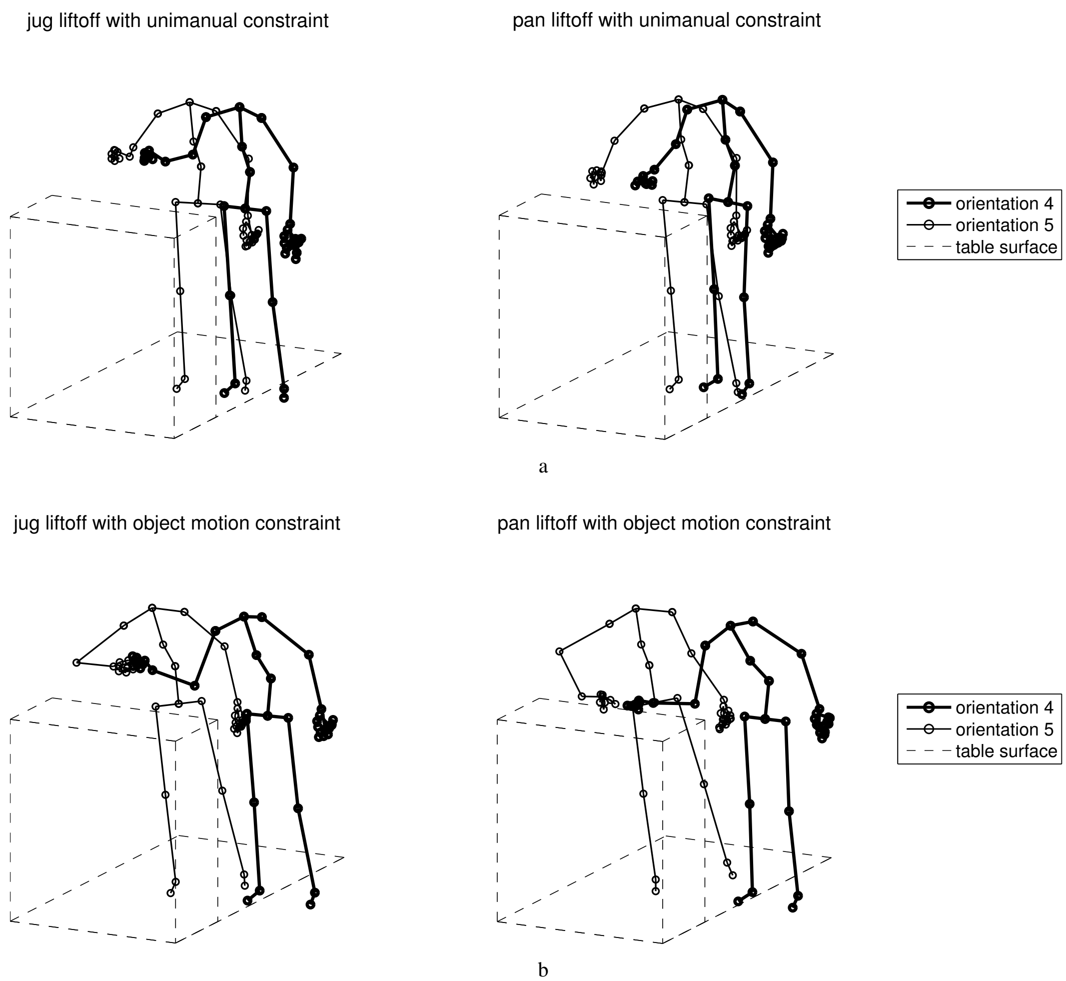

Figure 4: Visualization of the body postures at object liftoff for a sample subject. Poses are shown for the trials with initial object orientation 4 and 5, where the handle faced away from the participant. (a) Poses for the trials with the unimanual constraint. (b) Poses for the trials with the additional object motion constraint. The liftoff poses for the unimanual constraint trials were more similar to each other because the allowed object motion adjusted the handle direction toward the participant. When object motion was not permitted, the liftoff poses are more varied. In the most extreme cases for initial object orientation 4 and 5, the torso is tilted over the countertop and the elbow is held away from the side of the body.

and attempting to lift the pan from handle orientation 5 without object motion along the surface.

4.1 Timing

Differences in the timing between the unimanual constraint and object motion constraint trials suggests that rotation adjustment provides a trade-off between different segments of the movement (Table 3). Out of the 320 possible timing difference observations for each motion segment, only 318 could be computed because of the missing reference measurement due to the single aborted trial. Object manipulation duration $T2$ between initial object movement and object liftoff, for the unimanual constraint trials was longer than that in the reference object motion constraint trials for 93% of the 318 time differences, and the mean duration difference was 139 msec. This is not surprising since we expect object adjustment to require additional time to only lifting the object. However, the reaching time $T1$ and object transport time $T3$ were shorter for the unimanual constraint trials than for the object motion constraint trials for 90% and 81% of the 318 trials, respectively. The mean time differences were -199 msec for reaching and -105 msec for object transport. In addition, the total task time, $T1 + T2 + T3$, from initial body movement to object arrival at the goal position was shorter for the unimanual constraint trials for 75% of the 318 trials, with a total mean duration difference of -165 msec.

4.2 Object liftoff posture

The single aborted trial resulted in 2 missing difference metrics for the response variables computed from the object liftoff poses. In total there were 318 object rotation difference metrics and 318 joint torque difference metrics. Occlusions of the hand dorsum markers resulted in additional missing data points for the grasp configuration metrics. Overall, there were 296 grasp orientation differences and 307 grasp location differences analyzed in the following models.

Under the unimanual constraint, the amount and direction of object rotation varied depending on the initial handle orientation, as did the object orientation at the liftoff time frame (Fig. 5). In general, the selected handle orientation for lifting were clustered in the region between handle orientation 1 and 8 on the participants' right side. Thus, the scale for the handle orientation variable is centered around the orientation halfway between orientation 1 and 8 for all LME models. The centering is achieved by re-coding orientations 1 through 8 as values 0.5, 1.5, 2.5, 3.5, -3.5, -2.5, -1.5, and -0.5.

The differences in object rotation (Fig. 6) between the unimanual constraint trials and object motion constraint trials are largest for the initial handle orientation opposite the central handle direction facing toward the participant. The differences are small for the region near the central direction and then increase more quickly once the initial handle orientation is outside the region of preferred lifting orientations. The parabolic shape for rotation differences suggested the inclusion of the squared orientation term as a factor in the LME models.

Table 3: Timing duration differences for the three segments of the lifting task (Table 1). Each timing difference is the duration in one of the two unimanual constraint trials minus the duration in the corresponding object motion constraint trial. For each timing metric, there were a total of 318 timing differences.

	Timing difference, $T(\text{motion constraint}) - T(\text{unimanual constraint})$	
Timing segment	Mean (ms)	Number of negative differences (out of 318)
Approach and reaching, $T1$	-199	286
Manipulation and grasping, $T2$	139	21
Object transport, $T3$	-105	257
Total time, $T1 + T2 + T3$	-165	238

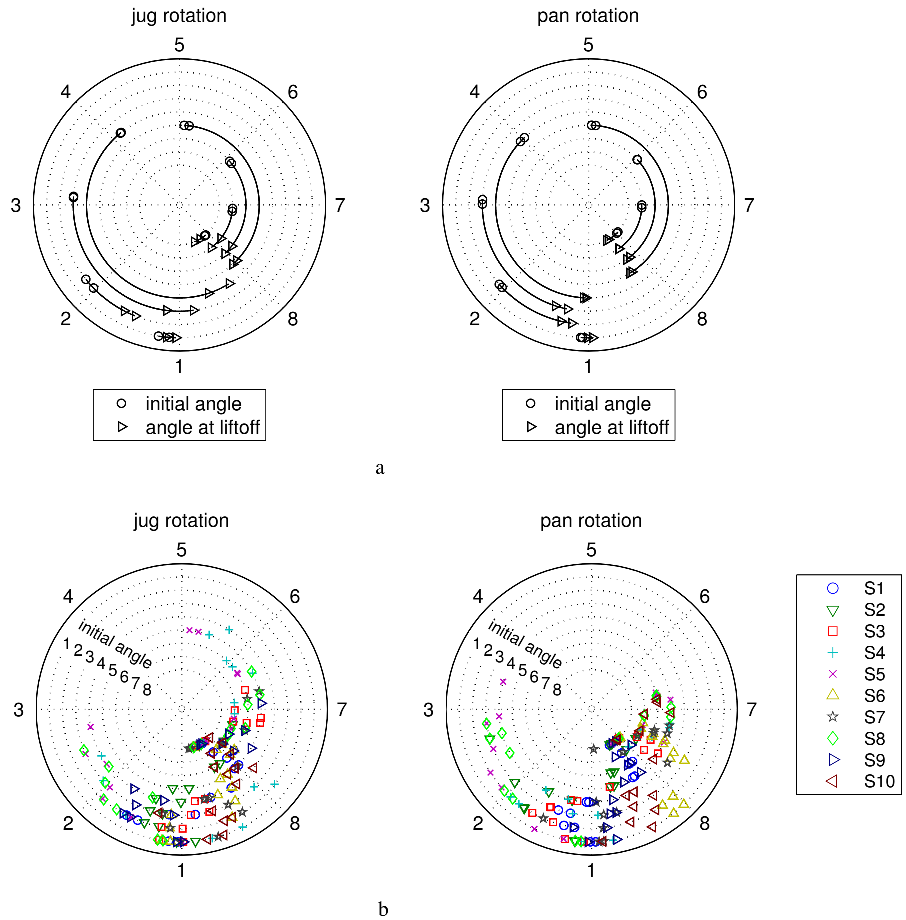

Figure 5: Visualization of the object rotation prior to liftoff for the different initial handle orientations. (a) Sample initial and liftoff orientations for the task trials with unimanual constraint for an example participant. (b) Object liftoff angles for the unimanual constraint phase for all subjects.

The final selected LME model for object rotation (Table 4) with the lowest BIC score includes an interaction effect of the squared orientation curvature with object. There is slightly more object rotation for the pan than the jug for handle orientations far from the center, as modeled by the orientation^2(object) interaction effect. The fixed effects of linear orientation, squared orientation, and orientation^2(object) interaction were all significant ($\alpha = 0.05$). In addition, the result of the likelihood ratio test confirms that the random effect of squared orientation should be included in the LME model ($p < 0.0001$) in addition to the fixed average effect to account for inter-participant differences in the curvature of the object rotation trend. The parameter estimates for the squared orientation effects convey that the individual curvature coefficients vary over a range of $(8.94 - 1.57) \pm 2(2.68) = (2.01, 12.73)$ rotation degrees per handle orientation units for the jug and $8.94 \pm 2(2.68) = (3.58, 14.3)$ rotation degrees per handle orientation units for the pan. The residual value indicates that the remaining error of the observations relative to the individual regression curves has standard deviation of 22.44 degrees of object rotation.

The difference in the sum of squared joint torques also exhibited a quadratic trend with initial handle orientation (Fig. 7). The joint torque metric for the object motion constraint trials was greater than those for the unimanual constraint trials, as seen from the primarily non-negative differences (Fig. 7). This suggests that there is a trade-off between pre-rotating the object prior to the liftoff and exertion of larger joint torques

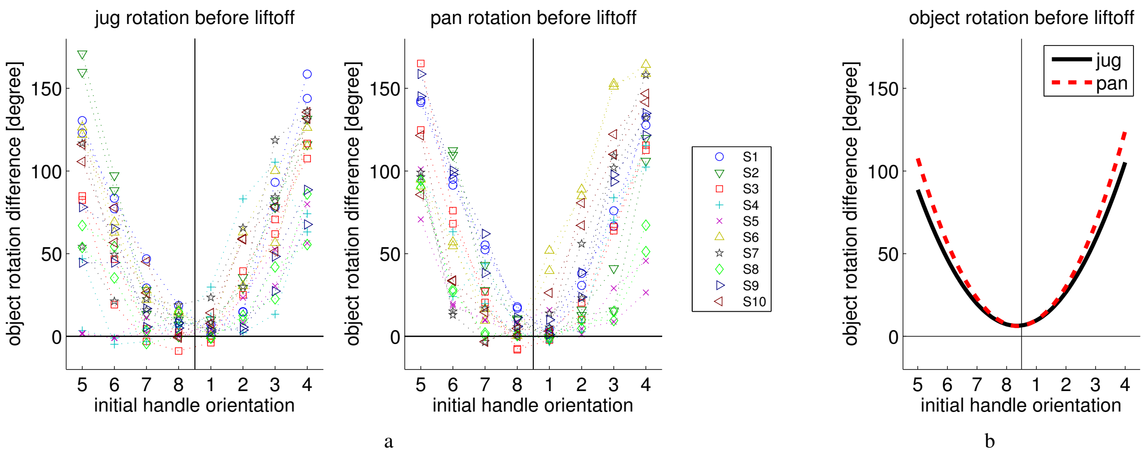

Figure 6: Difference in object rotation versus initial handle orientation. (a) Individual participant results. (b) Mean regression curve determined from the LME (Table 4). The differences are the object rotation amounts in the two unimanual constraint trials minus the object rotation in the vertical constraint trial. The amount of object rotation prior to liftoff increases as the handle orientation moves further from the baseline orientation naturally preferred for the lifting task.

Table 4: Results from linear mixed-effects (LME) model analysis for the object rotation difference as the dependent variable. The model estimates the parameters for the main effects and includes a random effect for squared orientation to model the individual participant variation. The t-test and L ratio test results indicate the significance of the fixed effects and random effects, respectively. Significant effects ($p < 0.05$) are highlighted in bold. In the model, the baseline object was the pan, such that the estimated parameters for object are the additive effects for the jug.

	Parameter estimates for object rotation [degree]			
Fixed effects	Value	Std. Error	$t(304)$	p
Main effects				
Intercept	6.41	2.70	2.37	**0.0184**
Object	0.19	3.82	0.05	0.9608
Orientation	2.37	0.55	4.28	<**0.00005**
Orientation^2	8.94	0.93	9.56	<**0.00005**
Interaction effects				
Orientation^2(object)	-1.57	0.55	-2.83	**0.0049**
Random effects	Std. Deviation		L ratio	p
Orientation^2	2.68		124.01	<**0.0001**
Residual	22.44			

at liftoff. As with object rotation, the fixed squared orientation, fixed orientation^2(object) interaction, and

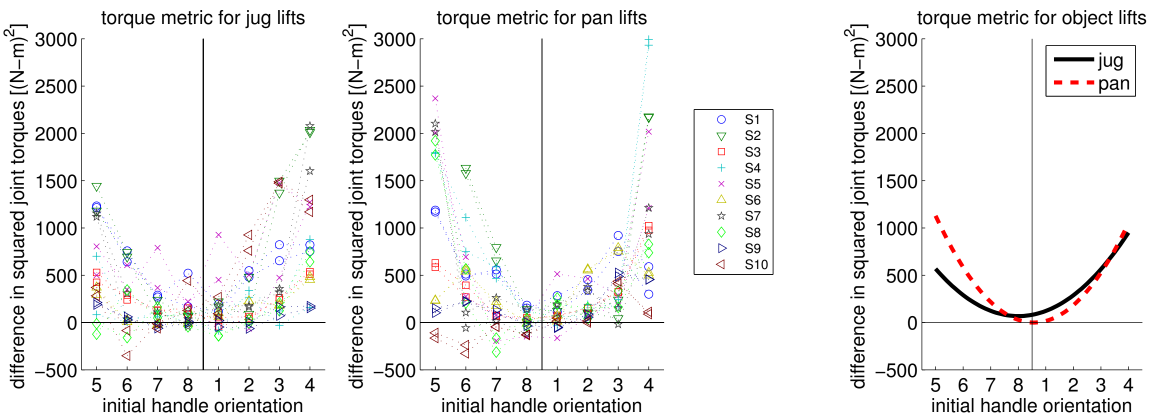

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Figure 7: Difference in the sum of squared joint torques versus initial handle orientation. (a) Individual participant results. (b) Mean regression curve determined from the LME (Table 5). The differences are the torque metrics in the two unimanual constraint trials subtracted from the torque metric in the vertical constraint trial. The trend in the torque metric is similar to that for the object rotation metric.

Table 5: Results from linear mixed-effects (LME) model analysis for the torque metric difference as the dependent variable. The model estimates the parameters for the main effects and includes two random effects (for object and squared orientation) to model the individual participant variation. The t-test and L ratio test results indicate the significance of the fixed effects and random effects, respectively. Significant effects ($p < 0.05$) are highlighted in bold. In the model, the baseline object was the pan, such that the estimated parameters for object are the additive effects for the jug.

	Parameter estimates for torque metric [(N-m)^2]			
Fixed effects	Value	Std. Error	$t(304)$	p
Main effects				
Object	81.20	83.63	0.97	0.3324
Orientation	-11.36	11.75	-0.97	0.3345
Orientation^2	88.86	14.76	6.02	**<0.00005**
Interaction effects				
Orientation(object)	66.06	16.45	4.02	**0.0001**
Orientation^2(object)	-33.53	6.95	-4.83	**<0.00005**
Random effects		Std. Deviation	L ratio	p
Object		232.06	28.35	**<0.0001**
Orientation^2		45.03	106.28	**<0.0001**
Residual		333.65		

random squared orientation were all significant effects ($p < 0.0001$) (Table 5). There is an increase in torque metric curvature for the pan over the jug, indicated by the negative coefficient for orientation^2(object) interaction. This is consistent with the increase in object rotation curvature for the pan over the jug, suggesting that the preparatory adjustment has a greater role in the pan lifting trials. Another result to note is the asymmetry of the regression curve fit for the jug lifting trials, indicated by the significant orientation(object) interaction. The smallest difference in the torque metric occurred closer to initial handle orientation 8 rather than between orientation 1 and 8.

Hand grasp configuration differences (Fig. 8) also increased when the initial handle directions faced away from the participant. The significant linear orientation effect for the grasp orientation (Table 6) suggests there is an asymmetry in the grasps used to the lift the object. The grasp differences are smaller for handle orientations 5 to 8, which were generally on the right hand side. Handle orientations 1 to 4 required the right hand to cross the body to reach the left side for the object motion constraint trials, which led to large differences in grasp orientation. In contrast, the response of grasp location (Table 7) was much more

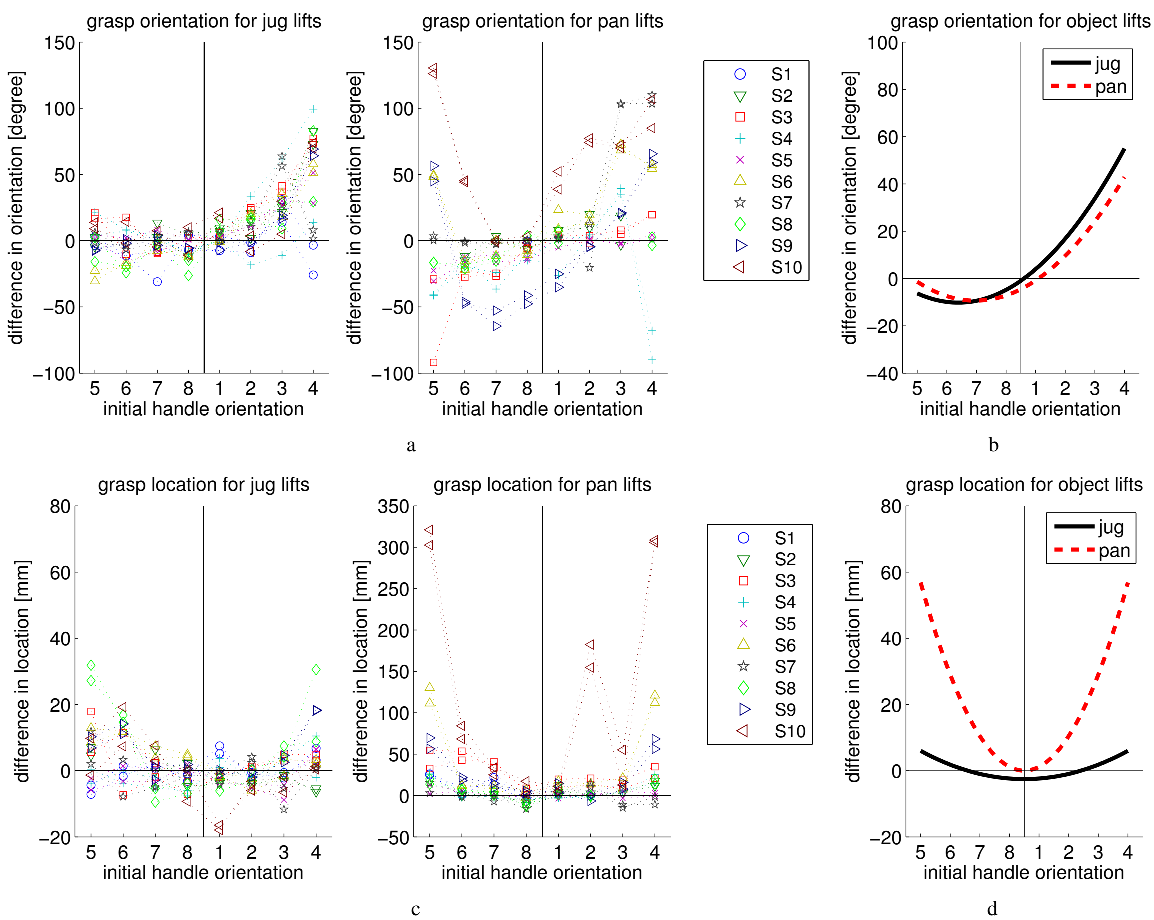

Figure 8: Difference in grasp as represented by the hand dorsum orientation and location with respect to the object frame. The differences are the grasp metrics in the two unimanual constraint trials subtracted from the grasp metric in the unimanual and object motion constraint trial. (a) Individual participant results for grasp orientation difference. (b) Mean regression curve determined from the LME for the grasp orientation difference. (c) Individual participant results for the grasp location difference. (d) Mean regression curve determined from the LME for grasp location difference.

Table 6: Results from linear mixed-effects (LME) model analysis for the grasp orientation difference as the dependent variable. The model estimates the parameters for the main effects and includes three random effects (for intercept, object, and squared orientation) to model the individual participant variation. The t-test and L ratio test results indicate the significance of the fixed effects and random effects, respectively. Significant effects ($p < 0.05$) are highlighted in bold. In the model, the baseline object was the pan, such that the estimated parameters for object are the additive effects for the jug.

	Parameter estimates for grasp orientation [degree]			
Fixed effects	Value	Std. Error	$t(283)$	p
Main effects				
Intercept	-4.52	5.95	-0.76	0.4480
Object	3.58	7.56	0.47	0.6357
Orientation	6.32	0.54	11.82	<**0.00005**
Orientation^2	2.06	0.64	3.20	**0.0015**
Random effects	Std. Deviation		L ratio	p
Intercept	17.20		40.77	<**0.0001**
Object	22.32		62.09	<**0.0001**
Orientation^2	1.85		29.96	<**0.0001**
Residual	20.81			

Table 7: Results from linear mixed-effects (LME) model analysis for the grasp location difference as the dependent variable. The model estimates the parameters for the main effects and includes a random effect for squared orientation to model the individual participant variation. The t-test and L ratio test results indicate the significance of the fixed effects and random effects, respectively. Significant effects ($p < 0.05$) are highlighted in bold. In the model, the baseline object was the pan, such that the estimated parameters for object are the additive effects for the jug.

	Parameter estimates for grasp location [mm]			
Fixed effects	Value	Std. Error	$t(295)$	p
Main effects				
Object	-2.55	3.48	-0.73	0.465
Orientation^2	4.64	1.10	4.22	<**0.00005**
Interaction effects				
Orientation^2(object)	-3.94	0.61	-6.48	<**0.00005**
Random effects	Std. Deviation		L ratio	p
Orientation^2	3.30		113.76	<**0.0001**
Residual	28.91			

symmetric, as indicated by the absence of any significant linear orientation effects in the LME model. As with the torque metric, the negative coefficient for the orientation^2(object) interaction suggests that the trade-off of preparatory rotation is more pronounced for the pan than for the jug. For some participants, the grasp location for lifting the pan in the object motion constraint phase changed dramatically. Instead of grasping close to the handle end as they did in the unimanual constraint phase, they lifted the pan with a grasp closer to the center of the pan when the handle was further from reach. The use of preparatory rotation strategy when it was permitted in the unimanual constraint phase might be due to the preference to grasp the object near the end of the handle, even though other grasps were feasible when object motion on the surface was not permitted.

For each of the four dependent variables computed from the liftoff pose, the final LME model did not include the effect of task repetition. The effect of task repetition was not statistically significant for significance level $\alpha = 0.05$.

4.3 Perceptual rating

The differences in perceptual response for comfort and naturalness between the unimanual constraint and object motion constraint phases (Fig. 9) were also tested with LME models (Tables 8, 9). Neither object

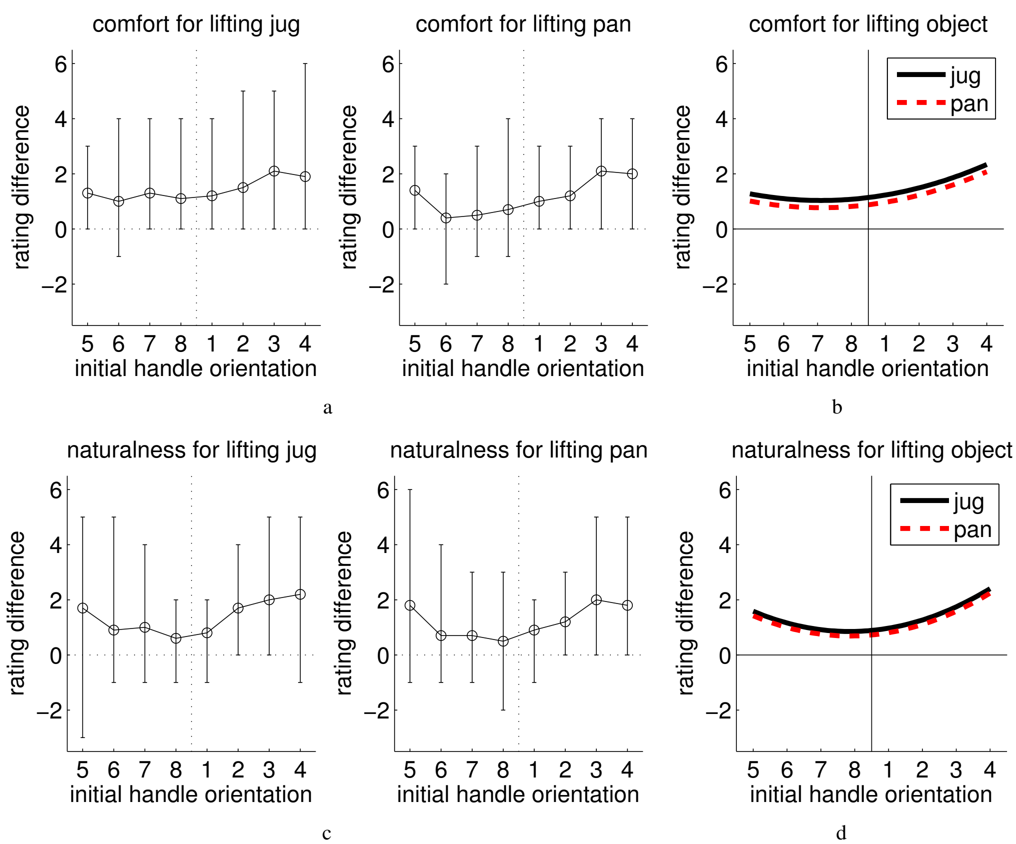

Figure 9: Difference in perceptual ratings over the 10 participants. The mean regression curve is determined from the significant effects as tested by the linear mixed model. The differences are the ratings for unimanual constraint tasks the rating for the object motion constraint task. (a) Comfort rating. (b) Naturalness rating. The positive mean values indicate that participants found the unimanual constraint lifting more comfortable and natural compared to lifting under the object motion constraint.

Table 8: Results from linear mixed-effects (LME) model analysis for the comfort rating difference as the dependent variable. The model estimates the parameters for the main effects and includes three random effects (for intercept, object, and squared orientation) to model the individual participant variation. The t-test and L ratio test results indicate the significance of the fixed effects and random effects, respectively. Significant effects ($p < 0.05$) are highlighted in bold. In the model, the baseline object was the pan, such that the estimated parameters for object are the additive effects for the jug.

	Parameter estimates for grasp location [mm]			
Fixed effects	Value	Std. Error	$t(307)$	p
Main effects				
Intercept	0.88	0.29	3.06	**0.0024**
Object	0.26	0.26	1.01	0.3132
Orientation	0.15	0.02	7.95	<**0.00005**
Orientation^2	0.05	0.04	1.45	0.1472
Random effects	Std. Deviation		L ratio	p
Intercept	0.87		75.88	<**0.0001**
Object	0.77		50.15	<**0.0001**
Orientation^2	0.11		83.22	<**0.0001**
Residual	0.78			

Table 9: Results from linear mixed-effects (LME) model analysis for the naturalness rating difference as the dependent variable. The model estimates the parameters for the main effects and includes three random effects (for intercept, object, and squared orientation) to model the individual participant variation. The t-test and L ratio test results indicate the significance of the fixed effects and random effects, respectively. Significant effects ($p < 0.05$) are highlighted in bold. In the model, the baseline object was the pan, such that the estimated parameters for object are the additive effects for the jug.

	Parameter estimates for grasp location [mm]			
Fixed effects	Value	Std. Error	$t(307)$	p
Main effects				
Intercept	0.73	0.34	2.12	0.0351
Object	0.16	0.42	0.39	0.6960
Orientation	0.12	0.02	6.01	<**0.00005**
Orientation^2	0.09	0.05	1.72	0.0872
Random effects	Std. Deviation		L ratio	p
Intercept	1.05		96.89	<**0.0001**
Object	1.28		117.43	<**0.0001**
Orientation^2	0.16		157.96	<**0.0001**
Residual	0.80			

nor squared orientation was a significant fixed effect for either perceptual rating. The intercept, object, and squared orientation were all significant random effects, indicating the high degree of individual variance. The lack of a consistent trend among the participants may be due in part to the variation in self-reporting of the perceptual response.

Overall, the mean regression curves fitted from the LME model are similar for both the comfort and naturalness ratings (Table 8). The differences of the unimanual constraint trials relative to the object motion constraint trials were primarily non-negative. This illustrates that the performance of the lifting task trials was more comfortable and more natural when preparatory object adjustment was permitted compared to when it was not permitted.

For both perceptual ratings, linear orientation was a significant factor such that the smallest differences in perceived comfort and naturalness occurred around orientation 7. This may be due to the difference in the rotation direction for starting initial handle orientations on the left side (orientations 1-4) and right side (orientations 5-8) of the central orientation (Fig. 5). Even though the object handle is rotated toward the central region, the unimanual constraint requires the dominant right hand to contact the object. When the handle starts on the left side, participants tended to rotate the object by contacting the handle with an extended wrist, while the wrist was flexed when rotating object handles from the right side. This quality of the object rotation may have influenced the participants' perception of the lifting task, even though the asymmetry was not reflected in the object rotation trend (Fig. 6).

5 Discussion

Overall, we have found that the preparatory rotation of heavy objects increases with the change in handle orientation away from the central preferred direction. When participants are instructed not to pre-rotate the object prior to liftoff, they are still able to successfully complete the lifting and transport task. However, without adjusting the object orientation prior to lifting, participants performed the lifting task with different body poses with tilted torsos and extended elbow positions in order to reach the object handle. In a comparison of the unimanual constraint trials to the object motion constraint, the differences in the joint torque metric and grasp configuration in the object frame computed from the body pose at liftoff follow a quadratic trend. This suggests that the preparatory object adjustment may be desirable because it allows the object lift to be performed with lower joint torque load in the upper body and/or with a preferred grasp of the object handle.

Our experiments investigated the preparatory object adjustment in the specific context of right-handed lifting and lateral transport across the body. We focused on the effect of the initial object orientation on the selected body posture at object liftoff, but several other factors may affect the preparatory manipulation. We would expect similar adjustment strategies in other tasks with different constraints. For example, changing the location of the goal may result in a shift in the region of handle orientations at liftoff. Other task constraints to consider include whether the object contact is performed with the right or left hand and timing restrictions for the completion of the task.

In particular, the difficulty of the task is expected to influence the degree of object adjustment. A small number of participants performed additional lifting trials for an extra object. For a lightweight cooking spatula, there was limited object rotation observed across the different handle orientations. Perhaps the ease of grasping the lightweight tool from its presented configuration did not warrant the cost of adjustment before lifting. In another example, two participants performed the lifting tasks for a plastic can whose handle geometry required specific placement of the thumb and fingers for a successful lift. The weight of the can when filled with water was similar to that of the filled jug and pan tested in the experiments. For this extra object, we observed similar amounts of object rotation as was observed for the jug and the pan. A possible future experiment might test the object rotation response to weight by changing the water level in the jug between different trials.

Our analysis focused on the difference in performance in terms of metrics computed from the single time frame defined by the object liftoff. The body pose at liftoff was chosen as a representative snapshot of the performance. It may be of interest to analyze performance metrics over the entire trial for a dynamic analysis of the motor task. In addition, an altered methodology designed for specifically measuring the time course of the different movement segments would allow for extended inquiry of the cognitive models for planning and evaluating alternative manipulation strategies.

The preparatory rotation strategy in response to lifting heavy object from different handle orientations is one example of how object configuration is adjusted in addition to the postural response. Preparatory rotation may also be a strategy used for in-hand manipulation of tools, such as wielding a hammer or bringing a fork into the grasp. For in-hand manipulation, the preparatory adjustment may depend highly on the final task intent more so than the difficulty of lifting the tool. Future directions for research also include the study of different preparatory manipulation strategies in context of other tasks. In addition to handle rotation, adjustment may include sliding, rolling, or tumbling maneuvers which re-configure the object to a more desirable state.

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References

Bongers, R. M., Michaels, C. F., & Smitsman, A. W. (2004). Variations of tool and task characteristics reveal that tool-use postures are anticipated. *Journal of Motor Behavior*, *36*(3), 305–315.

Chang, C. C., Brown, D. R., Bloswick, D. S., & Hsiang, S. M. (2001). Biomechanical simulation of manual lifting using spacetime optimization. *Journal of Biomechanics*, *34*(4), 527–532.

Chow, C. K., & Jacobson, D. H. (1971). Studies of human locomotion via optimal programming. *Mathematical Biosciences*, *10*(3-4), 239–306.

Clauser, C. E., McConville, J. T., & Young, J. (1969). Weight,volume and center of mass of segments of the human body. Tech. Rep. AMRL-TR-69-70, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio., Antioch College, Yellow Springs, OH.

Desmurget, M., Prablanc, C., Arzi, M., Rossetti, Y., Paulignan, Y., & Urquizar, C. (1996). Integrated control of hand transport and orientation during prehension movements. *Experimental Brain Research*, *110*(2), 265–278.

Dysart, M. J., & Woldstad, J. C. (1996). Posture prediction for static sagittal-plane lifting. *Journal of Biomechanics*, *29*(10), 1393–1397.

Engelbrecht, S. E. (1997). *Minimum-torque posture control*. PhD thesis, University of Massachusetts Amherst, Psychology. AAT 9721446.

Fischman, M. G. (1998). Constraints on grip-selection: minimizing awkwardness. *Perceptual and Motor Skills*, *86*(1), 328–330.

Jeannerod, M. (1981). *Attention and performance*, chap. Intersegmental Coordination During Reaching at Natural Visual Objects, (pp. 153–169). Hillsdale, NJ: Lawrence Erlbaum Associates.

Johansson, R. (1996). *Hand and brain: The neurophysiology and psychology of hand movements*, chap. Sensory control of dexterous manipulation in humans, (pp. 381–414). New York: Academic Press.

Latash, M. L., Gelfand, I. M., Li, Z. M., & Zatsiorsky, V. M. (1998). Changes in the force-sharing pattern induced by modifications of visual feedback during force production by a set of fingers. *Experimental Brain Research*, *123*(3), 255–262.

Li, Z. M., Latash, M. L., & Zatsiorsky, V. M. (1998). Force sharing among fingers as a model of the redundancy problem. *Experimental Brain Research*, *119*(3), 276–286.

Pinheiro, J. C., & Bates, D. M. (2000). *Mixed-effects models in S and S-PLUS*. New York: Springer.

R Development Core Team (2008). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org.

Rand, M. K., & Stelmach, G. E. (2005). Effect of orienting the finger opposition space in the control of reach-to-grasp movements. *Journal of Motor Behavior*, *37*(1), 65–78.

Rosenbaum, D. A., & Gaydos, M. J. (2008). A method for obtaining psychophysical estimates of movement costs. *Journal of Motor Behavior*, *40*(1), 11–17.

Rosenbaum, D. A., Marchak, F., Barnes, H. J., Vaughan, J., Slotta, J. D., & Jorgensen, M. J. (1990). *Attention and Performance XIII: Motor Representation and Control*, chap. Constraints for Action Selection: Overhand Versus Underhand Grips, (pp. 321–342). Hillsdale, NJ: Lawrence Erlbaum Associates.

Rosenbaum, D. A., Vaughan, J., Barnes, H. J., & Jorgensen, M. J. (1992). Time course of movement planning: selection of handgrips for object manipulation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*(5), 1058–1073.

Rosenbaum, D. A., Vaughan, J., Jorgensen, M. J., Barnes, H. J., & Stewart, E. (1993). *Attention and performance XIV - A silver jubilee: Synergies in experimental psychology, artificial intelligence and cognitive neuroscience*, chap. Plans for object manipulation, (pp. 803–820). Cambridge: MIT Press, Bradford Books.

Short, M. W., & Cauraugh, J. H. (1997). Planning macroscopic aspects of manual control: end-state comfort and point-of-change effects. *Acta Psychologica*, *96*(1-2), 133–147.

Stelmach, G. E., Castiello, U., & Jeannerod, M. (1994). Orienting the finger opposition space during prehension movements. *Journal of Motor Behavior*, *26*(2), 178–186.

Turvey, M. T., Shockley, K., & Carello, C. (1999). Affordance, proper function, and the physical basis of perceived heaviness. *Cognition*, *73*(2), B17–B26.

Verbeke, G., & Molenberghs, G. (2000). *Linear mixed models for longitudinal data*. New York: Springer.

Zhang, W., & Rosenbaum, D. A. (2008). Planning for manual positioning: the end-state comfort effect for manual abduction-adduction. *Experimental Brain Research*, *184*(3), 383–389.