Pre-grasp interaction for object acquisition in difficult tasks

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Abstract

In natural manipulation activities of daily living, actions for object grasping must respect several constraints for successful task completion. For example, grasping actions must satisfy at a minimum the reachability of grasp contacts on the object surface, collision avoidance with obstacles, as well as kinematic and strength limits of the hand. In challenging manipulation scenarios with high constraints, direct reaching actions to grasp the object in place may not be sufficient for object acquisition. We have observed that humans use *pre-grasp interaction* to adjust the object placement during the grasping process. For example, an object may be slid or tumbled on its support surface before the final grasp contacts are achieved. In this chapter we provide an overview of the variety of pre-grasp actions that we have observed from a video survey of human manipulation activities in natural home and occupational environments. We also present our studies of object reorientation by rotation, as a particular type of human pre-grasp interaction. Finally we also examine the utility of pre-grasp rotation for increasing object reachability and grasp reuse for a robot manipulator.

Index Terms

Pre-grasp interaction, manipulation, rotation, pushing, daily activities, task difficulty

I. INTRODUCTION

HUMANS typically use a few prototypical reaching and grasping actions to pick up objects during manipulation tasks. However, in daily life, humans must grasp objects from a variety of initial configurations, including many that may not be well-matched to canonical grasps and the arm approach directions. Observation of human grasping reveals that humans do not always grasp an object directly from its presented placement in the environment. Instead, humans often manipulate the object to adjust its configuration prior to grasping. For example, a person might slide a mug on a table closer to the body by pulling on the handle with unidirectional or non-grasping contact. When grasping a pen from a table surface, the fingers may quickly pivot the pen to orient the tip for the subsequent writing task.

These are examples of what we refer to as *pre-grasp interaction*. Pre-grasp interaction occurs whenever the manipulation first adjusts the object configuration prior to the final grasp. In several cases, the adjustment may occur while the object is partially supported by the environment, such as a table surface (Fig. 1(a)). This approach takes advantage of the object's movability on the supporting structure to effectively change the intermediate task parameters. Thus the anticipation of the grasping task includes object reconfiguration as a motion in addition to the arm reaching and hand pre-shaping movements.

[Fig. 1 about here.]

This chapter includes a description of typical types of pre-grasp interaction from our survey of human hand activity in natural settings. In the observational survey, we recorded video of people performing manipulation tasks in natural settings such as the home or place of occupation. The activities included tasks such as sorting office supplies, washing dishes, and moving furniture. We organized the survey examples into a framework that describes a pre-grasp interaction by the object reconfiguration and the task constraint that is modified. This framework provides

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the broad context of pre-grasp interaction strategies in which the specific example of pre-grasp object rotation is situated.

We also present studies of pre-grasp object rotation as a specific pre-grasp interaction strategy used by humans for manipulating objects by their handles. In our experiments on grasping familiar household objects in a kitchen setting, the action in anticipation of a grasp not only consisted of changes in the manipulator's posture such as arm reaching movement and hand pre-shaping, but it also included re-orientation of the object to reach its grasp handle. However, the pre-grasp object rotation occurred primarily when the task constraints were strict. That is, pre-grasp rotation was observed when the actions were restricted to one-handed object grasps, the object were heavy, and the post-grasp transport task required precision constraints on the object orientation. In a second study of pre-grasp rotation, the task difficulty factors of object mass and task precision were shown to decrease the variation in choice of object lifting orientations that resulted from pre-grasp rotation.

We observed in our human studies that it was often feasible to complete the instructed task by direct grasping without pre-grasp object adjustment, especially when the path to the hand is unobstructed by clutter in the environment. However, we also found that the hand grasp on the object changed when using the direct grasping strategy in these restricted maneuvers (Fig. 1(c)). The change in grasp may have accommodated the increased difficulty of reaching the object handle in the orientation outside a "comfort zone" suited to canonical reach-to-grasp actions while simultaneously avoiding the object as an obstacle. When a specific grasp of the object handle is required for the primary task, pre-grasp interaction such as object rotation may be utilized more frequently to achieve the desired grasp. In Section V, we present a kinematic analysis and experimental validation of the utility of pre-grasp rotation for re-using robust grasps on a robot manipulator.

The studies reviewed in this chapter represent an initial investigation of pre-grasp interaction strategies, with a specific focus on pre-grasp rotation. We conclude with a discussion in Section VI on directions for further examination of other types of human pre-grasp interaction that could inspire new robot manipulation strategies.

II. Related work

Many approaches to automating robot motion for object acquisition have focused on reach-to-grasp tasks, where the arm motion and hand configuration are planned for grasping an object. With these solutions, the object placement often remains fixed in the environment until the object is carefully grasped from its presented configuration. In contrast, humans often take advantage of an object's movability to reorient and regrasp an object during the acquisition process. Specifically we studied the strategy of pre-grasp object rotation for grasp acquisition prior to a transport task. The presented ideas build upon related work in human manipulation (§II-A) and human motor control (§II-B), which we review here.

A. Kinematic patterns in human manipulation

One contribution of this work is a framework for describing the types of pre-grasp interactions naturally used by humans in everyday tasks. The intent of the study is to provide insight and structure for understanding the complexity and variety of hand skills.

The dexterity of human manipulation has similarly motivated many researchers to understand the structure and motion of the human upper limb. The structural complexity of the human upper limb is both a source of its flexibility and an obstacle for understanding the biological mechanisms for control. Often the human arm is kinematically modeled with 7 degrees of freedom (DoFs) describing the shoulder (3-DoF), elbow (1-DoF), and wrist (3-DoF) joints. The redundancy allows multiple arm configuration solutions for a single configuration of the hand segment. In addition, the hand itself exhibits more than 20 DoFs for the palm, thumb, and finger joints. An overview of basic hand anatomy and function can be found in Napier [1993].

The high-dimensional kinematics allow for a wide variety of possible hand configurations. However, biomechanic and neuromuscular constraints suggest there are coordinated patterns underlying the apparent complexity. One approach to identifying such patterns has focused on categorizing hand poses as discrete grasp types. Napier [1993] proposed a basic taxonomy of power grasps and precision grasps, which are distinguished by contact with the finger or palm surfaces versus the finger tips. More detailed taxonomies have been used to describe functional grasps for activities of daily living [Edwards et al., 2002; Kamakura et al., 1980] as well as for skilled machining tasks

[Cutkosky, 1989]. Although a large variety of possible hand postures given the different joint configurations of the fingers, a smaller subset may be sufficient to complete a classes of daily or occupational tasks [Zheng et al., 2011].

In another approach, studies from the motor control community provide evidence that hand motion can be described as combinations of low-dimensional synergies or components. Work by Santello et al. [1998] and Mason et al. [2001] found that mimed reach-to-grasp hand shapes can be represented by just a few principal components in the joint angle space. This reduction of the hand posture description has also been used as a method to efficiently plan grasp postures for artificial robot hands with high-dimensional kinematics by Ciocarlie and Allen [2009a].

The survey of hand skills in §III provides a framework for describing pre-grasp manipulation as a set of manipulation skills beyond direct grasping. Pre-grasp manipulation involves object reconfiguration in the environment and thus cannot be described only by the hand pose as classified in grasp taxonomies.

B. Human motor synergies

The first portion of the chapter (§IV, IV) investigates the pre-grasp rotation strategy as a human behavior for manipulation tasks. The work contributes a study of pre-grasp manipulation to the field of human motor behavior and control.

Pre-grasp manipulation can be viewed as a coordinated pattern of movement for a certain class of manipulation tasks. Previous literature in the motor control community has already identified consistent patterns of human motion for the actions of reaching and grasping. Jeannerod [1981] has investigated the coordination between arm reaching motion and hand pre-shaping. The experiments analyzed timing correlation of the hand trajectory toward the object with the hand shape and also investigated the effects of sensory input during the reaching task. Lacquaniti and Soechting [1982] investigated the degree of coupling between the joints of the upper limb, and they found that shoulder and elbow but not wrist in particular were highly coupled during the tested reaching tasks. The research on grasp synergies by Santello et al. [1998] and Mason et al. [2001] demonstrated the low-dimensional variation in hand shape in response to different object geometries. Furthermore, Lukos et al. [2007] showed that hand grasp shape, as measured by fingertip contact points on the object, responded not just to object geometry but were also modulated in anticipation of asymmetries in the location of the object's center of mass.

Coordination of the hand for grasping also involves the regulation of force and compliance in addition to kinematic configuration. Johansson [1996] investigated how finger grip force magnitude responds to object surface friction. The experiments of Li et al. [1998] and Latash et al. [1998] suggest the existence of motor synergies in the force output of individual fingers, where force sharing patterns between digits in a multi-finger grasp address the motor redundancy of an overactuated system. The patterns of anticipatory contact point modulation in the hand grasp shape [Lukos et al., 2007, 2008] may be chosen to better reject force or torque disturbances during the grasp [Ciocarlie and Allen, 2009b].

A consistent pattern of coordination represents a particular subset of the full set of movements possible by a redundant and over-actuated system. One approach to understanding the selection of particular strategies is to describe manipulation actions by the optimization of some cost criteria. Previous studies of possible optimization criteria of arm control have investigated minimum jerk [Flash and Hogan, 1985] and minimum torque change [Uno et al., 1989] for arm motion trajectories. In addition, work in the biomechanics community has examined how static postures for lifting tasks may be predicted by energy or effort costs [Dysart and Woldstad, 1996; Chang et al., 2001]. For certain tasks such as one-handed lifting motions [Park et al., 2005], humans may select between multiple movement strategies according to individual preference or capabilities. In two-handed lifting tasks, the selection between either a stooping or squatting whole-body lifting posture may depend on factors such as individual height or strength [Burgess-Limerick and Abernethy, 1997].

The work discussed in §IV and §IV contributes to the literature by demonstrating the consistent pattern of pre-grasp rotation in humans and examining factors which affect the strategy selection. In particular, our work extends the understanding of human behavior to task domains where more complicated actions are performed. For tasks where the object is easy to grasp, a direct reach-to-grasp action may be sufficient. However, more difficult tasks may require or encourage the use of pre-grasp interaction as a more successful manipulation strategy. We show that humans use pre-grasp object rotation for demanding tasks involving heavy objects and strict angular precision requirements when the object is presented with the handle in a non-canonical orientation relative to the person's body.

III. Pre-grasp interaction in natural activities

For single objects placed in uncluttered environments, the object acquisition process may consist of only a direct reaching motion by the arm coordinated with the closing motion of the fingers that achieves a final stable grasp. However, the task conditions encountered in daily life can render a manipulation task more difficult, such as when the target object is in a tight space or near obstacles, or when the target object requires specific grasping points due to its weight, size, or shape. Figure 1(a) illustrated one example of how *pre-grasp rotation* re-orients a cooking pan as part of the acquisition process such that the handle is easier to reach.

This section describes further examples of *pre-grasp interaction* observed in a video survey of human hand activity in natural settings. We discuss the survey examples by two main attributes, the object reconfiguration and the task constraint that is modified, to illustrate the richness of how pre-grasp interaction is exhibited is in routine manipulation tasks. These examples provide a broad context of pre-grasp interaction strategies. The remainder of the chapter examines the specific example of pre-grasp object rotation as a representative example.

A. Video survey of natural pre-grasp interactions

Our goal was to identify attributes for classifying the variety of pre-grasp action primitives which are integrated into complex reach-to-grasp tasks. We were specifically interested in surveying human hand activity in natural settings in contrast to instructed tasks within a laboratory environment. In this way, we could capture the richness of pre-grasp interactions beyond the direct reach-to-grasp actions studied previously in the literature.

In the video survey of human hand activity, we filmed people performing manipulation tasks in natural settings such as the home or place of occupation. All participants provided informed consent. In all observations, the participants performed manipulation skills which had been practiced previously as part of their regular occupation. There were a total of 10 sessions of both individual and group manipulation activities, such that overall 38 people were filmed. The sessions covered a total of 165 minutes of filmed activities for housekeeping, food preparation, office work, and mechanical repair. Specific tasks include sorting office supplies, washing dishes, and moving furniture.

The video footage was reviewed specifically for pre-grasp interaction motions. In this context, we considered pre-grasp interaction to be any manipulation that reconfigures the object for a subsequent interaction when the task does not specify the reconfiguration. This definition allows for a broad concept of pre-grasp interaction as any "preparatory action" on the object prior to the final task phase. In this sense, many multi-step operations or complex manipulation processes inherently include pre-grasp interaction between the initial presented task conditions and the final primary interaction required for task completion. All actions that do not include pre-grasp interaction are referred to as "direct" manipulation strategies. Direct interactions consist of only the primary interaction that achieves the task goal.

We found that there is indeed a broad class of pre-grasp interactions where the object is not grasped directly from its presented placement in the environment. Our survey included observations from a range of manipulation scales from the in-hand manipulation to whole-body grasps. Examples of the different interaction scales observe include:

- unimanual grasp of a writing utensil,
- bimanual grasp of a large pot,
- whole-body grasp of large box making contact with the upper arm and torso, and
- cooperative manipulation between multiple agents for lifting a piece of furniture.

The scale of interaction is partially related to the object size and mass, because larger and heavier objects are likely to require wider grasp apertures and contact forces for manipulation. For example, objects manipulated purely by unimanual contact are expected to be smaller or lighter than objects handled in cooperative manipulation between two people. In addition, we observed that larger scale interactions also often included additional contact with the environment that effectively was an extension of the manipulator. This scenario often occurs when there is non-prehensile, or non-grasping, contact with the object, as in the case of pushing of an object which is supported against gravity by a table.

In the next sections, we describe the observed examples according to two aspects: (1) the object reconfiguration and (2) the pre-grasp intent relative to the primary task goal. Without either component, the interaction is instead a direct manipulation where there is only manipulator reconfiguration prior to the primary interaction. Note that the primary interaction may include object reconfiguration (such as in lifting or pushing), which is distinct from pre-grasp reconfiguration if the task explicitly specifies the motion.

B. Categorization by object reconfiguration

First, the pre-grasp object reconfiguration can be described according to the degrees of freedom which are reconfigured by the pre-grasp interaction. For example, the object motion may be completely comprised by planar displacement. This case is common in instances of non-prehensile pre-grasp interaction where the object is primarily supported on a horizontal surface. Alternatively, for a bulky piece of furniture, the pre-grasp tumbling interaction may result in general 6-degree-of-freedom rigid displacement. In more complex cases, the pre-grasp interaction may cause a morphological reconfiguration of a deformable or articulated object, such as a bucket with a hinged handle.

The main patterns of object reconfiguration observed in our survey were:

- Planar displacement – Rigid planar displacement consisting of 3-DoFs of 1-DoF in-plane rotation with 2-DoF in-plane translation is commonly observed for interactions where the object is supported on a flat surface such as a table. Pre-grasp planar displacement can also occur in the manipulation of stacked objects, such as removing the top stacked book by sliding (Fig. 3(a)).
- Rigid displacement – General 6-DoF rigid displacements include pivoting or tumbling out of the horizontal support plane. For example, a piece of furniture may be tumbled in order to reach a particular handhold before transporting (Fig. 3(b)).
- Morphological reconfiguration – Pre-grasp interaction can also change the shape of an articulated or deformable object. The change in shape may create a better hand-hold for a desired grasp, as in the case of reorienting the handle of a bucket before lifting (Fig. 3(c)). Morphological reconfiguration may also include the manipulation of a set of objects which are separate but conceptually linked to each other, as in a pile of homogeneous objects such as game tokens or an assembly of multiple objects such as a container with a matching lid.

It is assumed that the reconfiguration does not violate any specified task constraints. In fact, the motion should improve a presented object configuration that is suboptimal. This assumed improvement in the object configuration is related to the intent of the pre-grasp manipulation.

Figure 2 presents a taxonomy for classifying pre-grasp interaction instances by the degrees of freedom which were adjusted by the reconfiguration. Typical objects for each sub-class based on the observed examples from the video survey. Note that there were several examples of non-rigid pre-grasp reconfigurations for deformable objects or sets of multiple objects. This suggests that the pre-grasp interaction strategy is particularly relevant for describing more difficult object acquisition tasks that involve more than grasping a single rigid object.

[Fig. 2 about here.]

[Fig. 3 about here.]

C. Categorization by intended change in task constraints

Second, a pre-grasp interaction can be described by the intent of the object adjustment in relation to the final grasp. The intent of a pre-grasp interaction is described as the benefit of the object reconfiguration relative to the primary interaction. The presented object configuration in the initial task conditions may be suboptimal with respect to the environment, manipulator, or object. These constraints are described in terms of how they limit the final grasp if only direct grasping without pre-grasp interaction is used.

- Environment constraints – In the initial configuration, the desired contact surface on the object could be unexposed or blocked by an obstacle in the environment. The obstacle in the environment could be the supporting structure if the desired grasp requires contact with the object's bottom surface. This case occurs when a sheet of paper resting on a surface is to be grasped on both faces (Fig. 3(d)). Clutter in the environment may also block the approach to a desired contact area.
- Manipulator constraints – Given the initial configuration of the manipulator relative to the object, a desired grasp of the object could be limited by a suboptimal manipulator posture using direct reaching. For example, a direct grasp may require an arm posture associated with low kinematic manipulability. A person may prefer

to reorient an object using bimanual regrasping while maintaining manipulability in both arms rather than reaching across the body with one hand if it requires a near-singular arm posture (Fig. 3(e)). Other factors which might affect the preference for a particular manipulator posture include torque capability constraints and grasp stability.

- Object constraints – In some situations, the presented object morphology may not afford the desired grasp contacts or may have less desirable physical properties. The reshaping of an articulated object for grasping, such as the previous example of the bucket handle (Fig. 3(c)), is similar in intent to overcoming environmental constraints because the ungrasped object subparts are obstacles to the grasped subpart. In the bucket example, the reconfiguration also changes the grasp location relative to the object's center of mass. Pre-grasp manipulation may also gather deformable materials or a set of multiple objects into a compact shape more suitable for grasping. An example of this case is the scooping of food scraps into a cupped hand (Fig. 3(f)).

The different constraints addressed by the pre-grasp intent are not necessarily mutually exclusive. In the example of bimanual regrasp of a pan by its handle (Fig. 3(e)), the intent of the pre-grasp action could be a combination of avoiding environment clutter and using an arm posture with improved manipulability.

The presented configuration of the object in the environment could be suboptimal for direct reach-to-grasp object acquisition due to preferences for a particular body posture and/or grasp. When the handle on a cooking pan is oriented away from the person, a direct grasp of the handle may be feasible but could require lifting the heavy pan from an uncomfortable body posture with limited lifting capability. In other scenarios, the intent of the pre-grasp interaction may be to improve the grasp quality rather the posture quality. This grasp improvement is especially relevant to situations where environmental clutter occludes the desired grasp contact surfaces, as in the case of a shelved book where only the spine is exposed in the initial task condition. The observed examples suggest that the intent of pre-grasp interaction was often a combination of preferences for both posture quality and grasp quality, and potentially other optimization metrics that influence the constraints described above.

D. Discussion

The presented pre-grasp interaction framework suggests several approaches for improving the dexterity of robotic manipulators. Taking advantage of object movability may extend the effective workspace by changing the environmental constraints when direct reach-to-grasp actions are of insufficient posture and/or grasp quality. Non-prehensile pre-grasp interaction could reduce the load on the manipulator by using shared support with the work surface during the initial interaction with the object. Moreover, the expense of tuning control parameters for complex manipulators can be reduced if pre-grasp object reconfiguration enables the reuse of a single well-tuned grasp action for multiple initial placements. Finally, because pre-grasp strategies are part of natural human manipulation, incorporating them in the repertoire of assistive or teleoperated manipulators could facilitate more intuitive control for human operators.

IV. HUMAN PRE-GRASP ROTATION

The previous section presented examples of a broad set of human pre-grasp interaction strategies. In this section we describe a series of studies on human performance of pre-grasp object rotation. Pre-grasp object rotation is a specific example of planar pre-grap adjustment, where the object displacement occurs in the plane of the support surface. The first set of studies examines the consistency of the pre-grasp rotation patterns for human interaction with familiar household objects. The second set of studies demonstrate how the selected object orientation after pre-grasp rotation depends on the task difficulty, as measured by object mass and balance constraints.

A. Action adaptation to changes in object orientation

Movable objects often can be pushed or dragged along a tabletop surface using hand contacts that are less constrained than those for lifting grasps. For example, a person can use the fingers without the thumb to hook and drag a mug by its handle or to push a box to one side, and the table surface supports the weight of the object. In contrast, the hand interaction used to lift the same objects must use both thumbs and fingers in grasping, or prehensile, contact in order for the hand to fully support the load against gravity.

In general, planar sliding actions involve 3-degrees-of-freedom displacements of the object: two freedoms of translation in the plane of the surface, and one freedom of rotation around the axis normal to the plane. One subset of sliding actions are 1-degree-of-freedom rotations around a pivot axis of the object. In this chapter, pre-grasp rotation refers to pre-grasp interactions where the sliding is dominated by planar re-orientation of the object with little translation movement. In particular, pre-grasp rotation is useful for describing interactions with household objects that have a single asymmetric handles, such as mugs, pitchers, and pans.

In this section we highlight our observations of pre-grasp rotation that motivated the studies described later in Sections IV-B and V. Pre-grasp interaction strategies such as pre-grasp rotation appear to be most relevant in tasks that are more constrained or more difficult. In such tasks, pre-grasp interaction appears to enable reuse of canonical grasping actions for successful task completion, described in §IV-A1. Task constraints that affect the difficulty level can include the available freedoms of the manipulator, as well as object-centric task parameters such as weight and balance precision, described in §IV-A2.

1) Grasp choice changes without pre-grasp rotation: This study investigated how humans would adapt their manipulation actions in response to changes in object orientation and under different strategies. The primary results from the study suggest that pre-grasp rotation is used to adjust object placement in the world for reuse of "canonical" grasping postures at the time of object lift-off from the surface. In contrast, when participants were restricted to a direct grasping strategy without pre-grasp object adjustment, there was larger variation in the body postures and hand grasp shapes used to lift the objects.

The experiments recorded how people complete an object transport task that included choices in both upper body posture and lower body position relative to the task space. Participants started and remained standing during the transport task. In the starting position, participants faced a kitchen countertop structure and an object placed on the right side of the counter. The transport goal location was a marked area on the left side of the counter, which required participants to move the object laterally from right to left. All 10 adult participants (5 male, 5 female) were right-handed and provided informed consent. The protocol encouraged as natural behavior as possible by allowing the participants to select the standing position(s) before the counter, the movement speed, the grasp points on the object, and the orientation of the object at the goal location. Body posture, hand shape, and object pose were recorded during the transport task using a marker-based camera system. Here we describe the main responses to the experiment variables of initial object orientation and grasping strategy. Additional details of the participant pool and experimental protocol can be found in Chang et al. [2008] and Chang and Pollard [2008].

The two objects tested in the experiments were a large plastic water jug and a cast iron frying pan. The objects were filled with water to a total mass of 3.4 kg for the jug and 1.5 kg for the pan. Within a set of 8 trials, the objects were placed at the same start location on the right of the counter, in one of 8 orientations for a uniform discretized of possible handle directions. The region for "canonical object orientations" within a participant's comfort zone was hypothesized to contain the orientations where the handle was pointing toward or to the right of the participant.

Two strategy constraints were tested on the transport task: unimanual lifting, and unimanual lifting without sliding. In the first case, participants were instructed to complete the transport task using only their right hand to contact the object. Except for this unimanual constraint, there were no restrictions on the task performance. We hypothesized that participants would use some amount of pre-grasp interaction in response to object orientations outside the comfort zone. However, the verbal instructions did not suggest pre-grasp object motion as a strategy, in order to capture the participants' natural unimanual strategy. Two sets of 8 trials were completed per participant and per object. In the second set of trials, participants were instructed to transport the object with the right hand and without any lateral sliding on the surface prior to lifting the object from the start position. Participants were able to abort the trial at any time if lifting the object from its presented orientation was perceived to be too difficult or uncomfortable.

For each trial, the time of object lift was determined by the frame where the upward object displacement first exceeded 1 cm. The participant upper body posture and hand shape at this lift-off time point are together referred to as the *grasping posture*, where the object load is fully supported by the grasp and not the table surface. The object orientation at this lift-off point is referred to as the *lift-off object orientation*. The lift-off object orientation is used to compute the amount of pre-grasp object rotation in a trial relative to the starting object orientation.

The results compared the participants' grasping postures between the two strategy constraint cases. Under both constraints, there was no or little pre-grasp rotation when the object handle started in an orientation facing or to the right of the participant. The grasping postures used for these orientations in the comfort zone represent the canonical grasping postures that are used when direct grasping is sufficient and preferred.

In the unimanual case where pre-grasp interaction was implicitly allowed, the grasping postures were similar for different starting object orientations due to pre-grasp object rotation that adjusted the handle direction to be within the comfort zone. In particular, the type of hand shapes used to grasp the object handle were similar within trials for a single participant. For the jug, participants had individual preferences for grasping the upright handle with the palm facing either to the left side or toward the jug body. For the pan, participants had individual preferences for using either an oblique underhand grasp of the handle (Fig. 1(b)) or a straight overhand grasp.

In contrast, under the unimanual constraint without pre-grasp rotation, participant completed the task with new grasping postures for direct grasping in response to the 8 object orientations. Only one participant chose to abort a lifting trial, and otherwise the transport task was completed in all object orientation conditions. To reach the object handle when it faced to the side or away, several participants leaned their upper torso over the object and/or held their elbow out. Furthermore, the hand grasps changed for these direct grasping trials (Fig. 1(c)), unlike the grasp reuse observed in the cases with pre-grasp rotation (Fig. 1(b)). Quantitative results describing the degree of grasp changes can be found in Chang et al. [2008].

The results from this study suggested that grasp reuse was preferred to new grasping plans because the new grasping plans only appeared when the participants were instructed to restrict their natural pre-grasp interaction for object adjustment. The objects tested in this study would be considered heavy or difficult to lift for one-handed manipulation. The next section briefly describes task situations where there was diminished pre-grasp rotation relative to direct grasping. The examples observed on typical household objects motivated the studies described in §IV-B.

2) Response to different objects and task constraints: Here we highlight some informal observations about how task difficulty affects pre-grasp rotation choices. In the study described above in §IV-A1, the difficulty of the object transport task was characterized by multiple aspects. First, the available degrees of freedom from the arm and/or body joints determine the range of reachable grasping postures. Second, the object weight limits which grasping postures are sufficient for lifting off the table surface. Third, the task constraints on the primary task after lifting, such as the object transport to the goal, further limit which initial grasping postures are preferred after pre-grasp interaction. Our observations suggest that pre-grasp interaction strategies have more utility, and thus would be selected more frequently, when a task has greater difficulty.

The available degrees of freedom for the transport task in §IV-A1 consisted of the standing position, the torso orientation, and the right arm and hand. The transport task difficulty is lower when there are more available degrees of freedom that allow for a wider range of grasps. In the experiments with the jug and pan transport tasks (§IV-A1), participants were first familiarized with the task space during a few practice trials where there was neither a unimanual constraint nor a non-sliding interaction constraint. In these practice trials, several participants lifted the objects from the start position using two-handed grasps, where the right hand grasped the handle while the left hand supported an opposing surface. With these bimanual grasps, participants appeared to use less pre-grasp sliding and instead more direct grasping of the object from the surface.

The object properties can also affect the difficulty of a transport task, for example by the object weight or the location and shape of the handle. In the above experiments, pre-grasp rotation was observed for two objects with different handle characteristics, as the jug's handle axis was near vertical while the pan's handle was near horizontal. Further investigation is required to determine whether task difficulty could be quantified from object shape properties that affect allowable grasps. Object weight also can affect the allowable grasps for completing a manipulation tasks. A grasp that is sufficient for a lightweight object may not be able to support a heavier object. The jug and pan could be considered heavier objects, making the transport task more difficult such that pre-grasp interaction was necessary to obtain a desired grasp of the handle. In contrast, when a few participants completed the transport task in §IV-A1 for a lightweight spatula tool, we observed more direct grasping and less pre-grasp rotation. Figure 4 shows an example of the pre-grasp rotation results for the jug, pan, and spatula objects for a pilot study participant.

[Fig. 4 about here.]

Another aspect of task difficulty is constraints on the primary manipulation task that occur after the initial object acquisition from the support surface. One constraint that is common to the transport of container objects is the requirement to maintain the object in an upright position to avoid spilling its contents. This constraint can be cast as a tolerance or precision requirement on the angular deviation from the upright orientation. A task with lower tolerance would be considered more difficult. This constraint can affect the selected grasping postures after pre-grasp rotation because the grasping posture not only must support the object at the time of lift off but must also be able to maintain a stable grasp orientation over the duration of the following transport motion. For example, the transport of an empty jug does have a high orientation tolerance, and the decreased task difficulty may allow a wider range of grasping postures that are reachable without pre-grasp object rotation.

The following sections reviews the results of an experiment which quantifies formally how the task difficulty factors of object weight and required angular precision affect the usage of pre-grasp object rotation.

B. Effects of task difficulty constraints

This experiment studied the effect of object weight and balance precision constraints on the grasping postures following pre-grasp rotation. In particular, we examine the effect of these task difficulty factors on the selected object orientations comprising the “comfort zone” of a person’s grasping postures. The previous study [Chang et al., 2008] illustrated that pre-grasp rotation enabled reuse of similar grasping postures, and these selected postures corresponded to object orientations where the handle faced toward participant’s right side. These lift-off object orientations represent the preferred “comfort zone” that is the goal of the pre-grasp object interaction.

As a preview of the results, this study showed that increased task difficulty resulted in a smaller comfort zone for preferred object orientations. In this study, the range of the comfort zone is quantified by the variation in a set of lift-off object orientations. A large variation in object orientations corresponds to large set of object placements where direct grasping would be sufficient for task completion. In contrast, a small variation in selected orientation corresponds to a more constrained comfort zone that may require pre-grasp interaction to achieve.

The comfort zone for pre-grasp rotation was measured for a two-handed token retrieval task. Participants lifted a canister by their right hand to uncover a token that was then retrieved by their left hand. The token retrieval required that the grasping posture support the object weight by lifting the canister. Additionally, an upright orientation constraint was imposed with a ball balance apparatus on the canister lid. As in the previous study described in §IV-A1, the object position and orientation was tracked using a marker-based system. The time of object lift-off from the surface was extracted as the key time-point for measuring the amount of pre-grasp rotation from the initial object orientation.

During the experiment, participants performed the token retrieval task with geometrically-identical canisters with different weight and balance precision levels. The canisters were color coded by weight and the precision level was visible by the balance apparatus size. These visual codings were reviewed before the task retrieval trials such that participants could perceive the task difficulty level before physical object interaction. There were 4 versions of the canister to test 2 levels of object weight and 2 levels of upright orientation precision. The two weight levels were 0.40kg (light) and 1.20kg (heavy). The two precision levels were controlled by using two diameters, 3.6cm (wide) and 0.8cm (thin), of the ball support ring for the balance apparatus. The wide ring allowed low precision in the upright orientation while still supporting the balanced ball, and the thin support required high precision in the orientation.

Twelve adults (6 male, 6 female) volunteered for the study, and all were right-handed by self-report. All participants signed informed consent forms approved by the Institutional Review Board of Carnegie Mellon University. Each participant performed the token retrieval task for all four canisters. A single task difficulty condition is defined by the combination of the object weight and the precision level. For each of the four task difficulty conditions, multiple trials were tested where the canister was presented with its handle in each of eight initial orientations. The comfort zone was measured for a single task difficulty condition by the average absolute deviation (AAD) from the mean of the 8 lift-off orientations. Further details of the experimental procedure and data analysis can be found in Chang et al. [2010].

The object weight and precision level were both significant main effects on the comfort zone variation measured by the lift-off angle AAD. For the least difficult task condition with the light object weight and wide balance support for high tolerance, the AAD from the mean lift-off orientation was 43.0 degrees. This least difficult task condition was considered the baseline condition in the regression model. Compared to the baseline condition, the lift-off orientation variability decreased by 4.6 degrees for increased object mass ($t(34) = -2.12$, $p = 0.0414$). The variability also decreased 12.9 degrees for increased angular precision ($t(34) = -5.90$, $p < 0.001$). The results show that the two task difficulty factors of object weight and precision level both affect the goal states of pre-grasp rotation in the token retrieval task.

In additional experiments described Chang et al. [2010], it was found that the selection of the grasping postures in the comfort zone was correlated with the maximum lifting capability of the whole body posture. The effects of object weight and precision level may be related to this relation between lifting capability and comfort zone. The weight of the heavy canister was closer to the maximum mass liftable by the reachable grasping postures for the initial object orientation. Pre-grasp rotation adjusted the object to a new orientation where there was greater lifting capability for robust task completion. Similarly, postures with increased strength for supporting a static load may be similar to the postures with increased control ability for maintaining the grasp orientation that holds the object upright.

Together these results suggest that pre-grasp interaction has the most utility in difficult manipulation tasks because the object adjustment enables strong grasping postures to satisfy the task constraints. In less difficult tasks involving lightweight objects or low precision motion, task completion may be possible with a smaller amount of pre-grasp interaction.

V. Robot grasp reuse using pre-grasp rotation

The studies of human pre-grasp rotation suggested that one utility of object adjustment is the reuse of preferred grasping postures. In particular, the comfort zone of liftable object orientations was more restricted when the manipulation task was subject to constraints on allowable grasps. These conditions influencing human pre-grasp interaction are also relevant to the actions of a robot manipulator.

In this section, we present a workspace analysis comparison between a human model and a robot model. Even though the robot manipulator has large range of motion in several of its joints, there may still be a limited range of object orientations that are reachable with a specific desired grasp. In these cases where no direct grasping posture can complete the task, pre-grasp rotation can extend the effective workspace of the robot's grasping action.

In addition, a complete grasping action for object acquisition includes, besides the target grasping posture itself, the reaching motion to achieve the desired grasping configuration. Pre-grasp rotation can also be applied for reuse of such grasping actions. This is demonstrated on an example object acquisition task for a anthropomorphic robot manipulator.

A. *Grasp workspace comparison*

A workspace analysis provides an estimate of the reachable object positions based on the kinematic degrees of freedom and joint limits of a manipulator. The goal of the analysis presented in this section is the comparison between an example human model and a robot manipulator. The reachable object positions from a purely kinematic analysis represent the maximum feasible comfort zone of graspable object poses. The observed comfort zone for performed actions may be smaller due to additional constraints such as environmental obstacles, strength restrictions, or neuromuscular preferences. For a robot manipulator, we refer to the possible graspable poses as the capture region rather than the comfort zone.

The workspace results for an example grasping task show that the capture regions for the modeled human grasps is qualitatively similar to that observed in the motion studies. The capture regions for the robot are of similar size but may be shifted in orientation. In particular, even though the robot manipulator has larger kinematic limits for some joints, there are still workspace areas with small capture regions for direct grasping. It is in these regions where pre-grasp interaction strategies such as object rotation offer gains in the manipulator performance.

1) Manipulator kinematic models: For both the human and robot manipulators, we consider the reachable grasps for only a single, right hand. Each manipulator is modeled as a serial chain of single-axis joints using the Denavit-Hartenberg (DH) convention for describing kinematic chains [see, e.g., Spong et al., 2006]. Specific details of the kinematic models' parameters can be found in [Chang, 2010].

The kinematic model of the human right arm consists of 10 degrees-of-freedom (DoFs) representing the kinematics of a chain consisting of a 3-DoF trunk, 3-DoF shoulder, 1-DoF elbow, and 3-DOF wrist joints. The model limits the joint rotation to anatomic ranges of motion based on the average maximum voluntary range of motion for male and female adult (see [Chang, 2010]).

The robot manipulator model is based on a system consisting of a Mitsubishi PA-10 7-DoF arm with a 24-DoF Shadow Hand C3 end effector (Shadow Robot Company, London, UK). The kinematic model for this workspace analysis only considers the degrees of freedom required to the position the hand segment without modeling the finger joints. There are a total of 9 DoFs for the robot system from the 7-DoF PA-10 arm combined with the 2 wrist DoFs of the Shadow Hand Robot.

2) Example task scenario: The example scenario for the workspace analysis is a pan grasping task similar to the pan transport in the human studies described in §IV-A1. The task is to achieve a particular grasp of a cooking pan object on a tabletop surface, where the grasp is defined by the relative transform of the hand palm segment and the pan handle. The goal of the workspace analysis is to determine the initial pan configurations on the tabletop where such a grasp is kinematically feasible. The boundary of the workspace will indicate potential areas where a preparatory manipulation strategy such as object rotation can extend the reachability of the grasp.

In the kinematic analysis, the manipulator's base is fixed at the origin, and the $+z$ axis points upwards such that the table surface spans the x-y plane. For the example tasks, the table surface is set at 0.765m, based on a physical table used with the actual robot manipulator in the experiments described later in §V-B.

The cooking pan is an typical object relevant to pre-grasp interaction because desired grasps are limited to its handle area in many tasks. The two specific grasps considered in this analysis are (a) an overhand, straight cylindrical grasp where the thumb wraps under the handle and (b) an underhand, oblique cylindrical grasp, where the fingers wrap underneath the handle with the thumb above. These grasps are based on the two main styles of cooking pan grasps observed of the participants in the previous study (§IV-A1). The kinematic analysis focused on achieving the relative transformation between the pan handle and the hand palm. No inter-joint dependencies on joint limits are considered. For example, it is assumed that the finger configuration of the grasp is reachable regardless of the wrist configuration.

3) Computation of grasping postures: The grasp capture region is determined by the set of object configurations for which there exists a grasping posture satisfying the grasp constraints. The desired grasp is specified by a 6-DoF description of the hand palm pose relative to the object pose in the world. The grasping posture is the manipulator configuration, which is either has 10 DoFs for the human upper body model or 9 DoFs for the anthropomorphic robot model. The redundancy of the 9/10-DoF systems relative to the 6-DoF task space results in the possibility that a subspace of multiple grasping postures exist as solutions to the 6-DoF grasp constraint.

In general it is non-trivial to solve for a complete inverse kinematics (IK) solution, especially for high-dimensional redundant systems. The analysis presented here addresses the IK problem with a combination of sampling the manipulator joint-space configurations and a local search using the samples as initialization points. First, the configuration space is sampled at discretized joint angle values to pre-compute the forward kinematics (FK) of a representative set of possible end-effector configurations in the workspace. Then, given a desired hand configuration for the pan grasp, we search for an inverse kinematics (IK) solution for the arm configuration using the nearby pre-computed samples as initial guesses for a gradient-based search.

For high-dimensional systems it is prohibitive to compute and store a fine sampling of the configuration space for possible grasping postures. Our solution reduces the size of the FK pre-computation by decomposition of the 3 wrist DoFs from the remaining proximal arm joints. This provides a separation of the end-effector position and orientation. Details of the sampling and adjustment for non-intersecting wrist axes are described in Chang [2010].

Given a specific desired end-effector configuration for the palm, we determine a set of IK initialization points by choosing samples which approximately match the desired position and exactly match the desired orientation of the forearm. For the position, the candidate samples of the neutral wrist configuration must lie within a 10cm cube centered around the desired end-effector position. For the orientation, the candidate samples of neutral wrist orientations must be within the allowable set of neutral-wrist orientations which could reach the desired end-effector orientation with respect to the three wrist DoF joint limits. This allowable set of neutral-wrist orientations is computed by transforming the desired end-effector orientation by the inverse transformations of the pre-computed wrist orientation contributions. For an admitted IK initialization points which satisfies both the position and orientation criteria, the three wrist angles can be computed directly such that the initialization point is the full 9 or 10 DoF configuration rather than the 6 or 7 DoF neutral-wrist sample. We found that initializing with the wrist angles which achieved the desired end-effector orientation was important for successfully finding an IK solution which satisfies the wrist joint range of motion.

From this initialization set, the IK solution for the grasping posture was computed using an iterative pseudo-inverse Jacobian method, implemented by [Corke, 1996]. The implementation the pseudo-inverse Jacobian search does not respect joint limits, such that it was possible for the returned solution to violate the joint ranges of motion. This limitation is one reason why the success of finding a feasible IK solution that satisfies the joint angle limits is highly-dependent on the initial guess for the iterative search. Any IK solution which does not satisfy all the joint limits was discarded. All configurations in the initialization set were tested such that the overall search may generate multiple IK solutions which reach a single desired end-effector pose.

4) Reachable object configurations in workspace: For both manipulator systems, the reachable pan orientations were computed for both the straight and oblique cylindrical grasps for a set of sampled pan positions.

For the human manipulator, there are few pan positions for which more than 75% of the possible handle orientations can be reached by either grasp (Fig. 5). In particular, near the boundary of the workspace, only half or less of the pan orientations are graspable. For most pan positions, there is a larger capture region for the oblique grasp compared to the straight cylindrical grasp. The pan positions near the coordinates (-0.3m, -0.6m) are of particular interest since this region corresponds to the approximate x-y pan position relative to the waist for the lifting postures from the human motion capture experiments described in §IV. The limited reachability of the straight grasp compared to the oblique grasp for this region may be a reason that there were fewer examples of this grasp observed from informal inspection of the human pan grasping. The capture region size of about 210 degrees and direction toward the body of the oblique grasp in this area is consistent with the large variability in the observed lift angles observed from the human examples.

[Fig. 5 about here.]

[Fig. 6 about here.]

The robot manipulator has a larger workspace than the human manipulator due to the longer limb lengths (Fig. 6). Even though the robot has fewer degrees of freedom (9 versus 10 DoFs), the large range of motion of the PA-10 arm joints results in reachable pan configurations which are qualitatively similar in capture region direction as that for the human manipulator. Similar to the results for the human manipulator, the capture region size for the straight cylindrical grasp is generally smaller than that for the oblique grasp for radii greater than 0.5m. The area of interest for the lab demonstration setting are the pan locations about 1m in front of the robot ($(x, y) = (0m, -1.0m)$) due to the position of the table. In this area, the capture region points toward the manipulator's right side ($-x$) for the straight grasp and faces toward the manipulator ($+y$) for the oblique grasp, which is similar to the human manipulator. In terms of the potential for workspace extension due to pre-grasp rotation, there are also several pan positions for which only about half of the pan orientations are graspable. This case occurs particularly for the outer regions of the workspace with greater than 0.7m radial length from the base torso position.

For example, consider the initial object position in the robot workspace at (0m, -0.9m), which is centered in front of the base a radial length of 0.9m. Both the oblique grasp and the straight cylindrical grasp can reach a capture region which is larger than 180 degrees. However, at least one-third of the possible handle orientations are still unreachable by the manipulator. Objects starting in orientations outside the direct grasping capture region could be adjusted using pre-grasp rotation to complete an acquisition task over a greater range of initial task conditions. This example is considered in an empirical demonstration described in the following section.

B. Robot grasp reuse

The workspace analysis in the previous section (§V-A) illustrated regions where pre-grasp rotation may expand the grasp capture region beyond the direct-grasping boundaries. The analysis computed individual grasping postures that satisfied a desired grasp of the object handle without considering that motion required to reach a grasping posture.

In this section we examine the concept of pre-grasp object rotation as a strategy for reusing a single well-tuned grasp routine programmed for reaching a particular grasping posture on robotic manipulator system. Here the grasp routine that is reused consists of the complete arm reaching action and the grasping motion of the fingers after the palm is placed in the desired grasp frame relative to the object. A grasp routine may only successfully lift the object from a small set of initial poses if the finger closing action is small relative to the possible object orientations. Pre-grasp object rotation can extend the effective workspace of such a grasp prototype. Reusing grasping routines for larger grasp regions can reduce the number of motor action primitives necessary for robot manipulation. This reuse can save programming time for manual actions or search time for automated sequencing of action primitives.

The manipulation actions were implemented on the system, previously described in §V-A, consisting of a the 7-DoF PA-10 arm and 24-DOF Shadow Hand C3 end effector. The grasping routine completed a pan transport task similar to that in the human studies §IV-A1, where the object is grasped from a position in front of the robot base and then laterally transported to the left side. The object starting position on the table was located 0.9m in front of the manipulator base. The object goal position was located on the table 0.35m to the left of the start position. Twenty-four handle directions were selected to sample initial object orientations at 15-degree intervals. The object was an empty cooking pan with a handle that had a mass of 0.46kg. The pan pose was tracked by attached markers and a Vicon camera system.

[Fig. 7 about here.]

1) Open-loop routines for grasp reuse: The grasping strategy using pre-grasp rotation was implemented as two manually-programmed open-loop routines. One action is the pre-grasp rotation routine for reconfiguring the handle orientation prior to grasping. The other action is the grasping routine for lifting and transporting the pan by its handle. The two actions are executed sequentially for a complete manipulation action which transports the pan from any initial handle orientation.

The grasping routine is a sequence of three manually-programmed motion components. The robot arm with an open hand grasp shape is moved from an initial configuration on the right toward the pan position in the approach or reaching motion. In the grasp motion, the PA-10 arm configuration remains fixed while the hand's finger joints close around the handle. Finally, the hand maintains a closed grasp shape around the handle during the transport motion where the PA-10 arm lifts and moves left to the goal position.

The pre-grasp rotation routine was implemented as a pushing motion using single-finger contact with the object to turn the cooking pan around its natural pivot point. The index finger was flexed 90 degrees, normal to the palm, while the thumb and other three fingers remained extended in the plane of the palm and parallel to the table surface. With this fixed hand shape, the arm moved in an arc such that the index fingertip traced a circular arc of 315 degrees in a clockwise direction around the object perimeter and ended within the intended grasp capture region. Please see Chang et al. [2008] for illustrations of the pre-grasp rotation and grasping routines.

2) Empirical evaluation of workspace extension: We evaluated the effective capture region of the grasping routine alone in comparison to the sequence of the pre-grasp rotation followed by grasping action. The two methods were each tested on the different initial handle orientations in a set of 24 consecutive trials.

The empirical capture region of the grasping routine alone covered 4 of the 24 initial handle angles, for a region size of 45 degrees. Note that this capture region is much smaller than the capture region reported previously in the workspace analysis §V-A because the grasping routine is based on a single reachable grasping posture rather than the complete set of grasping postures for the object location.

In contrast, when the pre-grasp rotation routine preceded the grasping action, successful transport occurred for all 24 of the 24 consecutive trials. The pre-grasp rotation routine reduced the uncertainty in the object orientation by consistently rotating the pan into the center of the grasping routine's capture region. The handle angles after rotation and before the grasp were all within a 15-degree range.

VI. Discussion

First, we identified several types of human pre-grasp interaction strategies. A further examination of the specific example of pre-grasp rotation investigated possible factors that drive object adjustment over a direct reaching action in difficult grasping tasks. These factors include a preference for a reuse of a particular class of body postures and hand grasps, whose selection seems to be related to the strength capabilities for supporting the object in the post-grasp. Second, we performed a workspace analysis of both the human upper body and a robot manipulator. This demonstrates the potential advantages for a robot manipulator to use pre-grasp interaction strategies to increase the effective reachability of objects for specific desired grasps.

This work has investigated pre-grasp interaction as a manipulation strategy for successfully grasping objects during a difficult task. In our survey of human manipulation actions in natural settings (§III), we found several examples where humans do not or cannot grasp an object at the desired surface contacts without first re-configuring the object in the workspace. Regrasping is one method of reconfiguration, but pre-grasp interaction also occurs in the form of non-prehensile manipulation such as pushing or tumbling. We suggest that pre-grasp interaction may be especially useful for difficult tasks involving heavy objects and/or cluttered environments where the object is not conveniently presented for reaching the desired grasp.

Overall, we promote a broad view of the richness of manipulation skills for object interaction. We have shown that the seemingly simple skill of object acquisition can involve a sophisticated process of pre-grasp manipulation to achieve the desired grasp for the subsequent task. Here we review the highlights and limitations of our findings. We also suggest avenues for future research on human manipulation and commonalities with motion planning for robotic manipulation.

A. Human manipulation strategies

Pre-grasp object interaction is a broad description of one approach humans use to complete manipulation tasks robustly. Our experiments on human pre-grasp rotation represent an initial investigation of how object manipulation actions such as pushing or pivoting interact with the grasp acquisition.

Within the pre-grasp rotation category, we investigated the effect of particular task parameters such as initial object orientation, object weight, and lifting precision on the choice of object rotation. We also found that aspects of the manipulator, such as an individual's lifting capability or a robot's payload capacity, may drive the selection of a preferred grasping posture enabled by pre-grasp rotation. Other factors that plausibly influence the choice of preferred object orientation include the direction of transport to the goal location, the surface friction between the object and support surface, and obstacles in the environment. Learning how these factors change the performance of pre-grasp rotation may contribute to the understanding of why and when it is chosen as a motor action.

At a higher level, there remain several interesting questions about how humans choose among multiple strategies rather than the parameters for a single strategy. The taxonomy of pre-grasp interaction strategies presented in §III categorizes interaction examples based on the degrees of freedom in the object reconfiguration. The categorization provides a guide for classes of pre-grasp strategies, but it would benefit from a model of how the task specifications determine the choice between two possible strategies. For example, for articulated pliers, how does the primary manipulation task (for example, either transport, hand-off to another person, or bending a wire) determine whether the tool is pivoted, tumbled, or folded during the pre-grasp interaction?

We have shown for pre-grasp rotation that the choice of whether and how much to rotate the object is in part a response to the task difficulty factors of object weight and upright precision for our canister lifting task experiment Along these lines, it would be useful to develop a formal, generalizable representation of the primary manipulation task difficulty. Descriptors of task difficulty in such a representation may provide a mapping for predicting the probable resulting pre-grasp interaction. Example factors that we speculate contribute to difficulty and thus more sophisticated strategies include the number and occlusion of possible object surface contacts for grasps, the object inertial properties, and the friction in or resistance to the object or environment to the possible reconfiguration freedoms. Manipulator constraints of the human body – e.g., strength, bimanual availability, or position mobility – are additional considerations.

The uncertainty in and/or the human perception of these difficulty factors may be more critical than the actual values, such that cognitive load in planning a difficult maneuver is a driving factor. For example, the strategy choice will be limited by the perception of allowable object affordances, such as whether an object can be tumbled or whether a set of objects are stackable.

Finally, we have implicitly referred to pre-grasp interaction as an intentional, planned strategy that may optimize some aspect of the primary task. It is possible that some pre-grasp interactions arise from exploratory interactions with an object, such as in the haptic exploration of an unfamiliar surface for a grasp point, or from recovery responses to unintentional disturbances, such as when an object slips during an imprecise grasp action.

B. Generalization of manipulation planning optimization functions

While one approach to achieving robust and dexterous manipulation is to build a repertoire of task-specific behaviors, another avenue toward general manipulation capabilities is the identification of an explanatory optimization function for planning any action. In addition to providing insight into human cognition and motor skills, a unifying model for motor actions would avoid the need for manual observation and extraction of promising strategies for mimicry. The behaviors of gathering, separation, and bracing described previously are similar to pre-grasp interaction in that they involve some preparatory action to "set-up" a task.

Below is a non-exhaustive list of possible criteria from whose optimization could emerge the natural motor strategies of pre-grasp interaction and other behaviors:

- Time or speed
  - Time for task completion
  - Planning or decision time
  - Cognitive retrieval time or load for new versus repeated/similar actions
- Torque or load or effort
  - Total joint torque magnitudes
  - Torque of weakest joint
  - Margin from multiple joint torque limits
  - Margin from weakest joint torque limit (payload margin, lifting capability, or available strength)
  - Energy or perceived exertion
- Posture or form
  - Margin from joint limits (available travel)
  - Manipulability or margin from singularities
  - Balance or stance stability
  - Grasp stability
- Confidence, robustness, or flexibility
  - Reachability of target from multiple postures
  - Reliability of sensory information: visibility, tactile redundancy
  - Reliability of action execution or remaining within actuation capabilities
  - Availability of alternative exit strategies: setting object down, or changing grip mid-task
  - Collision avoidance or distance to obstacles
- Comfort in action execution, or avoidance of pain
- Interaction predictability or social acceptance: avoidance of awkward or unlikely postures

In this work we have examined a small set of metrics in the context of pre-grasp interaction. In the human motion studies, we found that time for task completion was not an explanatory metric for the pre-grasp rotation, since task completion took longer for pre-grasp rotation compared to direct grasping. However, time for planning initial movement was shorter and suggests that decision making or cognitive load could be a driving factor. We also tested metrics based on physical load at the time of object lift-off. These included the magnitude of joint torques over multiple joints. Furthermore we surveyed subject's self report of comfort but did not find a clear preference for the pre-grasp rotation method. An objective measure of discomfort, such as local muscle fatigue [Chaffin, 1973], may be a more reliable metric if it could be practically recorded.

Future research is required to determine if there is indeed an underlying optimization criteria driving general human manipulation actions. A holistic criteria such as robustness or success rate that includes multiple factors may be necessary for modeling complex human motion over a wide range of behaviors. In addition, human motion may not necessarily be optimal but instead merely sufficient to complete the task objective using any one of multiple similar strategies. It also remains to be seen whether identification and implementation of such an optimization criteria on a robotic system would result in the emergence of similar manipulation behaviors observed in humans, despite the differences in kinematic, sensory, actuation, and computation capabilities.

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Glossary

- **capture region**: The set of initial poses from which an object can be successfully grasped with a particular grasping strategy or routine. See also comfort zone.
- **comfort zone**: The set of object poses at the lift-off time point in a grasp acquisition action. See also capture region.
- **end-effector**: The rigid body segment or robot link of interest for task completion, usually the most distal segment, e.g. the hand or palm segment for a manipulation task.

- **grasping posture**: The manipulator configuration at the lift-off time point.
- **lift-off time point**: The first time when a grasped object is completely separated from the original support surface and completely supported by the manipulator.
- **nonprehensile interaction**: Non-grasping contact or interaction where the object is not necessarily fixtured rigidly to the hand or end-effector.
- **pre-grasp or preparatory interaction**: Contact or interaction that adjusts objects placement in the environment prior to grasping and a primary manipulation task.
- **pre-grasp rotation**: Pre-grasp interaction where the object adjustment consists only of changes in the object orientation in the plane of the support surface.
- **primary task or primary interaction**: The action following or requiring object acquisition in a grasp, e.g. transport of the object while fixture in a grasp.

INDEX TERMS

- balance constraints
- canonical posutres or grasps
- capture region
- comfort zone
- difficulty, task
- end-effector
- grasp reuse
- grasping posture
- lift-off time point
- manipulation or motion planning
- nonprehensile interaction
- object mass or weight
- posture selection
- precision constraints, task
- pre-grasp or preparatory interaction
- pre-grasp rotation
- primary task or primary interaction
- pushing
- reaching
- reuse, grasp
- rotation
- task difficulty
- taxonomy, grasp or activity
- weight, object

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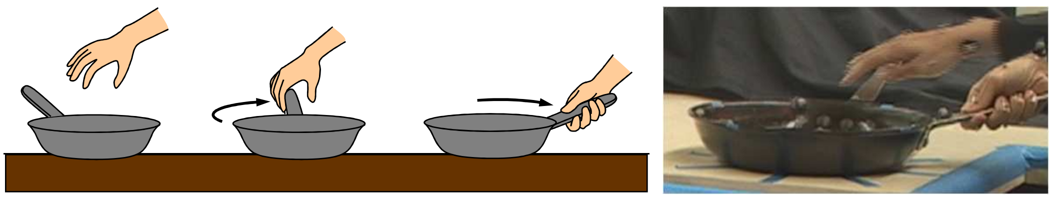
List of Figures

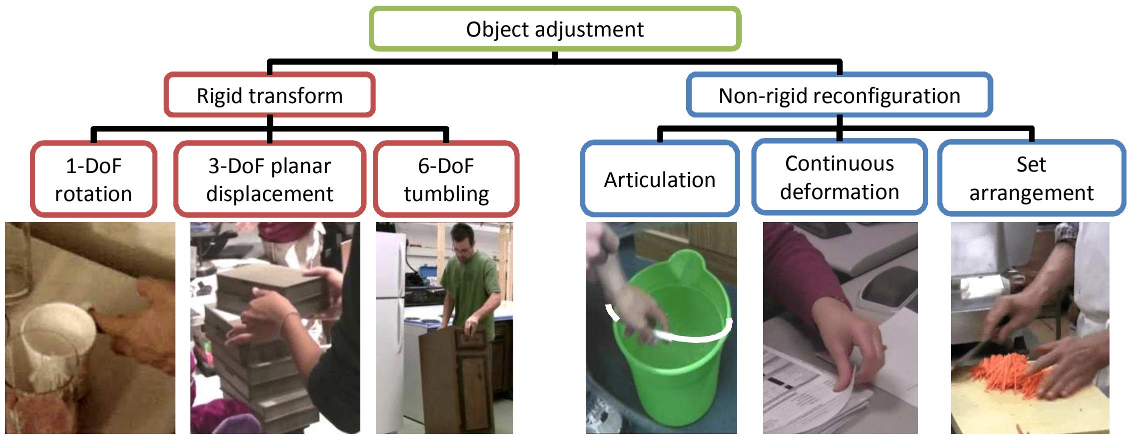


(a)

(b)

(c)

Fig. 1. (a) Pre-grasp rotation of a cooking pan adjusts its orientation before completing the final grasp of the handle. (b) Pan grasps at lift-off time using natural pre-grasp rotation strategy. The final grasps of the pan handle are similar when rotation has been used to adjust the object orientation. (c) Pan grasps at lift-off time using only direct grasping. Without object adjustment, the final direct grasps are much more varied than the grasp set that is reused after pre-grasp interaction.



Objects in observed examples

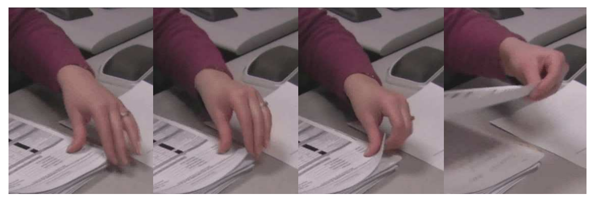
mug	books	cabinet	bucket	paper	peelings
stapler	CD cases	pan	ladder	rug	bolts
pan	pitcher	wrench		foil	paper stack
	large box	paperclip		plastic bag	set of jars
	plates	spatula			chopped produce
	food carton	chopsticks			
		books			

Fig. 2. Taxonomy for the object reconfiguration aspect of pre-grasp interaction. Examples of rigid planar transformations included rotation of a cup by its handle and sliding books off the top of a stack. General rigid tumbling was used to achieve a whole body grasp of a bulky piece of furniture. Pre-grasp interaction was also observed for non-rigid objects. A hinged bucket handle was rotated to achieve a hook grasp, and a piece of paper was curled to achieve a pinch grasp. Multiple objects were also rearranged as a set, such as in the scooping interaction with a pile of carrot peelings.

(a)

(b)

(c)



(d)

(e)

(f)

Fig. 3. (a,b,c) Examples of object reconfiguration classes for pre-grasp manipulation. (a) Planar displacement: Books are slid off the top of a stack to grasp the bottom surface. (b) Rigid discplacement: A cabinet is tumbled to reach a handhold on the bottom in order to carry it sideways. (c) Articulated motion: The bucket handle (highlighted in white) is lifted from the side to achieve a whole-hand grasp of the handle. (d,e,f) Constraints improved by pre-grasp interaction. (d) Environment constraints: The top sheet of paper is lifted from the stack to expose the underside for grasp contact. (b) Manipulator constraints: The pan is tumbled by the right hand so that the left hand can grasp the handle. (c) Object constraints: The pile of peelings is reshaped between two hands before lifting from the cutting board.

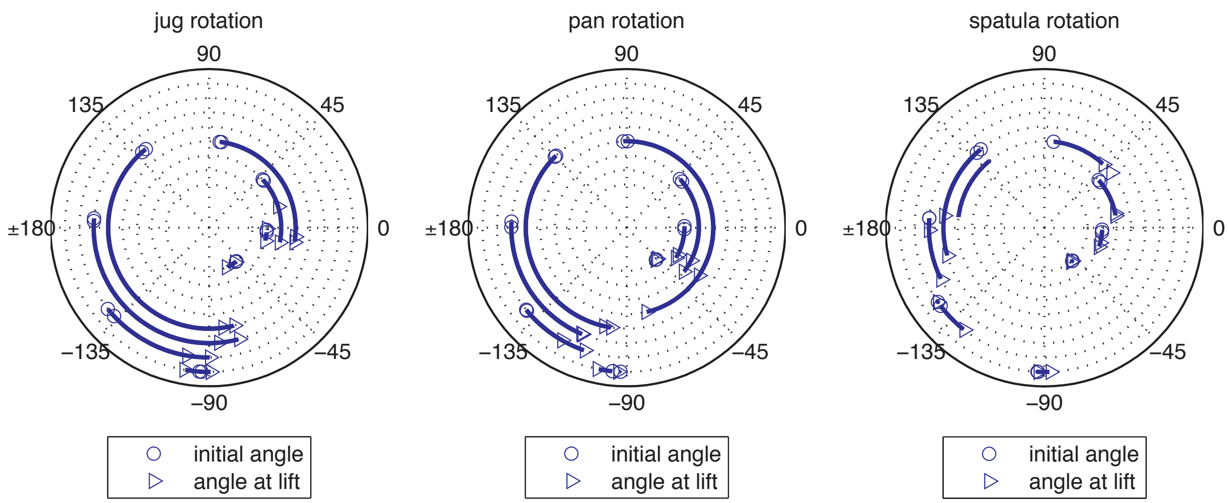


Fig. 4. Pre-grasp rotation for different household objects. The plots show the difference between the initial handle orientation and the lift-off orienation for one example participant. (a) Jug object. (b) Pan object. (c) Spatula object. There is less rotation for the lightweight spatular compared to the heavier jug and pan.

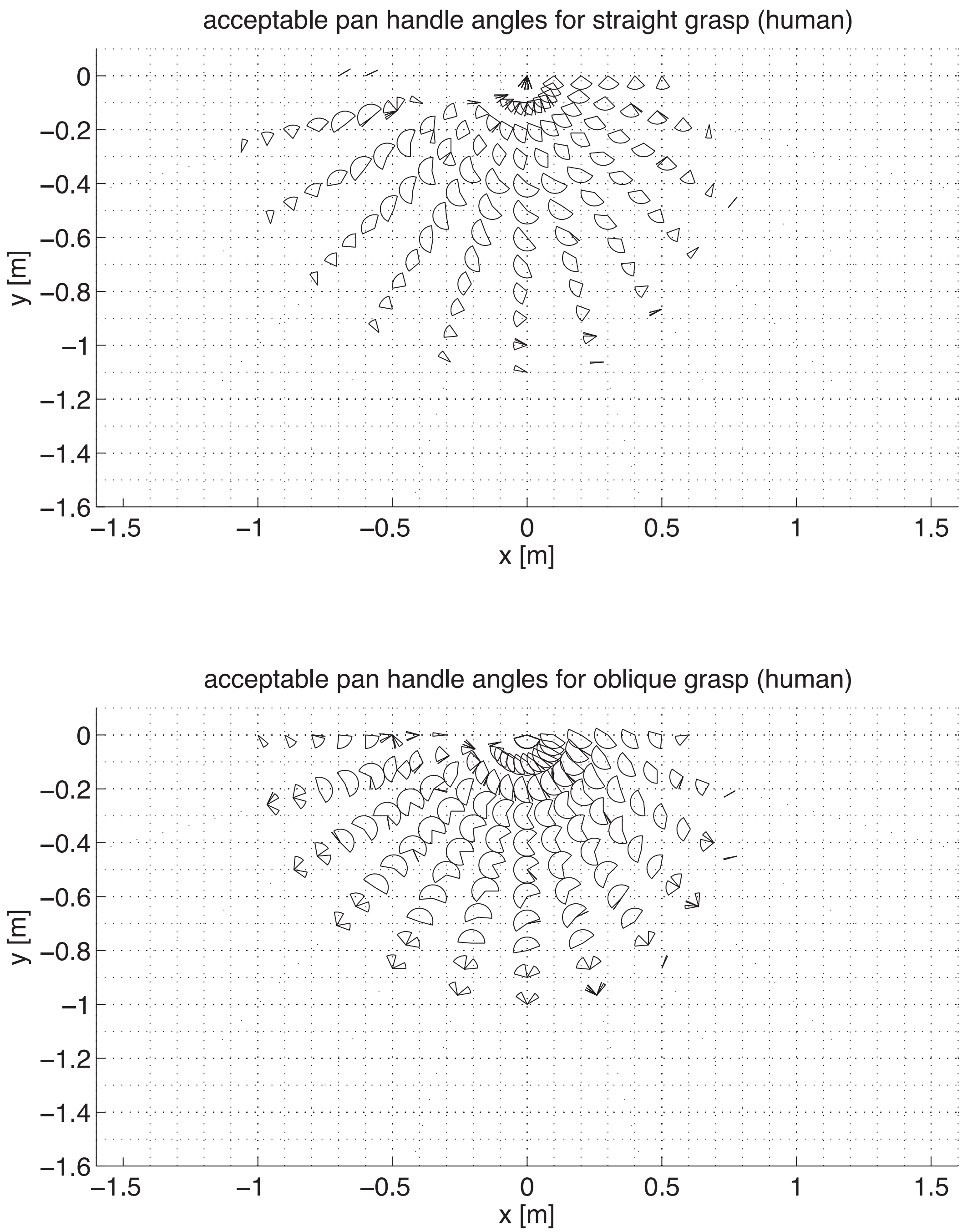


Fig. 5. Visualization of the pan orientations reachable by the human manipulator. The sectors at each selected tabletop positions denote the range of the graspable handle directions.

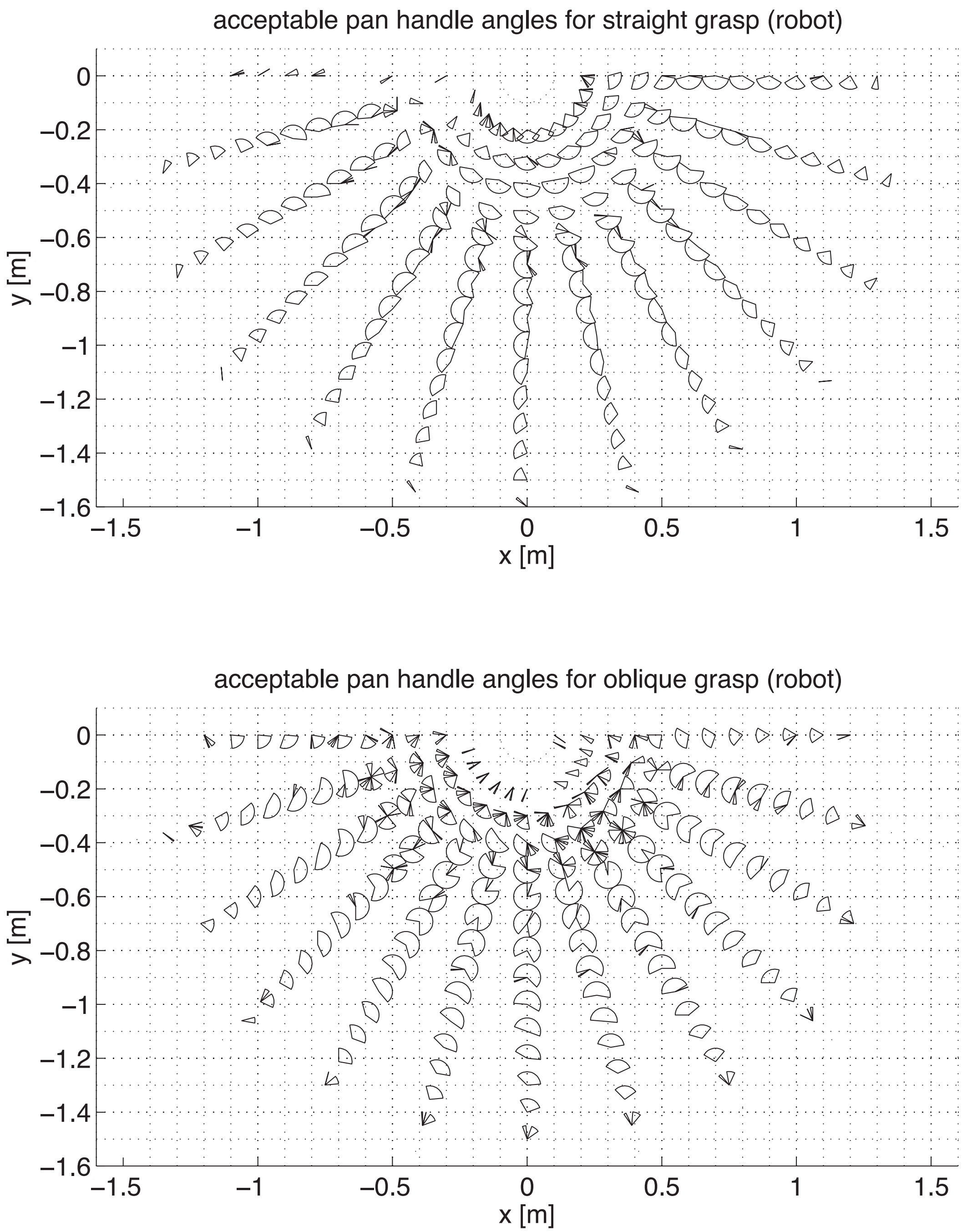


Fig. 6. Visualization of the pan orientations reachable by the robot manipulator. The sectors at each selected tabletop positions denote the range of the graspable handle directions.

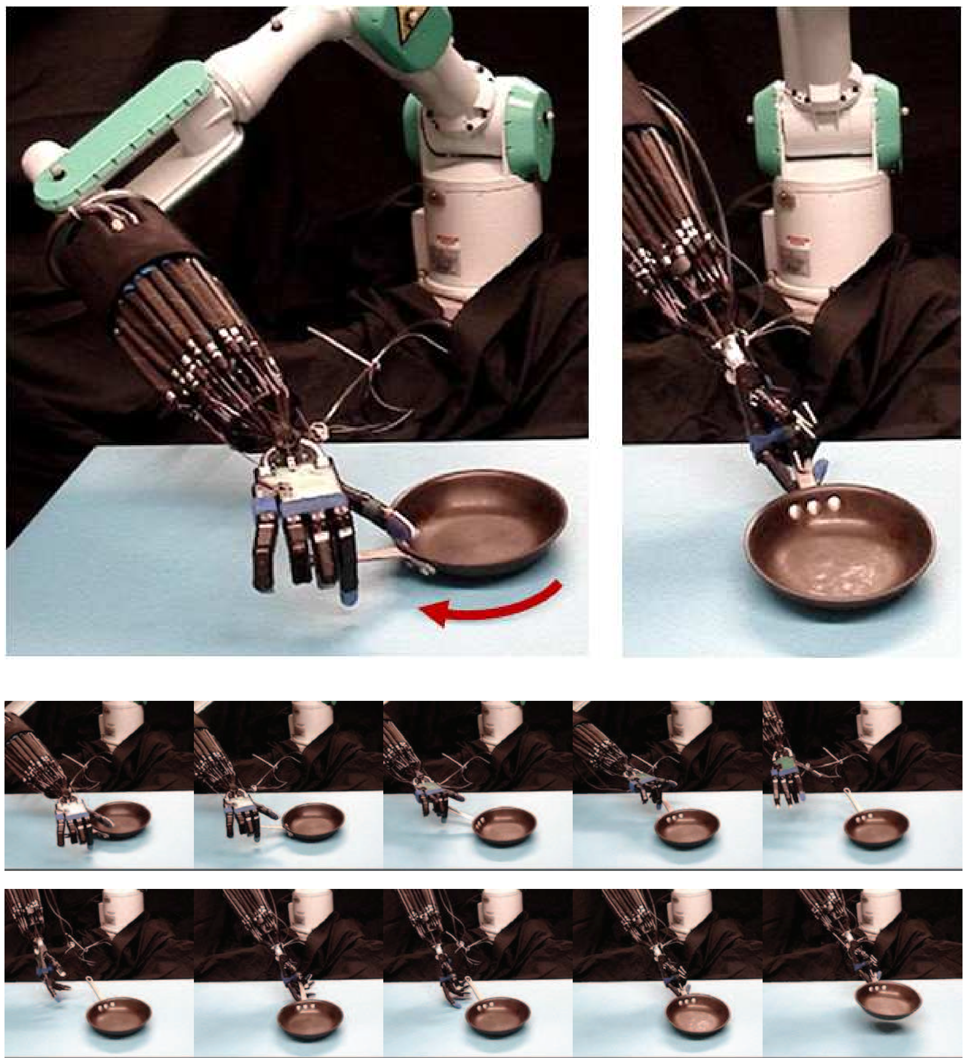


Fig. 7. Pre-grasp interaction improves the capture region of a pan-grasping routine for an anthopomophic robot manipulator. The pre-grasp rotation adjusts the object orientation in the environment prior to grasping, without requiring a new reach-to-grasp motion plans for each new orientatfion outside the reference grasping capture region.